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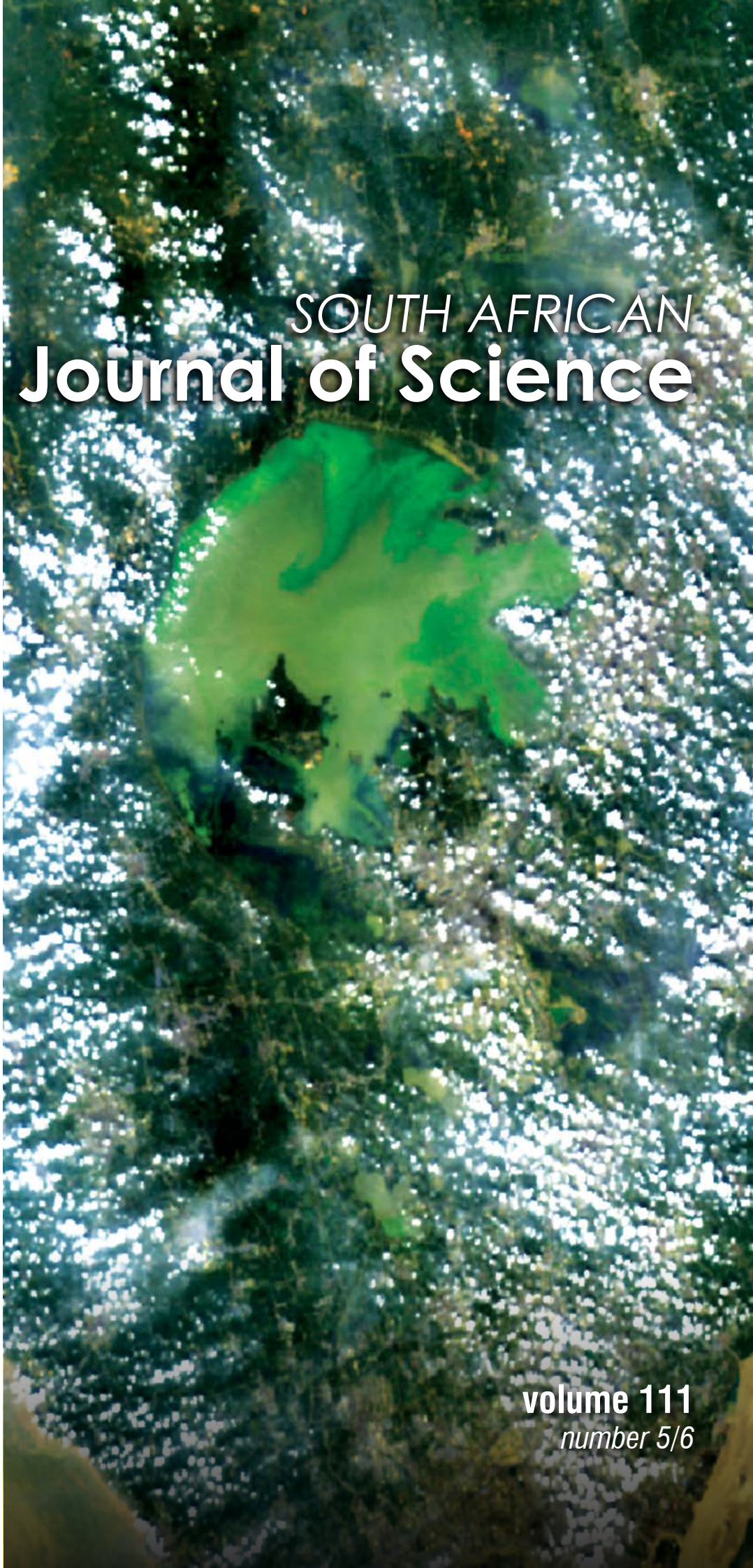

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Research Article

Women, productivity and progress

> *The challenge for Africa is to ensure that the gender imbalance in the practising of science, technology and innovation* [STI] *is addressed. None of us here underestimates the importance of science, technology and innovation for socio-economic development, in both the developed and developing world. The involvement of women in STI activities is thus crucial for contributing to the development of nations.*
>
> Minister Naledi Pandor, 2015[1]

In the 114 years over which Nobel Prizes have been awarded in six categories, 47 women have received the award, of whom just 16 have been in what might be called the 'disciplinary' areas of the awards (i.e. not including Literature and Peace). Two of these prizes were in Physics, five in Chemistry, eight in Physiology and Medicine, and just one in Economics.

In the 70 years during which Fields Medals have been awarded, only one woman has been a winner: Maryam Mirzakhani, in 2014. The Abel Prize (2003–2015) has never been won by a woman. And the Holberg Prize (2004–2015) has been awarded 14 times, but to women on just three occasions. It would be remiss if we were not also to mention that just 3 of the 13 members of the Council of the Academy of Science of South Africa (ASSAf) are women (although a woman leads the Academy internally as Executive Officer); and that the University of Cape Town has only just this year appointed its first ever woman Dean of Engineering and the Built Environment (Professor Alison Lewis, a Chemical Engineer) in the 186-year history of the institution.

Perhaps, however, one of the most deplorable cases of the marginalisation of women scholars is that of Amalie Noether (born in 1882) whose first great theorem demonstrates that 'symmetries give rise to conservation laws'. This insight has been the foundation for almost every fundamental discovery in Physics since then. Yet despite being recognised as a genius, and having a professor for a father, she was denied entry to a university on the basis of her gender. After a struggle, she was allowed to study and received a PhD, but was unable, as a woman, to find a university position. She was finally recognised as one of the world's leading experts in the mathematics of symmetry – without ever having had an appointment, a salary or a title.

It is probable that these rather gloomy conditions may be attributed to at least four fundamental causes. In many parts of the world, historically, girls and women have not had the same access to education as their male counterparts have enjoyed. There is a lingering tradition, in some schools, of encouraging boys to study physical science and girls to focus on biology and to become teachers while methods of teaching science have not been mainstreamed appropriately to consider gender equality in, for example, teacher education and curriculum development. Institutional structures, and a persistent lack of support in the workplace, have disadvantaged women in their quest to progress in scientific careers. And, finally, there has been, and remains, deliberate and persistent, although often hidden, discrimination in academia as elsewhere in society. A recent review of an article submitted to *PLOS One*, suggesting that the women authors find a man to work with if they wanted an acceptable paper, is just one example of blatant sexism.[2]

Yet the fact that women have won at least some of the world's most prestigious scientific prizes, and continue to play leading roles across the full range of scientific research, serves to remind us that the distribution of intelligence, research skills and imagination is not gender-based, any more than it is ethnicity-based, but fundamental to the human condition. For example, who, in South Africa and elsewhere, is not aware of the critical roles played in the identification of the coelacanth and its introduction to the world of science, by Marjorie Courtenay-Latimer and Margaret Smith?

Ms Pandor's urging has both moral and practical force. Moral, because there is absolutely no justifiable reason for the exclusion of over half the population of a country or continent – or the world, in fact. And practical because, like the rest of the world, Africa needs all the research and applied skills that can possibly be mustered across the complete spectrum of disciplines. The entire population needs equal access to education, training and employment.

It remains true, however, that women still are the minority members of science and engineering disciplines in academia. The Association of African Women in Science and Engineering estimates that women constitute no more than 20% of the academics in these fields in Africa[3], although even in the USA, the number reflects a minority: 46% of academics in science and engineering fields are women (the number is bolstered by the 16% in Life Sciences)[4]. In this regard, GenderInSITE (Gender in Science, Innovation, Technology and Engineering) southern Africa – implemented by ASSAf – seeks to: demonstrate how gender analysis of science and technology can lead to improved development in key development sectors; highlight women's transformative role in development and the contributions of women to SITE, and how science and technology can support women and men; and promote leadership of women in SITE.

WISE – the South African Association of Women in Science and Engineering – offers this apt observation:

> *Africa, including South Africa, has a critical shortage of trained technological people. ….Increasing the number of technologically trained people, both men and women, is essential for development.*[5]

The same is not only true for the academic world – the realms of teaching and research. Catalyst©, a non-profit organisation whose mission is to expand opportunities for women and business, has gathered research findings from a number of respectable sources. Their collected research shows that

> *women board directors make invaluable contributions to companies and the boards on which they serve. But the benefits of having women on the board go beyond simply influencing board deliberations, better meeting attendance and preparation, and improved boardroom behavior. In fact, having more women on the board may help companies solve the problem of insufficient numbers of women in their executive ranks.*[6]

They go on to say that

> *Fortune 500 companies with the highest representation of women board directors attained significantly higher financial performance, on average, than those with the lowest representation of women board directors.*[7]

In any sphere of the intellectual, public and private endeavours that manage critical physical and non-physical resources, and that contribute to their creation and effective use, it is people who are critical. But the Catalyst© research foregrounds the important finding that the dominance of men does not just limit the 'pool of skills' but also limits productivity – and creative, sound decision-making.

Various arguments around shifting the balance of ethnicity of staff in universities and other research institutions refer to the time it takes for black scholars to reach the levels of experience required for professorships. True or not, this case cannot be applied in women's

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circumstances. South Africa, at least, has a host of distinguished women scholars who, like Alison Lewis, are admirably suited to lead Departments, Faculties, Universities, Research Foundations and Institutes. This Journal supports their right to be fully recognised for the research, teaching and management leaders that they are – and to be appointed accordingly. Three of South Africa's seven world-leading researchers in their fields, as determined in 2014, are women.

There can be no more excuses.

References

1. Minister Naledi Pandor on women scientists [press release on the Internet]. c2015 [cited 2015 May 05]. Available from: http://www.gov.za/speeches/minister-naledi-pandor-women-scientists-28-apr-2015-0000
2. Cochran A. Sexism in peer review [homepage on the Internet]. c2015 [cited 2015 May 08]. Available from: http://scholarlykitchen.sspnet.org/2015/05/07/sexism-in-peer-review/?utm_source=feedburner&utm_medium=email&utm_campaign=Feed%3A+ScholarlyKitchen+%28The+Scholarly+Kitchen%29
3. African Women in Science and Engineering [homepage on the Internet]. No date [cited 2015 May 08]. Available from: http://www.aawse.org/
4. National Science Board. Science and engineering indicators 2014. Arlington, VA: National Science Foundation; 2014. Available from: http://www.nsf.gov/statistics/seind14/content/chapter-5/at05-15.pdf
5. The Association of South African Women in Science and Engineering [homepage on the Internet]. No date [cited 2015 May 05]. Available from: http://web.uct.ac.za/org/sawise/
6. First step: Gender diversity at the top pays off [document on the Internet]. c2014 [cited 2015 May 05]. Available from: http://catalyst.org/system/files/first_step_gender_diversity_at_the_top_0.pdf
7. Companies with more women board directors experience higher financial performance, according to latest Catalyst bottom line report [homepage on the Internet]. No date [cited 2015 May 05]. Available from: http://www.catalyst.org/media/companies-more-women-board-directors-experience-higher-financial-performance-according-latest

Ghosts

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Drinking with Ghosts: The aftermath of apartheid's dirty war

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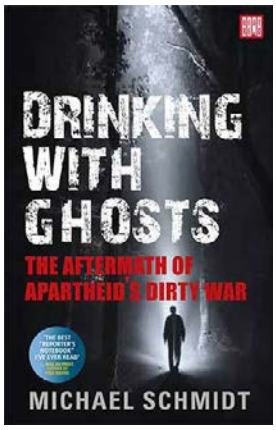

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Drinking with Ghosts: The Aftermath of Apartheid's Dirty War is a powerful work dealing with South Africa's violent political struggles, its political transition, and the ways dark and secret pasts continue to haunt post-1994 South Africa. South Africa's modern political history is covered in an ever-increasing number of books, both scholarly and more popular. Similarly, there is an ever-increasing amount of scholarly work concerned with trauma, forgiveness and reconciliation. Taking their cue from the post-1994 South African government's internationally heralded Truth and Reconciliation Commission, many research and publicly engaged institutes now address these very issues. Schmidt's book is quite different. He doesn't share the notion that forgetting can be part of healing, and is sceptical of narratives of the 'miracle' 'Rainbow Nation' or the 'New South Africa'. Whilst respecting the scholarly, he will have none of the celebratory. Schmidt's view is succinct: South Africans will neither reconcile nor develop a common humanity unless its many hidden and covered-up abodes of darkness and terror are exposed, confronted, and written into history.

This book is also unlike other recent books by journalists writing within this broader field. It is not a biography, such as that of Eugene de Kock, or ghost-written accounts of tortured victims of *MK* camps in Angola. It's not a conspiracy story on the trail of red mercury, or 'reds under bed'. Nor is it in the heroic *grensvegter* mould. Nor is this a current journalist publishing in book form lengthy texts of his own press reports. The journalist's personal story of self-enlightenment is not highlighted over the real story – as it is in a recent study of the Marikana massacre. Nor is it a cut-and-paste book from journalists' courtroom media tweets amidst international press attention. Nor is this journalism as exposé making or celebrity seeking. And, the book is well published – by the Human Sciences Research Council's BestRed imprint – and includes scholarly footnotes, a bibliography and index; all of which are refreshingly different from other recent publications in this genre. This is 'dark and stormy night…' journalism, but only in one breathless sense. There are plenty of dark nights, conspirators and conspiracies, burning dwellings, atomic explosions, different poisons, armoured battles the likes of which were last seen in Africa in 1943, global geo-political plots and calculations, and ruthless plotters and calculators. There's a sniper rifle to be aimed at Mandela that passes hands between the two major political adversaries. And there are plenty of bodies – tortured, screaming, writhing, poisoned, burning, rotting and, in their many hundreds, being thrown alive out of aeroplanes over the Atlantic. There are many hanging questions – which in a novel would be mysteries and riddles. But this is not creative writing. As Rian Malan rightly observes, here is a 'high speed ride through the nightmares of recent South African history, with a nerveless, dead-eyed journalist at the wheel' (back cover).

But this book is more than what South Africans would usually see as South African history. It has a truly southern African and global reach. Schmidt understands his southern Africa better than most. Implicitly he sees an area with vital common threads. This area was not just within the imperial sway of European powers. Nor was it just colonial penetration – ports, towns, plantations, mines, roads and railways. The greater southern African area was a vast area of settler colonialism. The challenge to these settler societies involved Marxist–Leninist or Maoist national liberation movements – all of which embraced various forms of armed struggles in a Cold War environment. So too Schmidt challenges South Africans' senses, from the National Party's to liberation movements', of their uniqueness and exceptionalism. South Africa bore marked similarities to the military dictatorships of the South American region, particularly Chile. Botha's mirror image was Pinochet. They were cold warriors using terror as a means of internal repression and part of a wider geo-political bulwark against communist expansion. Schmidt challenges liberation movements' triumphalist narratives of democratic transition. Post-apartheid South Africa is a child of the fall of the Berlin Wall and the collapse of the Cold War. As Schmidt sees it, from 1990 to 1994, international and national political forces, crossing the previous Cold War political divides, came together to hammer out the political consensus on which the new South Africa was founded. For Schmidt it is these forces which have no interest in uncovering the country's dark and haunting pasts.

As an investigative journalist, Schmidt has real concerns over the direction his chosen craft is taking. For him, investigative journalism is being supplanted by reporters presenting incidents in isolation. Without giving names he gives examples of such conduct. Schmidt has two core conceptual and methodological understandings. He recognises the difference between what the French refer to as *verité* (truth) and *veracité* (veracity). He sees both the historian and the journalist as having

> *as their task the search for veracity, rather than truth, for there are many truths, yet it is out of verifiable, established facts that the strands of different, sometimes competing, sometimes complementary, and often illuminating truths emerge.* (p. ix)

To gain this veracity he employs what he refers to as 'forensic meditation'. Using his investigative work on the Marikana massacre he develops the point further:

> *…in returning to the scene of a massacre – walking the paths of the killers to their termini, re-interviewing the victims and perpetrators, reconstructing the details and teasing out discrepancies. I have been 2 km down the Implats platinum mine, on the stopes where the rock-drillers sweat in 55 °C heat, the air thick with the bite of ammonia. I've yet to see our journalists walking the paths of the rock-drillers they are reporting on.* (p. 307–309)

What this means is that Schmidt needs to ask people question after question, find primary material sources, and find people to assist him. He is dogged in all regards, sometimes with absurdly amusing consequences. Importantly, this book is based on his notebooks, with some tidying up. It is so rare that journalist's notebooks make it into archives. This book is thus a fascinating look inside the craft of a good investigative journalist in a very dangerous high-stakes world. Indeed the book is comprised of such notes, placed within wider contexts. One chapter begins

with comment on judicial hangings in South Africa, to which is attached, appropriately, his January 2005 note of his investigations in Upington into the events of November 1985 and the 'Upington 14' and how these issues carry forward into the present.

Evelina de Bruin was the only woman amongst the 'Upington 14' sentenced to death for the murder of a municipal policeman in 1984 amidst street protests, rallies and running battles with police, who had opened fire on and tear-gassed protestors. Schmidt interviewed her in 2005. Ouma de Bruin has forgotten her name, but the only other woman then on death row was a *meisiekind* – a girl – from the Western Cape. She had just been moved to 'Die Pot', the preparation cell, and was to be hanged the following morning. As the 'fat warders' took her to the gallows, she called out to De Bruin '… I have hope that the cup that is passed to me will pass Ouma by'. In 1991, De Bruin and her husband and the other 'Upington 14' walked free, the Appellate Division having reduced their sentences to suspended sentences on the lesser charge of public violence. By that time they had spent 2 years on Death Row. Sadly her husband died 10 years after release, wracked by traumatic memories of the gallows doing its 'hungry work'. And, in a grotesque nuance altogether in harmony with so much else in this book, the only person who did give his life for the 'Upington 14' was their defence lawyer, Anton Lubowski, who was gunned down by an operative of the appallingly misnamed South African Police's Civil Cooperation Bureau outside his Windhoek home in 1989 (p. 284–289).

But, as Schmidt believes, the cup must pass to us. '[O]ur beloved fractured would-be 'nation' is withdrawing again into mutually hostile racial laagers [so] it is time that we sit down together and drink with our ghosts' (p. xiv). South Africans across the political spectrum have to unravel their own version of the Chilean 'Pact of Forgetting'. Across South America their 'drums of bones' are beating as they now seek to come to terms with their brutal age of the generals. Our 'drums of bones' are already beating. With the recent xenophobic killings, the imminent Constitutional Court hearing into why the state has consistently shied away from prosecuting the security policemen responsible for the death in detention of MK operative Nokuthula Simelane, and with 'Prime Evil' Eugene de Kock now seemingly assisting authorities with more than finding long-lost and ill-buried corpses of people who were brutally killed, the timing of that ghostly wake may come sooner than expected or preferred. For South Africans, a first date with our ghosts, and subsequent 'daylight' (p. 356), is to read the gritty body of this book. Schmidt could win prizes for this work. All South Africans will benefit by reading this book, episode by harrowing episode.

Professor Patricia Berjak (1939–2015): World-renowned plant scientist and exceptional mentor

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Professor Patricia (Pat) Berjak, a prominent South African scientist, died on 21 January 2015. Pat was a world-renowned botanical scientist who achieved remarkable breakthroughs in the understanding of recalcitrant seeds. Pat obtained her BSc Hons from the University of the Witwatersrand, Johannesburg, and her MSc and PhD from the University of Natal, Durban. After 3 years at the University of Leeds in the UK, she returned to South Africa in 1972 and worked at the University of KwaZulu-Natal in Durban for the rest of her career, during which she held various academic titles, including Head of Department and Chair of the Electron Microscope Unit.

Pat will be remembered for her substantial contributions to the field of non-orthodox seed biology (the so-called recalcitrant seeds), the problems associated with the storage of such seeds and germplasm cryopreservation of species producing such (non-storable) seeds. This research interest stemmed from her earlier PhD studies on the ultrastructural and biochemical aspects of deterioration of air-dry (orthodox) seeds during long-term storage and age-accelerating conditions.

Recalcitrant seeds were originally considered to be produced predominantly by tropical and sub-tropical tree species, but it is now clear that the phenomenon is also found in some temperate species. Using germplasm from a diverse selection of species and provenances, Pat's research was aimed at developing a comprehensive understanding of the consequences of the storage manipulations on the fundamental biology of species that produce recalcitrant seeds. This research included studies on the impacts of storage on ultrastructural integrity (e.g. cytoskeletal status) and biochemical interactions (e.g. roles of Ca^{2+} and Mg^{2+}) and studies at biophysical levels. These studies led to widespread recognition of the scientific merits of her laboratory's endeavours. For example, the International Plant Genetic Resources Institute identified her Plant Germplasm Conservation Research laboratory as an international centre of excellence. Further acknowledgement came from the UK government DEFRA's Darwin Initiative for a cryoconservation centre of excellence, in conjunction with the Millennium Seed Bank, Kew.

Pat's association with the International Seed Testing Association (ISTA) was also substantial – she was a member of the Seed Storage Working Group of the Moisture and Storage Committee from 1977 to 1980, and was thus a founding member of the Storage Committee from 1980. She was the Vice-Chair of the Storage Committee between 1992 and 1995, Chair between 1995 and 2001 and remained a member until her death. Her major contributions to ISTA were the development of the fundamental understanding of the difference between orthodox and recalcitrant seeds. In this regard, she participated in numerous workshops and contributed to ISTA handbooks.

It was her personal drive, exemplary work ethic and desire to make a difference that established her research group as one of the most respected in the field of recalcitrant seed biology worldwide. Patricia also understood the necessity for cross-disciplinary science and she consistently, and enthusiastically, collaborated with other people. She always maintained that her achievements resulted from those collaborations – most especially those with her life partner, Professor Norman Pammenter, with whom she shared many other passions including aerobatics, ballroom dancing, classic cars and cooking.

Pat's innovative research was recognised globally and her numerous accolades include being elected a member of the Academy of Science of South Africa (she was Vice-President at the time of her death), a member of The World Academy of Sciences, a Fellow of the Royal Society of South Africa and a Fellow of the University of Natal. During her career she was also president of the International Society for Seed Science. The South African Association of Botanists recognised Pat's contribution to the plant sciences with both their silver and gold medals. Pat also received the Order of Mapungubwe (silver), the highest honour granted by the President of South Africa.

Pat held a South African National Research Foundation (NRF) 'A' rating, signifying world leadership in her field, and received the NRF's President's Award for Lifetime Achievement.

On occasion Pat was called 'The Iron Lady', a title which she coveted. Many undergraduate students would agree with the statement and even go as far as to say 'move over, Margaret Thatcher'. However, beneath the steely demeanour and highly focused eyes was a person who had an unwavering belief in the uniqueness of other human beings and their ability to achieve. Over the years she helped many people in their quest for personal development and this was generally at the expense of her own private time and resources. Using her demanding yet exemplary supervisory skills, Pat gave South Africa, and indeed the international community, numerous academics, entrepreneurs and scientists. At whatever level of postgraduate training, students under Pat's guidance were stimulated towards self-improvement and a deep understanding of their research subject.

Pat was a socially aware scientist and was involved in numerous urban projects, such as the rehabilitation of the mangroves in the Durban area and the maintenance of the Hawan coastal forest north of Durban. She also served as a trustee on the board of the Durban Botanic Gardens. In those arenas, Pat was often a key player and it was her ability to bring her science and solid common sense together that led to fruition.

Associated with this generous nature was a delightful and often wicked sense of humour. At tense times, Pat could be counted on for her dry observation and sense of the ridiculous of any situation.

The South African botanical community has lost a dear friend, colleague and driving force.

Professor Benito Makhala Khotseng (1948–2015): A passionate, humanitarian educationist

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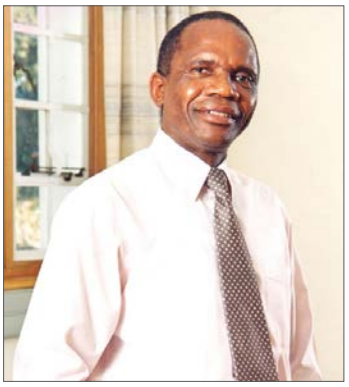

Professor Benito Khotseng died on 4 January 2015 at the age of 67, after suffering from ischaemic heart disease. A memorial service was held at the University of the Free State on 12 January 2015 and he was buried on 17 January 2015 at his homestead in Matatiele in the Eastern Cape.

Benito attained his primary education at Queen Mary Primary School and his secondary education at Moshoeshoe Secondary School. In 1969, he obtained a BA degree in Education from the University of the North, and went on to complete a BEd from the University of South Africa (Unisa) in 1974. As a principled thinker who was passionate about education and training, Benito Khotseng continued his studies and completed a PhD at the University of Natal in 1990. His thesis was titled *Polytechnic University and its contribution to manpower development in South Africa*, clearly indicating his commitment to initiating developmental opportunities for disadvantaged learners at all levels.

Benito started his career as an assistant teacher at Mount Hargreaves High School in 1971. In 1972, he was promoted to senior assistant teacher at Bensonvale High School where he taught Biology and Sesotho to Grade 11 and 12 learners. In 1974, he became a Vice-Principal at Bethlehem High School, where he also taught Biology, English and History to Grade 11 and 12 learners.

In 1976, Benito joined the Bonamelo Teachers College as Rector, a position which he occupied until 1978. In 1979, he joined the Qwaqwa Government Service as an education planner, and from 1991 to 1993, served the University of the North (Qwaqwa Campus) as a lecturer in History and Philosophy of Education. He joined the University of the Free State as a senior director managing strategic developmental programmes in 1993 doing trailblazing work in the interest of previously disadvantaged students and leading transformation at the University of the Free State. His principled and balanced leadership led to his promotion to Vice Rector/Deputy Vice Chancellor Student Affairs in 1996 – a position he held until 2003 when he joined the University of Cape Town. Benito served as a Deputy Vice Chancellor at the University of Cape Town until 2004. Benito was a visiting professor at Seton Hall University in New Jersey (USA) and also held positions as a senior researcher for the University of the Western Cape and as a consultant to the South African Management Development Institute. He attended numerous programmes at a number of universities, including the University of Huddersfield in the UK, Ohio State University in the USA, Harvard University, the National Coalition Building Institute in Washington DC, and the Indiana University of Indianapolis. Benito also presented research papers at many conferences in South Africa and abroad.

Benito dedicated his life to serving his community and country, and assumed leadership positions in various committees and groups around the country. He served as a chairperson in the Orange Free State Education Aid, the NECC Orange Free State, and the UDUSA Qwaqwa branch from 1985 to 1990. He was the treasurer of the Thusano Mobil Bursary Fund in Qwaqwa from 1990 to 1993, a consulting editor of *Perspectives in Education* between 1992 and 1995, a consulting editor of the *South African Journal of Higher Education*, and was the professional coordinator of the National Commission on Higher Education between 1995 and 1996. Furthermore, Benito was an International Advisory Board Member for the Department of Quality in Higher Education at the University of Birmingham in the UK.

Benito served on numerous boards and trusts, including the Matla Trust, the Trustees of Education with Enterprise, the Durban College of Education (1995–2001), the Financial Aid Scheme (2000–2003) and the Higher Education Quality Committee of the Council on Higher Education (2001–2005). He was elected as a Member of the Academy of Science of South Africa in 1996 and chaired the Free State Higher Education and Training Trust for many years until 2010. In addition to his involvement in community projects, Benito raised funds for student development, especially master's and doctoral programmes – between 1994 and 2000, he raised over USD27 million.

Benito contributed substantially to the body of knowledge of South Africa. Amongst others, he co-authored *Kenton Vintage* (1994), *Apartheid Education and Popular Struggles* (1991), *Mmane – Poetry Analysis for Std. 10* (1991) and *Mphatlalatsane Language Series – Std. 3, 4, 5, & 6* (1986). He also published in and contributed to accredited journals on subjects ranging from 'Rethinking the nature of the university in a post-apartheid South Africa', 'Universities and challenges of nation-building in the new South Africa' and 'Promoting multiculturalism at the university campus'.

Benito won numerous awards for his huge contribution to the body of knowledge in the country and around the world. He received a US–South Africa Faculty Fellowship in 1989, a Southern Book Publishers award for *Perspective on Higher Education* in 2002, and was named Bloemfonteiner of the Month in April 1996. He received a certificate of recognition for the excellent work done for the University through the Multicultural Project in 1998, from the University of the Free State, and a Free State Teachers Association Honorary Membership Award for Outstanding Performance and Service Delivery in Education in 1999. He was also given an Honorary Member Award for Service and Excellence from the Golden Key International Honour Society in 2002.

His family and church were central to his life and his three daughters – Nthabiseng, Manana and Matshidiso – are not only professionally successful but also are dedicated, like their father, to education and the community. Benito will be sorely missed, but his legacy will be the considerable contributions he has made to higher education in South Africa.

#RhodesMustFall: No room for ignorance or arrogance

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The 'Rhodes Must Fall' crusade, and its consequent movements, has had remarkable coverage in serious academic debate and in the popular press ever since the first rumblings of the protest began at the University of Cape Town. Comments on the news items have flourished; tweets have hit the highest song-bird notes. Former Vice-Chancellor of Rhodes University, Saleem Badat, has claimed: 'The recent developments at the University of Cape Town and at Rhodes mark the beginnings of a social movement. It comprises students and academics, mainly black, but some white. This social movement is likely to extend to other universities, expand, and strengthen over time.'

Jonathan Jansen, Vice-Chancellor of the University of the Free State disagrees. He says: 'No, there will not be wholesale changes to memorials on or off university campuses. No, the country is not about to implode because some UCT students tackled the Rhodes statue. This turmoil will pass.' The Institute for Future Studies at Stellenbosch University has another view. Their commentary on the events is that this all amounts to (as their headline spells out): 'The Pyrrhic Victory of the War on the Past.'

However, a senior staff member at the University of Cape Town feels otherwise, and expresses her personal views below.

Editor-in-Chief

The University of Cape Town (UCT) ticks all the boxes required to be a research-intensive institution of higher education on the African continent. UCT regularly appears as the leading African institution on Westernised ranking systems such as the *Times Higher Education* and Quacquarelli Symonds World University Rankings, and, within South Africa, research indicators show that UCT consistently outperforms competitors. As such there seems to be no problem in attracting top students and staff. Our unique location on the slopes of the Table Mountain nature reserve is often cited as an attraction for staff, and many do not leave. It is this same land that was 'donated' by British mining magnate Cecil John Rhodes, on which three of our campuses have been built. Since 1934, a bronze statue of Rhodes has stood on the Upper Campus, overlooking the rugby fields and the Middle and Lower Campuses, as well as much of the city and the Cape Flats.

Without warning, on 9 March 2015, our desire to be a leading African world-class research-intensive university came under scrutiny, with the start of a critical examination of our position as a public institution of higher education in a country two decades post-apartheid. UCT played an important role in the struggle against apartheid, yet not enough has been done post-1994 to bring about freedom and change into its classrooms, laboratories and demographic profiles. Over these past two decades, critical opportunities for change at UCT were instead missed, including during the period 1997–2008 under the respective reigns of the first two South African black Vice-Chancellors, Dr Mamphele Ramphele and Professor Njabulo Ndebele. In his installation address in August 2008, current Vice-Chancellor Dr Max Price charged that, despite UCT's success and guidance under the leadership of his predecessor, the 'record of assertive efforts at transformation is producing results through the recruitment of black academic staff, though this, and particularly retaining such staff, needs renewed focus'[1].

A few attempts by a group of UCT academics over the past few months to openly criticise and raise awareness about the lack of transformation at UCT, and specifically the lack of black academic staff,[2-4] were not sufficient to gain the attention of the university body. It was only when the statue of Rhodes was defaced on 9 March, that the university – and indeed the country and beyond – sat up to take note of why there is an urgent need to acknowledge and tackle the transformation-related challenges facing the university.

However, as one looked deeper into the situation, it quickly became evident that the student-led protest was not about Rhodes or his fall. It was rather a symbolic physical representation of all that is wrong with our universities and the country – summed up eloquently by Dr Price in his installation address, with reference to the 'Mafeje Affair'[5] that started in 1968 at UCT: 'That legacy still plagues UCT, and the university community has still inadequately tackled the need for attitude shifts, culture shifts, proactive redress, to ensure that black people and women feel at home here.' The reality is that the 'Rhodes Must Fall' (RMF) campaign would not have started if the university was successful in bringing about significant transformation-related change over the past two decades.

The RMF campaign has provided me with an opportune and unprecedented occasion for introspection, both as an administrative staff member of this prestigious institution, and someone who has spent half my life confined to the concept of segregation, inequality and injustice on the basis of skin colour. Despite my background, I have mostly neglected to give due consideration to the issue of transformation and my responsibility to the present-day needs of the country. The awkward realisation is that I find myself at an institution in which the structures, policies and processes work – but at a level that is relevant and acceptable to only those people, like myself, who have been less concerned with meaningful change and with a focus on 'getting the work done'. I now realise that we can achieve both – and should indeed aim to do so.

The defaced Rhodes statue (photo: Robert McLaughlin)

My self-examination and conversations with people on both sides of the RMF fence have raised a number of key issues:

- There is no room for ignorance, complacency or arrogance in our universities. Change does not happen on its own – as individuals we are the agents of change, and should take the lead in creating a vision for a transformed workplace and country. Importantly, there should be *acknowledgement* of the need for change, without which there will be no progress.
- Change also starts with leadership, and I believe there is a strong need for the design, implementation and monitoring of a consolidated UCT Transformation Strategy, which will enable us to move away from the Eurocentric and Westernised approach which typically governs our culture, towards an environment of representivity, inclusivity and relevance to the country. Importantly, this responsibility should be co-owned by staff (academic and administrative), students and management, and should come with the realisation that as a publicly funded institution, transformation is a *must*. It should address, amongst others, issues of institutional culture, affirmative action and race, access, language, organisational climate, staff retention, recruitment and training.
- There is an acute need for constructive engagement and platforms for discussion. I have been inspired by transformation-related conversations in my own department these past few weeks, and recognise the need for space for these conversations and debates to occur. These presently take the form of lunch-time seminars, working group discussions, online resources on a shared intranet site, and the use of Eskom's load-shedding 2-hour slot for what we call 'conversations in the dark'.
- There is a pressing need for the review of our curriculum and methodologies of teaching, taking into account our position within the country and continent, but not neglecting our desire to provide an education that is relevant to an international society.
- The RMF campaign has sparked debate at a number of other universities, including Rhodes University, and the universities of KwaZulu-Natal and the Witwatersrand.[6] There are of course a number of inequities across our higher education system; these are not confined to UCT. I have been impressed – yet often intimidated – by the young generation of students (the true 'born frees') who have been vocal throughout the RMF campaign. But they are our future – and a common denominator across our higher-education sector.
- The setting up of a national independent committee or body that actively oversees transformation in the national higher-education sector is needed. Matters pertaining to academic transformation could further be embedded into the responsibilities of bodies such as the South African Young Academy of Science, thus shifting some of this responsibility to the next generation of academics. The Department of Higher Education and Training's nGAP intervention to create more academic posts at universities is encouraging (with at least 80% of such posts to be filled by black South African academics), and more of such interventions are needed to grow the pipeline of black academic researchers.

We do not choose to be a born into a race or gender or even into a country. But for those of us who choose to be part of this country – irrespective of our origins – we should have as an ideal the need to contribute consciously to change and transformation on a daily basis.

The personal views of the author do not represent the views of the University of Cape Town.

References

1. Installation address by Dr Max Price, University of Cape Town, August 19, 2008 [document on the Internet]. c2008 [cited 2015 Apr 30]. Available from: http://www.uct.ac.za/downloads/uct.ac.za/about/management/vcinstallation/installation_address.pdf
2. Ripping the veil off UCT's whiter shades of pale [document on the Internet]. c2014 [cited 2014 Jul 06]. Available from: http://www.timeslive.co.za/sundaytimes/2014/07/06/ripping-the-veil-off-uct-s-whiter-shades-of-pale
3. O'Connell S. UCT: A campus at odds with itself [document on the Internet]. c2014 [cited 2015 Apr 30]. Available from: http://mg.co.za/article/2014-09-08-uct-a-campus-at-odds-with-itself
4. Macfarlane D. Iqbal Surve dumps UCT over 'lip service' [document on the Internet]. c2015 [cited 2015 Apr 30]. Available from: http://mg.co.za/article/2015-01-22-iqbal-surve-dumps-uct-over-lip-service
5. VC Installation 2008: The Mafeje Affair: Lessons of the Mafeje Affair – 40 years on [document on the Internet]. No date [cited 2015 Apr 30]. Available from: http://www.uct.ac.za/about/management/vc/installation/mafeje/
6. Pilane P. South Africa: #TransformWits – What students want [document on the Internet]. c2015 [cited 2015 Apr 30]. Available from: http://allafrica.com/stories/201503301350.html

The role of intellectuals in the state–society nexus

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In the recent Mapungubwe Institute for Strategic Reflection (MISTRA) & Lilliesleaf Roundtable held on 4 March 2015, leading figures in the intellectual life of liberation movements in sub-Saharan Africa reflected on the past, present and future relationships of such political intellectuals within the new independent states of the region. This self-reflection offered candid and striking views:

- As had already happened in all other sub-Saharan African countries, the South African liberation movements had 'consumed' its own intellectuals.
- Intellectuals within the liberation movements have to accept their share of responsibility for the dire predicament which independent Africa faces.
- Old paradigms must be questioned.
- Such intellectuals must now re-imagine their role, creating appropriate distance between themselves and the state and nationalist movements now in power so as to offer dispassionate analysis and public comment on governance and leadership.
- There is a great need for new ideas, particularly in the fields of development economics, governance, management, leadership and public policy.
- The spectrum of who is within the intellectual sphere must be broadened to include business and science and technology.

The social origins of black intellectuals in sub-Saharan Africa lie in the colonial period, most particularly in the later decades of the 19th century. Originally incorporated into the colonial enterprise, they at first sought greater spaces, particularly social and political, for a wider emancipatory vision within colonialism. Soon they were using the very components of modernity on the imperial margins – like Christianity, schools, literacy and communication, primarily newspapers – to challenge the claimed superiority of the coloniser. These were the men who imagined the new national image, and laid the intellectual and expressly often political dynamics of the national liberation movements. It was hardly an accident that the first president of the African National Congress (ANC) was Dr JL Dube, the publisher of *Ilanga lase Natal* and a famed educationist, and that Nelson Mandela voted at Dube's Ohlange Institute in 1994.

Prompted by the current crises within the ANC and the state, and held with considerable pre-publicity, the symposium was aimed at stimulating wider debate on the role of intellectuals in contemporary society. There were three sessions. In the first session on the southern African context, the speakers were Dr Ibbo Mandaza (Zimbabwe), Dr Ayanda Ntsaluba (former Director-General of International Relations) and Prof. Xolela Mangcu (University of Cape Town, UCT). In the second session on South Africa, the speakers were Mr Joel Netshitenzhe (MISRA and long-time ANC National Executive Committee member) and Prof. Ben Turok (long-serving and now retired senior ANC Member of Parliament). The final session concerned the humanities and social sciences and the 'race, class and gender' question speakers were Prof. Ari Sitas (UCT), Prof. Tshilidzi Marwala (Deputy Vice-Chancellor: Research and Innovation, University of Johannesburg) and Ms Nombonisa Gasa (UCT).

Throughout the sessions, common themes surfaced from both the presentations and the discussions:

- What is the real issue? That, on coming to power, independent states sidelined their intellectuals. Whilst it was always thought that southern Africa, and in particular South Africa, would be different, this has not been the case. This situation is a cause of much soul-searching amongst such intellectuals. As within the social strata of the political intelligentsia, they feel part of the ruling elite, and yet now have an ambivalent relationship to the very state they helped bring to power.
- What responsibility do intellectuals have for the crises befalling independent sub-Saharan Africa states? Here two themes were dominant. Firstly, intellectuals and their perspectives were part of the problems which saw new states get into difficulties. Secondly, intellectuals created problems for themselves. They idealised too much, turned ideas into dogmas, and were dismissive of contrary views – 'the weight of history was on our side', and allowed their close proximity to power to distance themselves from new currents in intellectual thinking. In this way they were not able to provide fresh advice to new states.
- Why do intellectuals not want to speak out now? Three themes came through strongly. Firstly, the emotional and political attachment, in many cases of a lifetime, to the struggle. Secondly, a 'fear of falling' – of falling from the new political elite, and their often precarious position within this elite. And yet, finally, the new post-colonial states are in deep trouble and are in serious need of new ideas. So, thirdly, these intellectuals fear speaking out because of the 'politics of retribution' – as currently exemplified in the current behaviour of the ANC.
- What are the relevant concepts for intellectuals and who can be considered an intellectual? Here debate concerned the integrity of concepts – such as Afrocentrism or Marxism, the 'hegemony of the West', and identity: 'revolutionary', 'radical', 'organic', 'grassroots', etc. There was much consensus, prompted by comments from the audience, that openness and inclusivity, in terms of both approaches and who intellectuals were, was preferred, as was a more global and open rather than an Africa-centric vision. From within the audience, there was a strong undercurrent of tiredness that the term intellectual is too closely associated with the 'humanities and social sciences', and with certain elements of Africanism – for example, 'Just because the light bulb wasn't invented in Africa doesn't mean we [Africans] have to live in the dark.'

A final theme from the audience also had traction: why was the symposium perpetuating the dominance of black political men, particularly in a symposium to discuss crisis: why was there no real gendered understanding of these issues in terms of crisis, cause and resolution? In press comment subsequent to the symposium, some participants expressed concern over tensions within their identities as 'black' 'radical' 'intellectuals' as a result of the behaviour of the state to which they had so much affinity, and the charges, all too often valid, against such black governmental competence and even legitimacy.

Internationally, the status of intellectuals, primarily but not exclusively public intellectuals, in politics is a long-standing theme in academic, political and public policy discussions and writing. Significantly, there are now increasing calls for intellectuals to play a more high-profile role in South Africa's public culture. The discussion trends in this symposium reaffirm these same wider calls. If the comments in this symposium are taken up, South African public culture can only become richer.

Transdisciplinarity within South Africa's global change research: How (well?) are we doing?

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The Global Change Programme (GCP) of the Department of Science and Technology (DST) of South Africa is one of the 'Grand Challenge' programmes that comprise a 10-year Innovation Plan (2008–2018), which aims to transform South Africa into a greater knowledge-based economy through stimulating transdisciplinary research to resolve, inter alia, specific energy, economy, society and technology needs. Meeting these challenges epitomises the necessity of effective transdisciplinary research, which can be defined as research specifically orientated to resolve 'real-world' (i.e. encompassing policy-driven research toward societal benefit) problems that are too complex and multidimensional to be answered by singular research disciplines.[1] We present a first-order evaluation of the transdisciplinary capacity building within the GCP programme at its halfway stage, with an aim to test its effectiveness.

We base our analyses of transdisciplinarity after calculating the level of transdisciplinary research across the various themes presented at the 2nd Biannual Conference for Global Change (CGC), held in early December 2014, at the Nelson Mandela Metropolitan University in the Eastern Cape. Our model evaluates links created between the research papers to the overarching themes of the conference by considering key words/phrases within each research paper. These links are inculcated within this model to establish the network of interconnectivity across the conference research themes and its success in catalysing transdisciplinarity research amongst young graduate students in South Africa.

We specifically highlight non-linkages between themes that are known to be important to meeting Global Grand Challenges. Non-linkages are also related to shortfalls in accelerated policy development and implementation of important facets relating to the Innovation Plan. We show that an analysis of this nature helps to highlight the need to re-direct some of the key research links to better facilitate the aims of South Africa's Grand Challenges.

Global change background

In 2008, the DST launched its 10-year Innovation Plan for South Africa: *Innovation towards a Knowledge-based Economy 2008–2018*. This plan identified five challenges on which efforts were to be focused to bring about social, economic, political, scientific and technological benefits, namely:

1. The 'Farmer to Pharma' value chain to strengthen the bio-economy
2. Space science and technology
3. Energy security
4. Science and technology for global change with a focus on climate change
5. Human and social dynamics

The scale of the proposed key knowledge and innovation priorities is ambitious, and DST has thus described them as Grand Challenges. One of the Grand Challenges – the Global Change Grand Challenge – is related to global change, with a focus on climate-linked changes in the Anthropocene.[2] These climate changes are caused by ever-increasing human activities, including environmental and social disruptions, and often have perceived negative connotations, e.g. rapid biodiversity collapse, increasingly severe weather fluctuations, extensive land degradation, energy–food–water insecurity and growing social and economic inequality and unrest. Global change research aims to investigate how these effects are interconnected and how human behaviour may be stimulated to mitigate negative side-effects as much as possible. The *10-Year Global Change Research Plan for South Africa* is inter alia notable for the following reasons:

1. It adopts a systems approach, and is strongly interdisciplinary.
2. It is based on the unique geographical location and developmental challenges of South Africa and is grounded in its socio-ecological needs.
3. It aims to advance a better understanding of the functioning of the earth system and to support efforts to respond effectively to changes.
4. It has a strong focus on climate change, and takes into consideration contemporary debate and discussion in this regard.
5. It supports making a contribution to the international knowledge base as well as to locally relevant and required research, and it is intended to be policy relevant.

Each of these Grand Challenges was designed to stimulate multidisciplinary thinking and to challenge the country's researchers to answer existing questions, increase interdisciplinary collaboration and develop new technologies. The success of the Innovation Plan therefore clearly hinges largely on successful transdisciplinary research and an understanding that selective and singular research themes will not be able to realise its goals.Transdisciplinary research evokes an evolution of these themes through learning from the logic among them, creating perpetual knowledge gain.[3,4] This mechanism is also vital for successful policy-driven research.[5] Evaluating the level of transdisciplinary research has remained largely underdeveloped.[6,7] The most common methodology used for evaluation is formal surveying among researchers and stakeholders and numerical analyses of captured data.

Models of this nature have been applied toward designing and assessing research in specific fields, e.g. in building linkages between health and social sciences[8-12]; in methods for defining research related to ecological economics[13] and in cognitive informatics and computer sciences[14]. We now consider a new approach by evaluating discourse at a recent scientific conference toward evaluating the level of transdisciplinary research.

At the start, the Global Change Research Plan of DST identified four major cross-cutting knowledge challenges – understanding a changing planet, reducing the human footprint, adapting the way we live and innovation for sustainability – and a further 18 key research themes (for more details the reader is directed to: http://www.gov.za/documents/global-change-grand-challenge-national-research-plan). For 5 years now, the Global Change Grand Challenge initiative has supported science and technology as well as key socio-economic development and environmental research projects across the country at most universities and national research institutes, to meet these challenges. It is worth asking therefore how successful this plan has been, and what further challenges should be met to enable success.

Here, we present a numerical model for analysing the level of transdisciplinary research shown within the GCP. To do this, our model is applied to the Conference for Global Change (The full conference programme is available from http://globalchange2014.nmmu.ac.za/Programme). This conference was chosen because it epitomises the research (Figure 1) being undertaken within the GCP and the progress toward resolving its specified Grand Challenges.

A method for analysing transdisciplinarity

The level of the transdisciplinary research encompassed within the GCP was calculated by considering all research papers presented during the conference (i.e. the themes denoted in Figure 1). A numerical model was built to inculcate how often key words or phrases related to each research paper could be linked to the various themes of the conference. Where a research paper was related to a theme, a link was created between the paper and each related theme. This link serves as a level of transdisciplinarity between research and theme. Using this model, we can assess each research paper within the conference, calculating total linkages and using this total as a proxy for the level of transdisciplinary research. The relation between the research papers and themes can be denoted as:

$$RTn \subseteq Tn, \qquad \text{Equation 1}$$

where RTn represents the number of research papers presented in the various themes, with Tn denoting the total number of different themes. The level of transdisciplinary research is then calculated as:

$$\sum_{i=Ta}^{Tn} \frac{k(RT(a,b,c...n) \approx kRTn}{RTn}, \qquad \text{Equation 2}$$

where Tn is again the total number of themes (i.e. as shown on Figure 1), Ta is the first theme (i.e. Poverty) and k represents a key word/phrase used as linkage. RT represents the individual research paper in each theme ($a, b, c \ldots n$ representing the individual papers presented), with RTn again being the total number of research papers in each theme. Once equated, the results are plotted and interpolated on a graph where the themes comprise both axes. This approach produces a graphical representation in which the level of transdisciplinary research forms linkages across the conference themes. A graphical example (using the Economic session of the conference) illustrating how the model functions is shown in Figure 2.

Results of the analysis

An overview of themes showing transdisciplinary research within the conference is shown in Figure 3. A total of 164 transdisciplinary linkages were created from the 234 research papers. Figure 4 shows a graphical representation of how these linkages are distributed across all the research themes. Circles display linkages with their size and colour highlighting the level of transdisciplinary research linkage. Where no circles are shown, no linkage between themes is implied.

Lessons learned

The results of the numerical model indicate that the following themes are most often incorporated within individual research papers (Figure 3): Monitoring (26%), Climate (10%), Economics (10%), Species (8%), Conservation (8%), Ecosystems (7%), Ocean (6%), Modelling (6%) and Agriculture (5%). Similarly, these themes form the most common transdisciplinary linkage across several themes (Figure 4), e.g. Monitoring–Remote Sensing/Climate/Species, Economics–Mining, and Agriculture–Species.

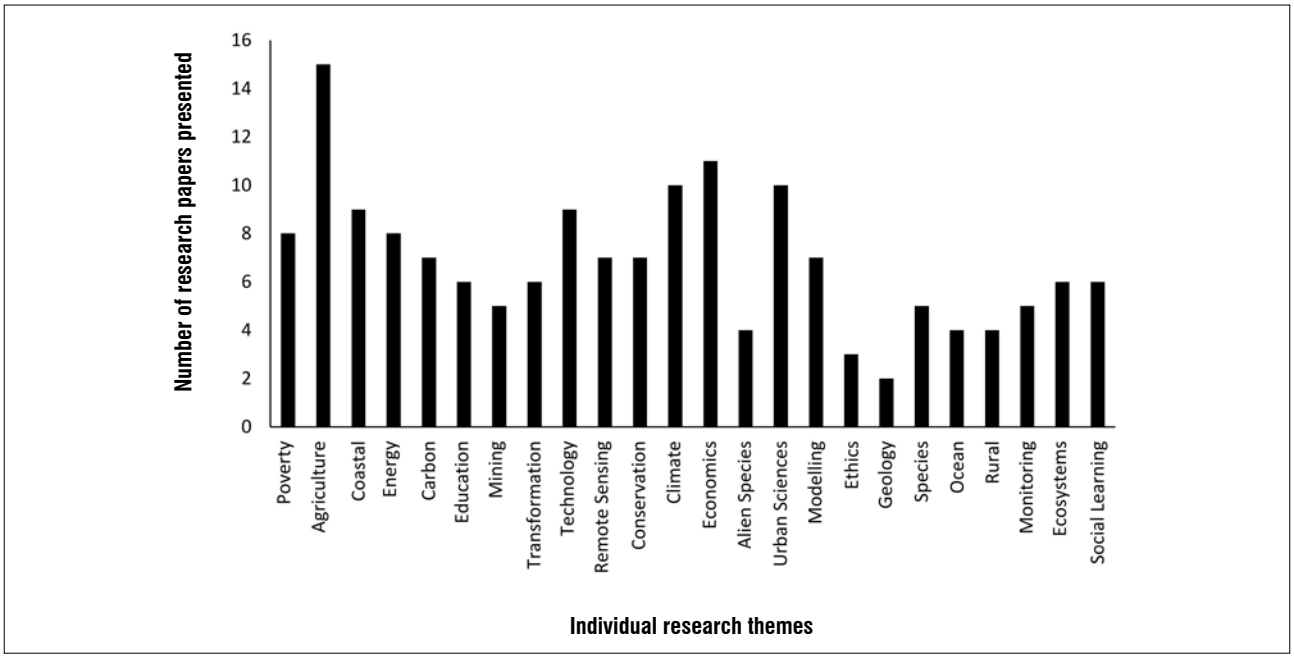

Figure 1: Breakdown of the number of presentations within each theme during the Conference for Global Change.

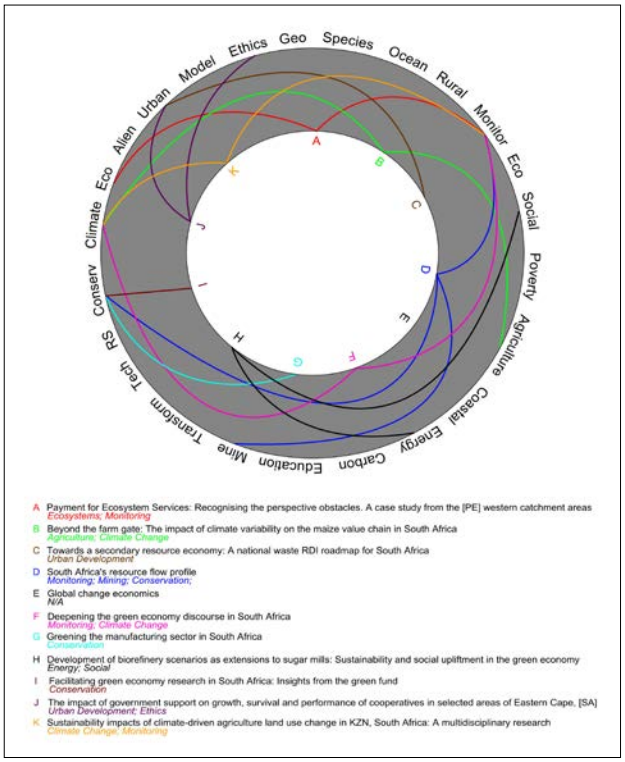

Figure 2: A graphical illustration, based on the 'Economic' session of the 2014 Conference for Global Change, of how transdisciplinary linkages are created within the model. Themes are denoted along the outer circle and the various research papers presented within this session along the inner circle. The titles of the research papers is given in the key.

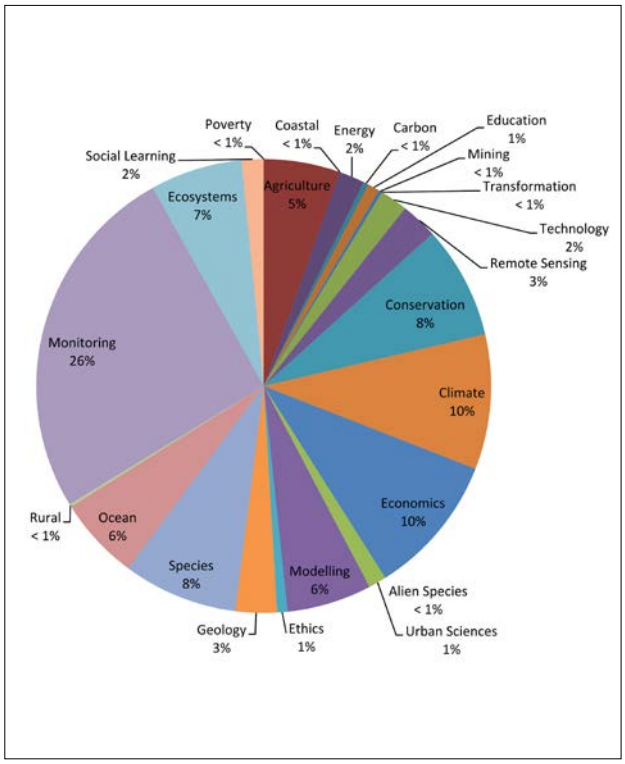

Figure 3: Overview of the most transdisciplinary themes displayed at the 2014 Conference for Global Change.

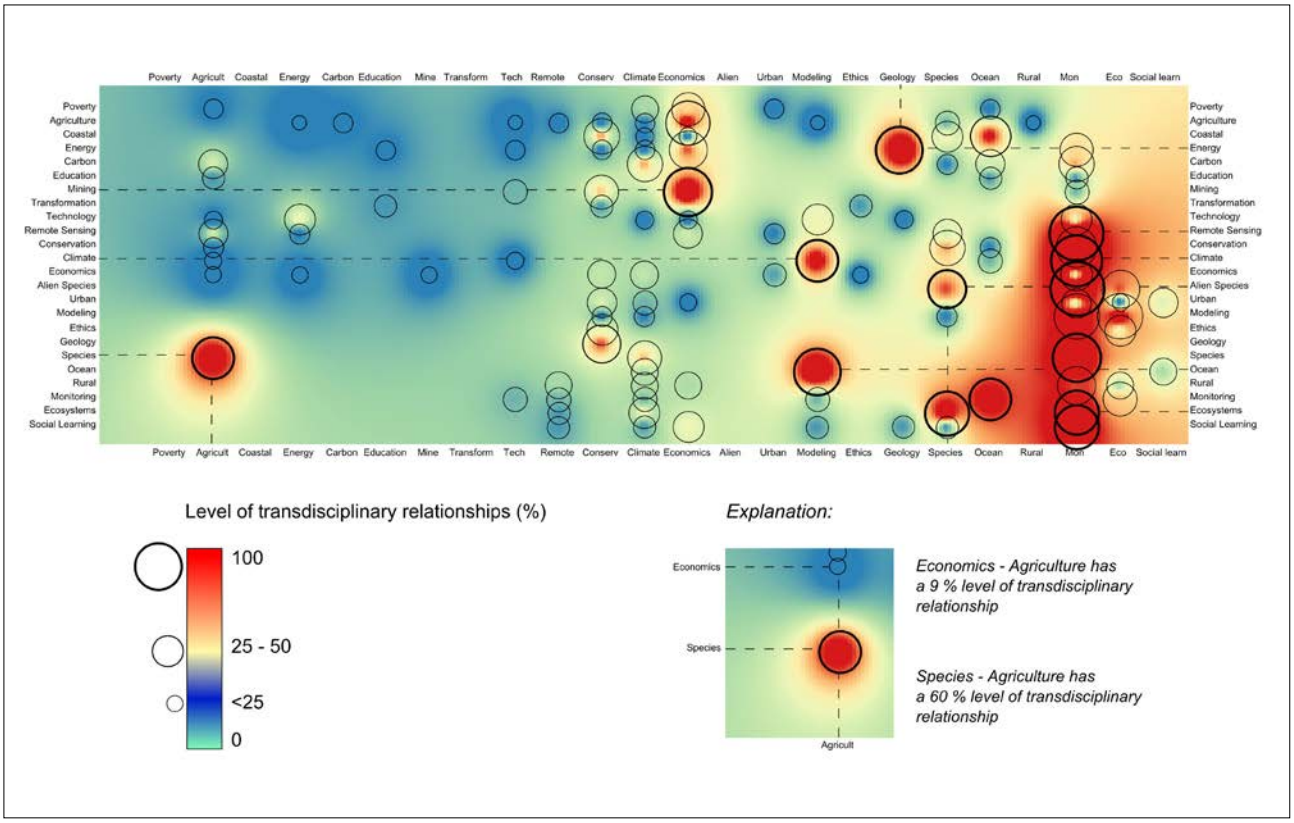

Figure 4: Overview of the degree of transdisciplinary within the Conference for Global Change, 2014. Circles indicate the intersection points between themes with a transdisciplinary nature; the colours represent the ratio (equated to a percentage within each theme) of the papers presented with transdisciplinary topics. Where no circle is shown, transdisciplinary relationships are absent.

The results also highlight many important non-linkages between research themes. Here we find a strong correlation between these non-linkages and some of the Grand Challenges that are unlikely to be met by the 2018 deadline:

1. Developing sustainable energy mix. South Africa struggles to maintain energy security and has failed to develop aggressive resolving policies related to energy security, which has resulted in negative economic consequences.[15-17] Failure to improve this area could reflect the <25% transdisciplinary link between Technology–Energy and Energy–Climate and a lack of policy development research being undertaken. It should also be noted that there is a very strong transdisciplinary link between Geology and Energy. This link largely stems from increasing shale gas research (e.g. http://www.karooshalegas.org/).
2. Human development and social dynamics. South Africa has seen advancement in social development[18]; however, inequality and youth unemployment continues to grow rapidly[19-21]. Is this a reflection of apparently poor links between Economics–Transformation/Education and Poverty/Rural Development, both of which have negligible shares of the total transdisciplinary research in the CGCG programme (Figure 3)? Education has been proven to be a vital aspect of any developing society.[22,23] Our analyses indicate that it needs to be better expressed within South African transdisciplinary research of the GCP.
3. Farmer to Pharma and the bio-economy. South Africa remains a net importer with negligible pharmaceutical or other beneficiation exports.[24] Interestingly, there is no dedicated Health theme in the CGCG programme, and <25% of research in Agriculture has a transdisciplinary link to Technology. Most transdisciplinary research within Agriculture is focused toward optimisation and increased productivity.

Today's strongly connected global process networks are highly interdependent systems that we do not understand well.[25] These systems are vulnerable to failure and can become unstable at all scales even when external shocks are absent. As the ever-increasing complexity of interactions in global networked earth and life systems becomes better understood, we may develop technologies to make the anthropogenic systems manageable so that fundamental redesign for future systems may become a reality. This aim is surely part of South Africa's plan to move towards a knowledge-based economy. But our results do not bode well for achieving this aim by 2018.

We are at the threshold of new transdisciplinary thinking about human and natural system complexity, and there is a long list of relevant questions that we must ask, and the relatively poor growth in transdisciplinarity over the last 5 years remains the most serious challenge to achieving Global Change Grand Challenge goals in South Africa. There is currently no way of establishing whether this poor growth may be related to 'top-down' initiatives or a lack of 'bottom-up' response. However, there is arguably a need for greater understanding at (under)graduate level in universities to better enable students from an early stage to grapple with the Grand Challenges of their global commons. A better understanding of the greater global needs of transdisciplinarity from an early stage in their careers may encourage them to extend their interconnectivity through the 'Internet of things' to shape their research direction early on.[26]

References

1. Wickson F, Carew A, Russel A. Transdisciplinary research: Characteristics, quandaries and quality. Futures. 2006;38(9):1046–1059. http://dx.doi.org/10.1016/j.futures.2006.02.011
2. Lewis S, Maslin M. Defining the Anthropocene. Nature. 2015;519:171–180. http://dx.doi.org/10.1038/nature14258
3. Nowotny H. The place of people in our knowledge. Eur Rev. 1999;7(2):247–262. http://dx.doi.org/10.1017/S1062798700004026
4. Wodak R, Chilton P. A new agenda in (critical) discourse analysis: Theory, methodology and interdisciplinary. Vol. 13. Amsterdam: John Benjamin Publishing Co.; 2005. http://dx.doi.org/10.1075/dapsac.13.10wod
5. Pohl C. From science to policy through transdisciplinary research. Environ Sci Policy. 2008;11(1):46–53. http://dx.doi.org/10.1016/j.envsci.2007.06.001
6. Häberli R, Grossenbacher-Mansuy W, Klein J. Summary. In: Klein J, editor. Transdisciplinarity: Joint problem solving among science, technology and society. Basel: Birkhäuser-Verlag; 2001. p. 3–5. http://dx.doi.org/10.1007/978-3-0348-8419-8_1
7. Somerville M, Rapport D. Transdisciplinarity – Recreating integrated knowledge. Montreal: McGill-Queens University Press; 2002.
8. Rosenfield P. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med. 1992;35(11):1343–1357. http://dx.doi.org/10.1016/0277-9536(92)90038-R
9. Lawrence R. Housing and health: From interdisciplinary principles to transdisciplinary research and practice. Futures. 2004;36(4):487–502. http://dx.doi.org/10.1016/j.futures.2003.10.001
10. Abrams D. Applying transdisciplinary research strategies to understanding and eliminating health disparities. Health Educ Behav. 2006;33(4):515–531. http://dx.doi.org/10.1177/1090198106287732
11. Kessel F, Rosenfield P. Toward transdisciplinary research: Historical and contemporary perspectives. Am J Prev Med. 2008;35(2):225–234. http://dx.doi.org/10.1016/j.amepre.2008.05.005
12. Van Noorden R. Seven thousand stories capture impact of science. Nature. 2015;518:150–151. http://dx.doi.org/10.1038/518150a
13. Baumgartner S, Becker C, Frank K, Muller B, Quaas M. Relating the philosophy and practice of ecological economics: The role of concepts, models, and case studies in inter- and transdisciplinary sustainable research. Ecol Econ. 2008;67(3):384–393. http://dx.doi.org/10.1016/j.ecolecon.2008.07.018
14. Wang Y. Cognitive informatics: A new transdisciplinary research field. Brain Mind. 2003;4(2):115–127. http://dx.doi.org/10.1023/A:1025419826662
15. England A. South Africa growth fears prompt Moody's downgrade. Financial Times. 2014 Nov 6; Global Economy – Africa Economy. Available from: http://www.ft.com/intl/cms/s/0/2117e62c-65e1-11e4-a454-00144feabdc0.html#axzz3MoPh4JJh
16. England A. Worsening electricity crisis adds to South Africa's economic woes. Financial Times. 2014 Dec 9; World – Africa. Available from: http://www.ft.com/cms/s/0/69aa4a9e-7f89-11e4-b4f500144feabdc0.html#axzz3MoPh4JJh
17. Steyn L. Sinking into Eskom's black hole. The Mail and Guardian. 2015 Feb 6; Business. Available from: http://mg.co.za/article/2015-02-05-sinking-into-eskoms-black-hole
18. South African Press Association. SA to reach UN millennium target by 2015. The Citizen. 2014 Dec 19; National. Available from: http://citizen.co.za/296424/sa-reach-un-millennium-target-2015/
19. Altbeker A, Storme E. Graduate unemployment in South Africa: A much exaggerated problem [document on the Internet]. c2013 [cited 2015 Apr 28]. Available from: http://sun025.sun.ac.za/portal/page/portal/Arts/Departments/political_science/docs/Tab/GRADUATE_UNEMPLOYMENT_IN_SOUTH_AFRICA__A_much_exaggerate.pdf
20. Humphries T. Blended approach to empowering South Africa's youth. Huffington Post. 2014 Dec 1; Skoll Foundation. Available from: http://www.huffingtonpost.com/skoll-foundation/blended-approach-to-empow_b_6250230.html
21. Kings S. Inequality mocks SA's freedom. Mail and Guardian. 2014 Oct 31; National. Available from: http://mg.co.za/article/2014-10-30-inequality-mocks-sas-freedom
22. United Nations Educational, Scientific and Cultural Organisation. Teaching and learning: Achieving quality for all: Summary [document on the Internet]. c2014 [cited 2015 Apr 28]. Available from: http://unesdoc.unesco.org/images/0022/002256/225654e.pdf
23. United Nations Educational, Scientific and Cultural Organisation. Sustainable development begins with education: How education can contribute to the proposed post-2015 goals [document on the Internet]. c2014 [cited 2015 Apr 28]. Available from: http://unesdoc.unesco.org/images/0023/002305/230508e.pdf
24. International Federation of Pharmaceutical Manufacturers & Associations. Facts and figures [document on the Internet]. c2014 [cited 2015 Apr 28]. Available from: http://www.ifpma.org/fileadmin/content/Publication/2014/IFPMA_-_Facts_And_Figures_2014.pdf
25. Helbing D. Globally networked risks and how to respond. Nature. 2013;497:51–59. http://dx.doi.org/10.1038/nature12047
26. Rifkin J. The zero marginal cost society – The Internet of things, the collaborative commons, and the eclipse of capitalism. New York: Palgrave Macmillan; 2014.

Ancient DNA comes of age

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If you think about it, extracting DNA from bones of people long dead is an impressive achievement. The decomposition of soft tissue is a fairly quick (and smelly) process that generally takes about 2–3 months under normal South African summer weather conditions. Buried bone tends to lose its soft tissue components after a few years, becoming light and friable. Most archaeological bones have lost the integrity of their collagen matrix after a century or two, and structurally and microscopically well-preserved bone elements are fairly rare after a few thousand years. That is what makes it absolutely amazing that the detail of DNA can survive such long periods and can be recovered by scientists.

Our first attempt to extract ancient DNA from South African human skeletons was done by Alec Knight, then of Stanford University, and myself in 2002. We sampled 22 Later Stone Age skeletons ranging from 400 to about 6000 years old. Alec did the laboratory work back at Joanna Mountain's lab in California, but despite his meticulous efforts, the project was a complete failure. Not one ancient DNA sample was retrieved. Our frustration was extreme because other researchers had managed to extract DNA from the far more ancient bones of Neanderthals in Europe.[1] We now know that we faced several problems which resulted in our failure. DNA was present in the samples, but it was extremely fragmentary and technically difficult to extract with the technology available then. DNA does not exactly 'decompose' with time. Rather it fragments into small sections. One of the calling cards of ancient DNA is fragments of less than 50 nucleotide base pairs in length.

Twelve years later I linked up with a different research group to try again. The University of Cape Town archaeologist Andy Smith had carefully taken bone samples from a newly excavated skeleton at St Helena Bay and sent samples to Vanessa Hayes in Sydney, Australia, for analysis. With vastly improved laboratory technology and better methods of sequencing the DNA fragments, we were able to obtain a complete mitochondrial sequence for the 2300-year-old skeleton from St Helena Bay.[2] The St Helena Bay ancient mtDNA produced a new L0d2c lineage (L0d2c1c), most closely related to contemporary indigenous San speakers (specifically the Ju) in the northern Kalahari and unlike its sister clades (L0d2c1a and L0d2c1b) which were found amongst Khoe-language speakers. Although the results are intriguing, the fact is that this lineage from a single individual elicited more questions than it answered.

Essentially, the gates for ancient DNA research in southern Africa are now open. Already a substantial body of DNA knowledge for living Khoesan peoples is available,[3-5] which gives us a tremendous capability for comparison. The race is on to extend this work back in time through ancient DNA.[6,7] To my knowledge, there are now several projects in preparation, nearing completion, or already done. The analysis of specimens from the Later Stone Age and the Early Iron Age have produced some results for which there should be publications in the near future. Earlier specimens from the dawn of modern humanity 100 000 years ago or more have also been sampled, but we shall have to wait to see if enough DNA can be extracted for analysis. Laboratories in Germany, Denmark, Sweden, Australia and the USA have been involved. This is truly a rush for knowledge in a new field. Amongst the studies is one which has looked at the genetics of the oral bacteria preserved in the dental tartar attached to the teeth of ancient specimens. So it is not only ancient humans we can analyse, but also the DNA of species that have co-evolved with us.

Johannes Krause of Tuebingen University and Tasneem Salie of the University of Cape Town (UCT) sample ancient DNA from Later Stone Age specimens in the Department of Human Biology's Osteology Laboratory at UCT. This project looks specifically at the 2000-year-old site of Farasokop near Vredendal in the Western Cape. Professors Nicola Illing (UCT Molecular & Cell Biology), John Parkington (UCT Archaeology) and Raj Ramesar (UCT Human Genetics) look on. (Photo: Alan Morris)

I remain intrigued by the information gleaned from a genetic study of human body lice done several years ago[8] in which the lice tracked at least two separate human lineages from ancient times to now.

The technological advances that have enabled the study of ancient DNA in southern Africa have also expanded the range of genetic data available. The earlier work primarily focused on mitochondrial and Y-chromosome DNA lineages. These track female and male lines, respectively, back in time and give a good guide to the timing of population splits, but they are of relatively limited value in identifying specific relationships between individuals and miss large blocks of ancestry not represented in the surviving female or male lineages. The latest research has looked at nuclear autosomal DNA and has begun to provide data on admixture between populations and the impact of natural selection on specific genetic traits.[9-12] The 'Holy Grail' in ancient DNA work is now to extract this nuclear information from long dead southern African individuals and even possibly to generate a complete genome for a representative individual. I suspect that a publication announcing this feat will not be too far in the future.

References

1. Krings M, Stone A, Schmitz RW, Krainitzki H, Stoneking M, Paabo S. Neandertal DNA sequences and the origin of modern humans. Cell. 1997;90:19–30. http://dx.doi.org/10.1016/S0092-8674(00)80310-4
2. Morris AG, Heinze A, Chan E, Smith AB, Hayes VM. First ancient mitochondrial human genome from a pre-pastoralist southern African. Genome Biol Evol. 2014;6(10):2647–2653. http://dx.doi.org/10.1093/gbe/evu202
3. Barbieri C, Vicente M, Oliveira S, Bostoen K, Rocha J, Stoneking M, et al. Migration and interaction in a contact zone: mtDNA variation among Bantu-speakers in southern Africa. PLoS ONE. 2014;9(6):e99117. http://dx.doi.org/10.1371/journal.pone.0099117
4. Schuster SC, Miller W, Ratan A, Tomsho LP, Giardine B, Kasson LR, et al. Complete Khoisan and Bantu genomes from southern Africa. Nature. 2010;463:943–947. http://dx.doi.org/10.1038/nature08795
5. Schlebusch CM, Skoglund P, Sjodin P, Gattepaille LM, Hernandez D, Jay F, et al. Genomic variation in seven Khoe-San groups reveals adaptation and complex African history. Science. 2012;338(6105):374–379. http://dx.doi.org/10.1126/science.1227721
6. Lombard M, Schlebusch C, Soodyall H. Bridging disciplines to better elucidate the evolution of early *Homo sapiens* in southern Africa. S Afr J Sci. 2013;109(11/12):27–34. http://dx.doi.org/10.1590/sajs.2013/20130065
7. Lombard M. Human DNA and Stone Age archaeology. The Digging Stick. 2014;31(2):6–10.
8. Reed DL, Smith VS, Hammond SL, Rogers, AR, Clayton DH. Genetic analysis of lice supports direct contact between modern and archaic humans. PLOS Biol. 2004;2(11):e340. http://dx.doi.org/10.1371/journal.pbio.0020340
9. Pickrell JK, Patterson N, Barbieri C, Berthold F, Gerlach L, Güldemann T, et al. The genetic prehistory of southern Africa. Nat Commun. 2012;3, Art. 1143. http://dx.doi.org/10.1038/ncomms2140
10. Pickrell JK, Patterson N, Loh P-R, Lipson M, Berger B, Stoneking M, et al. Ancient west Eurasian ancestry in southern and eastern Africa. Proc Natl Acad Sci USA. 2014;111(7):2632–2637. http://dx.doi.org/10.1073/pnas.1313787111
11. Schlebusch, C, Lombard M, Soodyall H. mtDNA control region variation affirms diversity and deep sub-structure in populations from southern Africa. BMC Evol Biol. 2013;13:56–76. http://dx.doi.org/10.1186/1471-2148-13-56
12. Breton G, Schlebusch CM, Lombard M, Soodyall H, Jakobsson M. Lactase persistence alleles reveal partial East African ancestry of southern African Khoe pastoralists. Curr Biol. 2014;24:852–858. http://dx.doi.org/10.1016/j.cub.2014.02.041

Fruit waste streams in South Africa and their potential role in developing a bio-economy

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Current and previous studies on bio-based (fruit) wastes and wastewaters, with a particular emphasis on research in South Africa, were reviewed. Previous studies have focused predominantly on the beneficiation and application of fruit waste as a feedstock for renewable energy. A definite gap in knowledge and application of fruit waste streams with regard to enzyme production as a value-added product is identified. The characteristics and composition of each type of fruit waste are highlighted and their potential as feedstocks in the production of value-added products is identified. The conversion of agri-industrial wastewaters to bioenergy and value-added products is discussed, with special mention of the newly published South African *Bio-Economy Strategy*, and the potential production of biofuels and enzymes from waste streams using recombinant *Aspergillus* strains. Finally, to maximise utilisation of waste streams in South Africa and abroad, a conceptual model for an integrated system using different technologies is proposed.

Introduction

Biorefineries and the bio-economy

For the past millennium, the world has run on crude oil and coal as the main energy source. In the past decade, the price of crude oil has doubled, and with climate change imminent, the world has to re-evaluate its economic growth and energy policies. South Africa, as part of Africa, has the added burdens of rising unemployment and poverty and the need to decouple its economy from fossil fuels. At the same time, the gap between the rich and poor is growing and food security remains high on the agenda. South African energy needs have been highly dependent upon abundant coal supplies; about 77% of South Africa's energy is directly derived from coal, with the balance stemming from nuclear power and hydroelectric resources. The demand to replace conventional industrial processes with those that generate fewer or no pollutants is increasing as a result of the need to minimise anthropogenic environmental impacts.[1] Our ability to meet market demands while maintaining environmental integrity is critically important for our future on earth.

Major considerations, with respect to the availability of renewable resources, as well as the appropriate technologies for converting these resources into the required commodities, are pivotal in the process of a societal transition to a bio-based economy.[2] Theoretically defined, a bio-based economy is an economy in which all inputs are derived from renewable resources.[3] The term 'bio-economy' was coined by the Biomass Research and Development Board in 2001, which used it to describe the revolutionary transition to a sustainable future by implementing a technology-driven model for economic development.[4]

In January 2014, the South African Department of Science and Technology revealed the national *Bio-Economy Strategy*.[5] In this document, the term bio-economy 'encompasses biotechnological activities and processes that translate into economic outputs, particularly those with industrial application'. The vision for South Africa sees the bio-economy contributing significantly to the country's gross domestic product by 2030 through the creation and 'growth of novel industries that generate and develop bio-based services, products and innovations'[5]. The potential of a thriving bio-economy will affect the country on a macro-economic scale, making South Africa internationally competitive (especially in the industrial and agricultural sectors) by creating more sustainable jobs, linking the countries first and second economies, enhancing food security and creating a greener economy.[5] The strategy presents a framework for the development of a thriving bio-economy, in which collaboration between role players (including, among others, the biotechnology sector as a whole, environmental agencies and social scientists) is the key to success. The three key economic sectors identified for inclusion in the strategy are agriculture, health and industry.[5] In order to sustain a future bio-based economy, methods for the conversion of renewable feedstocks into the respective value-added products will need to be efficient. Furthermore, there is a need to explore all possibilities in the use of sustainable resources to ensure the extraction of maximum value with minimum negative impact.

Accompanying the worldwide paradigm shift to environmental responsibility and sustainable development, there has been an increasing amount of research focused on developing technologies to produce or process biomass, for example, biofuel production, animal feedstock applications and extraction of value-added products. Generally, it is agreed that the development of biorefineries is crucial for the development of a bio-economy. The most inclusive of many definitions of a biorefinery was coined by the International Energy Agency Bioenergy Task 42 as 'the sustainable processing of biomass into a spectrum of marketable products and energy'[6]. The biorefinery concept neatly adheres to the ideals of a bio-economy, in which bio-based, renewable inputs are converted to valuable products using a wide range of technologies. It is imperative that negative environmental and social impacts are limited during these processes.

South African fruit industry

The long-term sustainability of biorefinery processes and products is reliant on a dependable supply of starting materials or substrates. The identification and quantification of potential input material is therefore a critical starting point in biorefinery design. This review is focused on the wastes generated from the fruit-processing industry in

South Africa. In order to be considered a useful, feasible feedstock, fruit wastes must:

- be produced in sufficient quantity (seasonality of the feedstock is an important consideration – see section on a conceptual model to maximise utilisation of fruit-waste streams for more information regarding this aspect) and
- have sufficient potential for value-addition, which outcompetes that of the current disposal method.

It must also be borne in mind that the carbohydrate content of most of the fruit-waste streams may be low, which also renders their commercial use a challenge (see section on a conceptual model to maximise utilisation of fruit-waste streams for more information on how this issue may be addressed).

The South African fruit industry produces a large variety of fruit, with citrus fruit, grapes, apples, pears, peaches and pineapples produced in the greatest quantities. A comparison of the amounts of fruits produced and processed in 2011/2012 is given in Table 1 (2011/2012 data).

Table 1: Production and processing data for various fruit crops in South Africa[7]

Fruit crop	Total production in tonnes (2011/2012)	Volume processed in tonnes (2011/2012)
Citrus (oranges, lemons, limes, grapefruit and naartjies)	2 102 618	441 899
Grapes	1 839 030	1649 (processed) 151 628 (dried) 1 413 533 (pressed)
Apples	790 636	244 469 (processed) 1110 (dried)
Bananas	371 385	Not indicated
Pears	346 642	120 811 (processed) 9872 (dried)
Peaches	190 531	125 706 (processed) 8994 (dried)
Pineapples	108 697	81 753
Watermelons and melons	93 277	Not indicated
Avocados	87 895	Not indicated
Apricots	66 762	48 792 (processed) 8725 (dried)
Mangoes[8]	65 439	~50 000
Plums	60 925	1712
Guavas	23 699	20 896
Papayas	12 565	Not indicated
Litchis	7782	Not indicated
Strawberries	5543	2724
Other berries	5073	3914
Prunes	3426	Not indicated
Figs	1925	448
Pomegranates[9]	1324	883
Cherries[10]	775	83
Granadillas	484	Not indicated
Quinces	208	Not indicated

Note: processed = canned and/or juiced; dried = prepared as dried fruit; pressed = pressed for winemaking

South Africa comprises different temperate zones and fruit production is therefore scattered throughout the country. Production of the major crops – grapes, apples and citrus – is mainly centred in the Western Cape and Eastern Cape Provinces. In addition to deciduous fruit, sub-tropical fruit and other common fruit crops, South Africa also has a thriving olive industry, which is mainly based in the Western Cape Province. Presently, South Africans consume about 3.5 million litres of olive oil annually, of which local production only contributes 20%. The olive industry is one of the fastest growing agricultural sectors in South Africa with a growth rate of approximately 20% per annum. Olive production was estimated at 1500 tonnes for 2012/2013.[11]

Fruit processing (canning, juicing, winemaking and drying) generates large quantities of waste, both solid and liquid. For example, approximately 25–35% of processed apples (dry mass), 50% of citrus and 20% of grapes end up as waste.[12] The solid waste, often called pomace, is the portion of the fruit that is not utilised, such as skins, pips and fibres. The pomace has a high lignocellulose content and is very recalcitrant to degradation. In addition, large volumes of liquid wastes are generated from washing during processing. According to the *South African National Water Act of 1998*, wastewater must meet specified standards before it can be discharged into rivers or used for irrigation. Based on composition, there are limits to the volume of wastewater permitted for irrigation usage. For example, wastewater with a chemical oxygen demand (COD) of less than 400 mg/L can be used for irrigation at volumes of up to 500 m^3, while irrigation volumes may not exceed 50 m^3 on any given day if the COD is between 400 mg/L and 5000 mg/L. The average COD of wastewater in the juicing and canning industries is often as high as 10 000 mg/L and therefore requires extensive treatment before discharge into the environment.[12]

In a recent study by Burton et al.[13], it was recommended that maximum beneficiation of waste streams can be achieved through supplementation of the wastewater with solid waste, especially if the waste is targeted for microbial biomass or bioenergy production. South Africa produces sufficient fruit-processing wastes (solid and liquid) for the development of a biorefinery to be a viable option.

Composition and potential value of waste from selected fruits

Waste streams should be characterised to determine the potential for extraction of valuable products, microbial growth and/or enzyme production. The levels of nutrients need to be quantified to ascertain whether supplementation is necessary. Waste generated during the processing of an emerging crop (olives) and the major fruit crops produced in South Africa (citrus, grapes and apples), their potential for the generation of value-added products, as well as relevant research studies performed in South Africa, are summarised in Figures 1–4. A summary of potential beneficiation of agri-industrial wastes (solid and liquid) is provided in Figure 5.

South African studies on bio-based (fruit) wastes

Various studies have been carried out on wastes from the South African fruit industry to address aspects of waste treatment and beneficiation (Table 2). Work conducted on olive, citrus, grape and apple waste, is summarised in Figures 1–4. Many of these studies have taken place with funding obtained from the Water Research Commission of South Africa and the Wine Industry Network of Expertise and Technology (Winetech).

Burton et al.[72] carried out a feasibility study on the potential for energy generation from wastewater. They identified fruit industry wastewater as one of three wastewater sources with the greatest potential as sources of renewable energy. Fruit processing in South Africa includes canning, juicing, winemaking and fruit drying. Heavy water consumption occurs during these processes (7–10.7 m^3/tonne of raw produce) and the wastewater generated typically contains particulate organics, suspended solids, various cleaning solutions and softening or surface-active additives.[72] A compositional analysis of wastewater from an industrial fruit processor in the Western Cape Province revealed that fruit-processing wastewater could be a feasible feedstock for the production of bio-ethanol and biogas, but factors such as COD levels,

Fruit profile: Olives

Data on olive processing

South African 2012/2013 season: 2000 tonnes processed for olive oil production; 1500 tonnes processed for table olive production[11]

For olive oil production[14]: 3-phase – 80-120 L olive mill wastewater and 55 kg olive husk per 100 kg olives processed; 2-phase – 80 kg olive mill waste per 100 kg olives processed (one waste stream; solid and liquid combined)

Solid and liquid waste composition[14]

Press process: Solid and liquid waste

- Solid: fats and oils (~9%), proteins (~5%), total sugars (~1%), cellulose (~24%), lignin (14%), phenolic compounds (~1%)
- Liquid: low pH (4.5) and slightly more total sugars (~2.6%)

2-phase process: Solid waste only

- 56.8% moisture content compared to 27.2% from the press process; total sugars (~1%), cellulose (~14.5%), lignin (~8.5%), phenolic compounds (~2.43%)

3-phase process: Solid and liquid waste

- Solid: moisture content at 50.23%, total sugars (~1%), cellulose (~17%), lignin (~10%); phenolic compounds (~0.3%)
- Liquid: low pH (4.8) and 1.61% total sugars

Potential uses of olive-processing waste and potential for production of value-added products

- Bio-energy[15]
- Enzymes[16]
- Direct soil application (fertiliser/carbon sequestration)[17]
- Animal/fish feed[18,19]
- Composting[20]
- Pectin extraction[21]
- Source of polyphenols[22]
- Functional beverages[23]
- Sorbent for heavy metals from aqueous solutions[24]
- Novel materials, bio-plastics[25]

Research performed in South Africa

Focus of the studies: Bioremediation and beneficiation

Targeted waste stream: Table olive processing wastewater

Major conclusions/outcomes: Designed a bioreactor for the extraction of hydroxy-tyrosol, a potent antioxidant (beneficiation); microorganisms isolated from the waste showed great potential in the bioremediation of the wastewater.

References: 26, 27, 28

Figure 1: Olive waste profile – solid and liquid waste composition and potential for application and production of value-added products.

Fruit profile: Citrus

Data on citrus processing

South African 2011/2012 season[7]: Citrus (oranges, lemons, limes, grapefruit and naartjies) – 441 899 tonnes processed

Waste generated: > 1.5 ML of wastewater generated per tonne of citrus fruit processed[29]; Solid waste generated: peels, seeds, membranes and juice vesicles[30]

Solid and liquid waste composition

Liquid waste:

- 15% soluble solids and 30% pulp may be present; high COD (100-2000 mg/L) and biochemical oxygen demand (BOD; 20-1400 mg/L)[31]
- Wastewater nutrient concentration (in terms of phosphorous and nitrogen) is quite low, pH values are variable, various antioxidant compounds, as well as essential oils and heteropolysaccharides are present[29,31]
- The presence of terpenes in citrus-processing wastewater often makes biological treatment of the waste quite difficult because of the genotoxic effect of the terpenes on various prokaryotic and eukaryotic organisms[31]

Solid waste:

Citrus waste contains (g/100g)

- 8.1-10.1% total sugars
- 0.5-4.0% fat
- 7.0-12.5% protein
- 8.5-23% pectin
- 7.5-11.6% lignin
- 22.5-37.1% cellulose
- 5.60-11.0% hemicellulose[32]

Potential applications of citrus-processing waste and potential for production of value-added products

- Enzyme production[33]
- Biofuel production[34]
- Animal feed[35]
- Bioactive compounds such as antioxidants[36]
- Citric acid production[37]
- Heteropolysaccharide xanthum (gum)[38]
- Substrate for single cell protein production[39]
- Mushroom production[40]
- Composting[41]
- Ethylene production[42]
- Immobilisation carrier in solid state fermentation[43]
- Source of limonene and pectin[34]

Research performed in South Africa

Focus of the studies: Bioremediation and beneficiation

Targeted waste stream: Citrus solid waste and wastewater from citrus processing

Major conclusions/outcomes:

- Citrus solid waste can be used as composting material
- Organic oils present have potential application in cosmetics
- It is rich in antioxidants and antioxidant-rich dietary fibre
- Most of the waste streams are dilute, a pre-concentration step may be required and supplementation with solid waste would be required for full beneficiation

References: 13, 29, 41

COD, chemical oxygen demand

Figure 2: Citrus waste profile – composition of the waste and potential uses and application for the production of value-added products.

Fruit profile: Grapes

Data on grape processing

South African 2011/2012 season[7]: 1649 tonnes processed for preserves and canning; 151 628 tonnes are dried; 1 413 533 tonnes pressed for wine, spirits and juice production

Waste generated: 1 billion L wastewater generated per annum[44]; solid waste (typically 30% w/w of fresh grapes) includes skins and seeds (pomace or marc) and stalks[45]

Research performed in South Africa

Focus of the studies: Bioremediation

Targeted waste stream: Winery and distillery wastewater

Major conclusions/outcomes:

- Various treatment technologies can be applied for the treatment of winery wastewater
- Microorganisms and to a lesser extent, plants, play a key role in the treatment processes involving the use of constructed wetlands
- Upflow anaerobic sludge blanket reactors combined with ozonation, is a feasible treatment method for the bioremediation of winery wastewater
- Constructed wetlands (planted and unplanted) are inexpensive, low maintenance alternatives for the treatment of winery wastewater.

References: Various Winetech projects (1999-current)[46], including the following project numbers: WW 19/01, 120H, MV 04, US GMW, WW 19/05, WW 19/07, WW 19/08, WW 19/09, WW 19/11, WW 19/12, WW 19/13, WW 19/14, WW 19/15, CRSES 201227 and SU 2013/27; 44, 45, 46, 47

Solid and liquid waste composition

Liquid waste: Composition is variable and generally dilute; COD of 800-12 800 mg/L with glucose, fructose, ethanol and acetic acid contributing towards the COD[48,49]; low levels of organic acids and slowly biodegradable phenolic compounds; pH ~4.5.

Solid waste: Composition is variable, depending on the component and cultivar analysed; g/100 g: 1.8-3.7% soluble sugars; 1.8-3.8% protein; 0.3-1.0% lipids; 19.5-40.8% cell wall polysaccharides and lignin (dietary fibre)[45]

Potential applications of grape-processing waste and potential for production of value-added products

- Enzyme production[51]
- Biofuel production[52]
- Composting[53]
- Animal feed[54]
- Resin formulation[55]
- Pullulan production[56]
- Lactic acid and biosurfactant production[57]
- Substrate for growth of edible mushrooms[58]
- Source of polyphenolic and phenolic compounds (including antioxidants and pigments)[59, 60]

COD, chemical oxygen demand

Figure 3: Grape waste profile – waste composition and potential uses and application for the production of value-added products.

Fruit profile: Apples

Data on apple processing

South African 2011/2012 season[7]: 244 469 tonnes processed for juice, jams, preserves, etc.; 1110 tonnes dried.

Waste generated: Apple processing results in 25-30% solid mass or pomace and approximately 5-10% liquid sludge is produced[61]

Solid and liquid waste composition

Liquid waste:

The apple process sludge typically has a pH of 3.3±0.1, 115-135±5.0 g/L total solids, total nitrogen of 2.2-2.9 g/L, 44.3-51.9 g/L total carbon, 56.2-66 ±1.7 g/L total carbohydrates, 28.8-33.8 ±2.0 g/L protein, 5.1-5.9 g/L total lipids and various micronutrients[61]

Solid waste:

Biochemical composition of apple pomace is dependent on the variety of apple used as well as the stage of ripening at harvest[62]:

- 7.2-43.6% cellulose, 4.26-24.4% hemicellulose
- 15.3-23.5% lignin, 3.5-14.32% pectin
- 48.0-83.8% total carbohydrates
- 2.9-5.7% protein
- 1.2-3.9% lipids
- 10.8-15.0% total sugars (glucose, fructose and arabinose as major components and sucrose, galactose and xylose as minor components)[61]

Potential applications of apple-processing waste and potential for production of value-added products

- Enzyme production and induction[61]
- Biofuel production (ethanol and biohydrogen)[63]
- Incorporation into food products[64]
- Source of polyphenols (e.g. antioxidants)[63]
- Cultivation of edible mushrooms[65]
- Production of aroma compounds and pigments[63]
- Production of lactic acid[66]
- Production of citric acid[61]
- Substrate for microorganisms for the production of biopolymers[61]
- Animal/livestock feed[61]

Research performed in South Africa

Focus of the studies: Renewable energy, bioremediation and beneficiation

Targeted waste stream: Apple-processing wastewater, unprocessed fruit and apple pomace

Major conclusions/outcomes:

- Anaerobic ponds for the treatment of apple-processing wastewater are effective for the bioremediation of the wastewater and can be applied in the production of biogas (methane)
- Biogas production from excess, unprocessed fruit is feasible; due to seasonality of the waste, supplementation with another waste type was necessary
- Enzyme cocktails can be used for the breakdown of recalcitrant waste components; release of sugars sufficient for bio-ethanol production

References: 47, 67, 68, 69

Figure 4: Apple waste profile – composition of the pomace and sludge generated during apple processing, potential uses and applications in the production of value-added products.

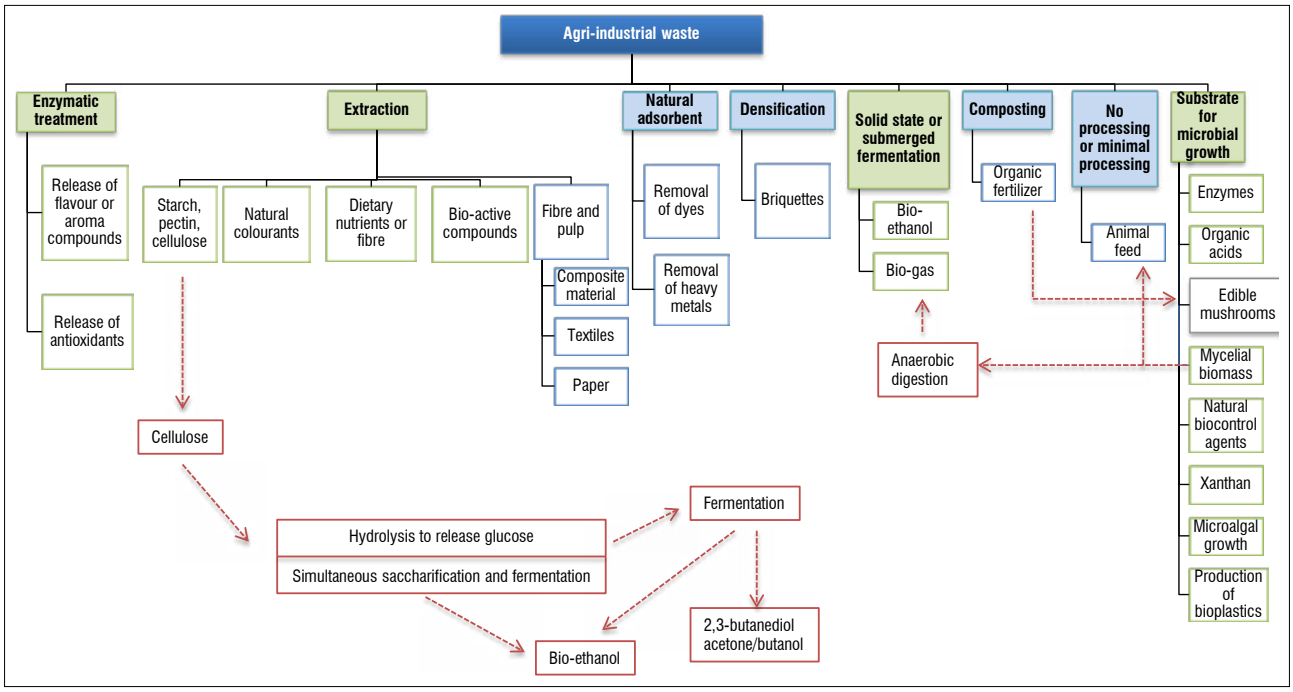

Figure 5: Potential beneficiation of agri-industrial wastes with a focus on fruit wastes. Green blocks indicate possible pathways for beneficiation of liquid waste and/or solid waste, while blue blocks represent possible beneficiation pathways for solid waste.

Table 2: Research performed in South Africa with a focus on bio-based waste (solid and liquid)

Focus of the study	Targeted fruit waste	Major conclusions/outcomes	Reference
Scoping study for bioremediation and beneficiation application	Pineapple cannery wastewater	The high carbohydrate content (19.8 g/L) of the wastewater makes this wastewater an attractive substrate for the production of yeast and/or ethanol.	73
Water and wastewater management in fruit- and vegetable-processing plants	General	A large volume of wastewater is generated during fruit processing; the report was written in the form of a guideline on how to minimise water intake and wastage.	74
Renewable energy	Fruit cannery wastewater	Biogas production from fruit cannery wastewater through the use of an upflow anaerobic sludge bed bioreactor is possible, but certain parameters need to be monitored (e.g. salt accumulation).	75
Renewable energy	Various fruit-processing wastes	Theoretical: Identified the fruit and beverage industries (brewery, distillery, winery, fruit juicing and canning) as one of three sectors for potential energy recovery from waste; sugar-rich wastewaters are a potential source for bio-energy production.	72

Note: Studies on olive, citrus, grape and apple waste are presented in Figures 1–4.
Sources: adapted from Dhillon et al.[61], Padam et al.[70], Martin[71].

sugar concentration and volumes generated should be considered during feasibility studies.[72]

An early study by Prior and Potgieter[73] explored the potential use of pineapple cannery wastewater and other fruit- and vegetable-processing waste as a substrate for the growth of a yeast strain and ethanol production. Pineapple cannery wastewater was found to be sufficiently high in carbohydrate content for bio-ethanol production. Binnie and Partners[74] mainly focused on water practices at fruit- and vegetable-processing plants. An evaluation of the water intake and wastewater generated, showed that excessive water wastage occurs in these processing plants. The study evaluated different types of processing plants receiving different types of fruit and/or vegetables, and presented a set of guidelines for these industries for the management of water intake and wastewater generation. However, industrial practices may have changed since these studies were undertaken and no new comprehensive evaluations have been performed since then. Subsequent studies on fruit waste (solid and/or liquid) have become more focused and aimed at bioremediation, beneficiation and/or renewable energy generation.

Interestingly, there is only one other reported study on the production of renewable energy from fruit cannery wastewater.[75] The main obstacle in the use of this wastewater stream is that the wastewater was found to be alkaline and contaminated with lye which is used during the canning process (for cleaning of tanks etc.). Sigge and Britz[75] were, however, successful in the application of an upflow anaerobic sludge bed reactor for biogas production but, over time, experienced excessive salt accumulation and ultimate failure of the bioreactor, indicating that an additional process for the removal of salts would be required.

On a larger scale, we are aware of one company in South Africa that utilises a fruit waste input. Brenn-O-Kem, with plants in Wolseley and Worcester in the Western Cape, successfully utilises grape pomace and lees from the wine production industry (grape processing) for the production of various valuable products.[76] These products include cream of tartar, calcium tartrate and grape seed extract. The remaining wastes after processing are dried and burned for fuel, which reduces the volume which is subsequently composted. Brenn-O-Kem is an excellent example of a company with a successful production strategy based on a sustainable waste stream.

Even though aspects of beneficiation and the application of fruit waste as a feedstock for renewable energy generation have been the focus of fruit waste studies in South Africa, there have been no studies regarding the production of enzymes as value-added products with fruit waste as the feedstock. The following sections will focus on the feasibility of fruit waste and waste streams as a feedstock for the production of value-added products, including industrially important enzymes.

Production of value-added products from bio-based (fruit) waste

Studies frequently cite production costs as one of the constraints in the scaling up of enzyme production for commercial or industrial exploitation. One of the most important cost considerations is the high price of culture media. In a recent study, Osma et al.[77] showed that for all the 46 different enzyme production systems they investigated, the cost of culture medium was consistently higher than the cost of equipment and the operating costs. It is therefore important for researchers to explore new and inexpensive media for enzyme production. Fruit waste streams can be potential substrates for the production of enzymes and other value-added products. Cellulase production, for example, may occur via solid-state fermentation or submerged fermentation.[78] Solid-state fermentation has many advantages over submerged fermentation as it requires less capital, lower energy, uses a less complex medium, results in higher productivity, requires less rigorous control of fermentation parameters, and produces less wastewater.[78] Krishna[79] made a direct comparison between solid-state and submerged fermentation using banana waste and found that cellulase production was 12-fold higher using solid-state fermentation. For reviews on solid-state fermentation see Couto and Sanroman[80] and Pandey et al.[81]

In many studies, the agri-industrial waste substrates were supplemented with further nutrients such as glucose, and/or nitrogen sources such as yeast extract or inorganic sources such as ammonium sulphate or sodium nitrate. Other supplements included mineral salts and trace elements. Supplementation with wheat bran is also common. The extent of supplementation is influenced by the substrate characteristics, as well as the growth requirements of the microorganism used. Where fruit-processing waste is used, the substrate may contain many of the minerals required, as well as residual sugars, and will therefore require less or no supplementation.[82] A viable alternative is the supplementation of the fruit-processing wastewater with solid waste to effect a bioremediation–beneficiation result.[13] Ideally there should be minimal supplementation in order to minimise costs.

Enzyme production through Aspergillus *strains on fruit wastes*

Local production of useful enzymes is encouraged under the new bio-economy strategy.[5] Currently, South Africa imports the majority of its enzyme requirements and the development of local manufacturing capabilities will decrease reliance on imports. Not only will this decrease the cost of enzymes, but the cost reduction will encourage their use in the development and establishment of environmentally sustainable industrial processes. Industrially important enzymes are a strategic area of interest as their use can translate to reductions in water usage, energy consumption, greenhouse gas emissions and other toxic waste emissions.

Aspergillus spp., notably *A. niger* and *A. oryzae*, have been used in the Orient for more than 2000 years for the production of fermented food and products such as citric acid and soya.[83] These fungi produce copious amounts of enzymes that can hydrolyse starch, pectin and cellulosics.[84,85] *Aspergillus* spp. can also degrade and utilise a wide range of phenolic compounds[86], including compounds present in olive mill wastewaters[87-89]. The ability of *Aspergillus* spp. to produce extracellular enzymes in large quantities and to utilise recalcitrant phenolic compounds, make them ideal for degrading more complex organic matter in waste streams.

Aspergillus niger has long been used for industrial enzyme production, in particular by companies such as Novozymes and DSM, and is the preferred organism for industrial enzyme production. Various *A. niger* strains capable of overexpressing cellulases, xylanases, mannanases[90,91] and a laccase[92] have been developed and tested. Enzyme production in grams per litre was demonstrated for a mannanase.[93] Furthermore, studies showed the production of cellulase and xylanase by *A. niger* strains cultured on the waste lignocellulosic streams remaining after fermentation of sugarcane bagasse and northern spruce.[94,95] In principle, it should be possible to grow *A. niger* strains on spent fruit waste streams after ethanolic fermentation, and on olive mill waste streams, with the simultaneous production of high-valued enzymes.

Conversion of agri-industrial wastewater to bioenergy

The first version of the Biofuels Industrial Strategy was released in 2007 with the overall aim of contributing up to 50% of the national renewable energy target of 10 000 GWh[96] through 4.5% blending of biofuels with petroleum. Before the release of the final strategy, commercial sugar producers and maize farmers represented the majority of the parties looking to drive the South African biofuels industry. However, the final Biofuels Industrial Strategy reduced the target to 2% of the liquid road transport fuels market. A 2% mandatory blending (for implementation from 1 October 2015) was only gazetted in 2012.

To date, the Department of Energy has issued and granted nine licences for the production of at least 500 million litres per annum of bioethanol and biodiesel from grain sorghum, soybean and waste vegetable oils. The biofuel plant to be built in Cradock in the Eastern Cape Province, funded by the Industrial Development Corporation of South Africa, has received the most attention as it will be seen as a case study for the nascent biofuels industry. In the first phase, 225 000 tonnes of grain sorghum will be imported from around the country and the second phase will use the produce from local farms, purchased by the Department of Rural Development and Land Reform. Mainly sugar beet and sorghum will be used to produce 90 million litres of bioethanol a year. The development of these biofuels facilities appears to be delayed by financing, availability of suitable land, incentives and policy decisions. Unfortunately, none of the initiatives of the initial stakeholders (maize and commercial sugar producers) has become established, mainly because of the Strategy's restrictions on the type and source of feedstock, as well as on the type of farmers (subsistence versus commercial) who would be subsidised. Considering the sensitivity of the food versus fuel debate, as well as sensitivity around land use and ownership, feedstocks outside these contentions would be ideal for biofuels production. The use of fruit waste for bioethanol production does not affect food security or land use, is readily available and, as a value-added by-product of wastewater treatment, is economically beneficial to industries.[97]

Potential production of biofuels from fruit waste streams

A variable portion of fruit waste contains fermentable sugars that can be directly converted to ethanol. In the case of fruit streams, the bulk of the fermentable sugars are hexoses that can readily be fermented with industrial strains of *Saccharomyces cerevisiae* (bakers' yeast). Several previous reports alluded to the potential use of sugar-rich fruit wastewater for the production of bioethanol but all concluded that the sugar content (typically <10%) needs to be higher to ensure minimum ethanol levels of 4% to make distillation cost effective.[13,72,73] The major challenge would be to concentrate the wastewater streams to about 20% sugar, which is optimal for ethanol production.[98] If fruit streams could be handled or sorted such that high sugar streams are available, direct fermentation to ethanol could be one approach to produce ethanol for in-house energy generation, or for local use in ethanol-gel, a safe and renewable replacement for kerosene.[99] Examples of ethanol production from fruit wastewater have been reported from apple pomace[100] and citrus leachate[101]. However, because of the variable and inevitably low sugar concentration of fruit waste streams, enzyme hydrolysis is required to release more fermentable sugars from starch, pectin and cellulosics in the waste streams to boost sugar concentrations to levels of 20% and higher.[34,102-105]

Current status of advanced cellulosic ethanol technologies

Advanced technologies for the conversion of lignocellulosics to ethanol are slowly but surely coming to fruition. Several companies have

demonstrated novel processes for the conversion of woody biomass to ethanol and the first commercial plants in the USA and European Union were commissioned in 2013.[106,107] A large variety of thermochemical and biochemical routes (as well as hybrids of both) are exploited by different companies, although production of bioethanol represents the largest portion of commercial initiatives with major players such as Abengoa Bioenergy, Beta Renewables, DuPont Biofuel Solutions and POET exploring simultaneous saccharification and fermentation processes using commercial enzymes and primarily herbaceous feedstocks, notably corn stover and cobs, switchgrass or *Arundo* reeds.[106] Mascoma, in partnership with Valero, is the only company exploring consolidated bioprocessing (one-step conversion of lignocellulosics to ethanol), using a proprietary recombinant yeast strain that produces key cellulase enzymes and which can utilise both hexoses and the pentose sugar xylose (called CBP yeast). Mascoma is focusing on hardwoods and pulps as feedstocks.[107]

In South Africa, there have been several breakthroughs in expressing cellulases in the yeast *S. cerevisiae*[108-113] and in the development of a consolidated bioprocessing yeast strain capable of converting pre-treated hardwood to ethanol with significantly reduced enzyme addition[114]. Pre-treatment of different agricultural residues, with the aid of a 15-L reactor steam gun, has been evaluated with South African sponsored research funding in anticipation of an emerging cellulosic ethanol industry.[115-118] Researchers have also developed the capacity to generate pyrolysis and gasification products from different cellulosic feedstocks to substitute fossil fuels such as coal, coking coal and reductants.[119,120] These studies also support developments toward the realisation of a bio-economy. Apart from the development of both biochemical and thermochemical technologies, expertise in process modelling, energy efficiency optimisation, economic viability assessment and life-cycle analysis have also been developed.[121] Such technology assessment is critical for both technology selection and technology integration into future biofuels/bioenergy/biorefinery industries.

Potential for biofuel production in South Africa

When advanced generation biofuels technologies come to fruition and 50% of the residual lignocellulosic biomass (almost 50 million tonnes produced annually in South Africa) can be used, biofuels could play a significant role in South Africa's transport fuel future. The potential contribution from different sources to the current total fossil fuel usage of 23 x 10^9 litres would be: 9.7% ethanol from agricultural residues, 3.2% ethanol from forestry residues, 10% ethanol from burned grasses (if these can be optimally utilised), and potentially 4.2% ethanol from the utilisation of invasive plants.[122,123]

The paradigm shift from fossil fuels to biofuels-generated energy will have far-reaching positive consequences; beyond the development of a sustainable energy resource, it will also impact on society. The decrease in levels of unemployment will play a major role in alleviating many social problems in South Africa related to unemployment and poverty.

A conceptual model to maximise utilisation of fruit-waste streams

The current management plans for many fruit wastes do not extract the full value from these wastes before disposal. In line with the bio-economy strategy, the full beneficiation potential of these wastes should be evaluated. Overall, the beneficiation potential of fruit wastes includes: extraction of valuable chemicals, provision of nutrient sources for the growth of alternative biomass (for either consumption or the production of valuable products like enzymes), feedstock for biofuels production, and composting or land application. These potential uses are not necessarily mutually exclusive and the full extraction value should be considered. Previous studies explored the utilisation of fruit and olive waste streams through different technologies. Although all the technologies have merit, none provides a complete solution in isolation. The concept of a biorefinery includes the separation of biomass resources (using a range of technologies) into their building blocks which can then be converted to a variety of value-added products. With this in mind, a non-exclusive biorefinery using fruit and olive wastes is proposed. This approach maximises the potential of fruit and olive waste streams through the integration of different technologies. This integration is shown as a conceptual model in Figure 6.

Combining fruit wastewater streams with lignocellulosic streams could overcome the limitation of both processes – that is, combining the low sugar content of fruit waste streams with the costly enzymatic conversion of lignocellulosics – in a manner analogous to the integration of ethanol

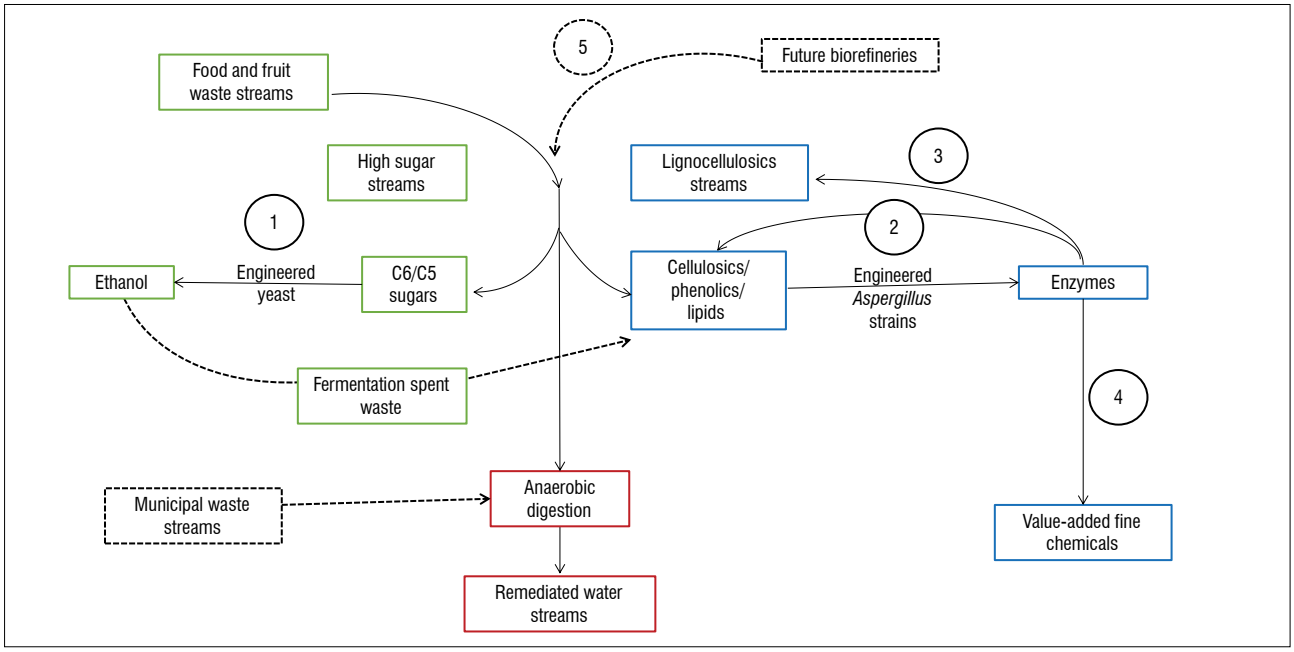

Figure 6: Integrated approach for remediation and beneficiation of fruit waste streams (ReBenFruWaste). Waste streams can be divided into (1) sugar-rich streams for ethanol production and (2) cellulosic/phenolics/lipid-rich streams for enzyme production by *Aspergillus* strains. Enzymes can be used for (3) bioconversion of lignocellulosic streams or (4) the production of value-added fine chemicals. The process can also include (5) biorefinery waste streams of future bio-economies.

production from sugarcane juice and sugarcane bagasse.[112] The ideal approach would be to first ferment high sugar streams to ethanol, or to combine such streams with lignocellulose sugar streams generated by employing commercial enzyme preparations, or enzymes produced with recombinant *Aspergillus* strains on spent fermentation streams. Subsequently, waste streams with lipids and high phenolic content (such as olive mill waste streams) or higher lignocellulosics (fruit slops or citric wastes) would be used to produce enzymes with recombinant *A. niger* strains. The remainder would be exploited for biogas production, or combined with municipal waste for biogas production.

Some disposal strategies for fruit waste (e.g. use as feedstock) utilise all components of the waste. Alternative beneficiation methods should also minimise waste in order to minimise environmental pollution. A biorefinery approach, with individual applications that may utilise different elements of the pomace, is capable of coupling complementary processes to achieve zero waste.

A fruit waste biorefinery should not only be able to produce valuable products, but also be sustainable in the long term and result in economic, environmental and social gains. The social and environmental impacts of some current disposal methods for most fruit wastes are clear: evaporation lagoons and direct soil application that lead to malodours and environmental toxicity if legal limits (which are often lacking) are not adhered to; ever-increasing transport costs for landfill disposal; as well as energy costs for drying wastes for animal feed. Aside from economic gains and decreases in environmental impacts, the implementation of beneficiation strategies in a fruit waste biorefinery could also result in social development in rural fruit-growing regions, with increased employment opportunities and skills development.

Disadvantages facing the application of the beneficiation technologies discussed are that fruit crops (and hence processing wastes) are seasonal, there are costs of transporting wastes for processing and there is variability in waste composition within and between fruit crops. These challenges can be overcome by centralising biorefineries in areas where fruit-processing plants are clustered and ensuring that the technologies used are robust and flexible enough to handle variable inputs. Centralising waste beneficiation plants in fruit-processing areas would reduce transport costs. For example, in South Africa, the grape and apple production and processing areas are in close proximity and a biorefinery that could extract the value from wastes from both crops would be advantageous. Furthermore, to decrease downtime, the processing of other agri-industrial wastes in the region could occur in the off-season/s.

Innovative solutions to overcome the challenges faced are required for the implementation and success of the new *Bio-economy Strategy.* Beneficiation of fruit wastes could play a role in the development of a bio-economy. It is important to note that the viability of waste source beneficiation is not determined by the ability to provide/fulfil all the needs of a country (for example, the entire biofuel requirements) in a particular sector; rather beneficiation should be considered feasible if the beneficiation potential is currently not being met and if a given process could contribute towards meeting these needs while resulting in decreased environmental impacts and positive social and economic gains.

Conclusion

In conclusion, it is clear that South Africa has vast resources in the form of fruit waste materials and waste streams that can be channelled into the production of various value-added products, notably biofuels and enzymes. The proposed conceptual model for an integrated system that utilises fruit and olive waste streams falls within the objectives of the South African bio-economy and the vision for the development of the industrial bio-economy and sustainable environmental management in South Africa (Figure 7). Not only does it address the extraction of bio-based chemicals and bio-energy, but also the need for bioremediation of (agri-) industrial wastewater. The conceptual model proposed (Figure 6) effectively addresses a number of strategic interventions laid out by the South African *Bio-Economy Strategy* which include the development of integrated biorefineries from bio-based feedstocks and strengthening of wastewater and solid waste research, development and innovation.[5] A successful integrated system would be beneficial for the country with regard to: (1) a reduction in the use of fossil fuels, (2) the treatment of waste streams and waste materials currently posing a threat to the environment, (3) job creation, (4) development of sustainable green processes and (5) the production of value-added products with the potential for South Africa to expand into a global, multimillion rand market.

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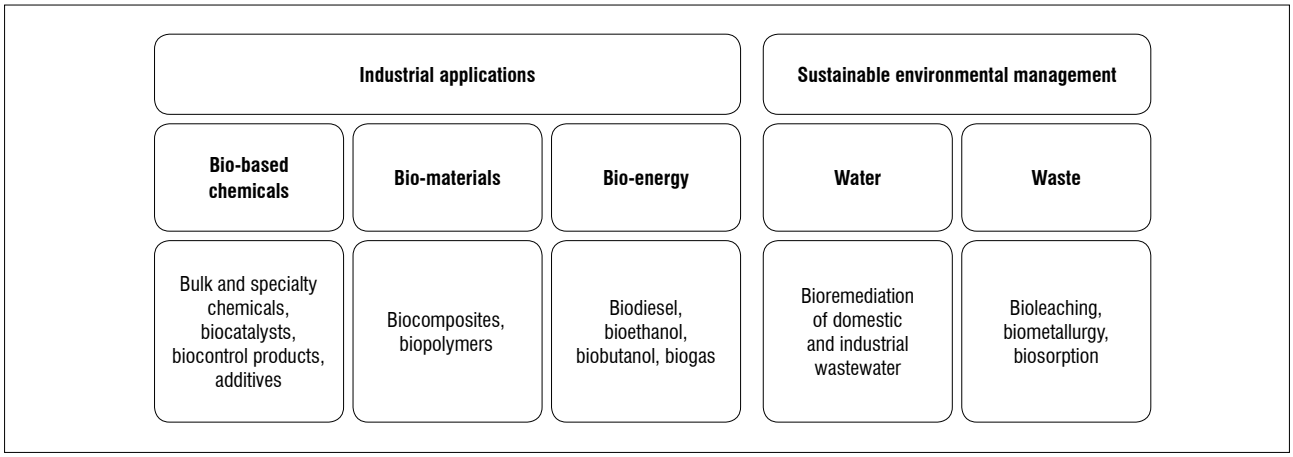
Authors' contributions

B.I.P was the project leader; W.H.v.Z. and M.L.R-H. were co-investigators on the project; and N.K., P.J.W., K.A.G., T.K., J.S.v.D and C.O. all contributed to the writing of the manuscript. Final proofreading and preparation of the manuscript was performed by N.K., M.L.R-H., W.H.v.Z and B.I.P.



Source: adapted from the Department of Science and Technology Bio-Economy Strategy[5]

Figure 7: Thematic areas that are the focus for the development of an industrial bio-economy in South Africa. Focus areas and products addressed by the conceptual model for the utilisation of fruit and olive wastes are highlighted in bold.

References

1. Demarche P, Junghanns C, Nair RR, Agathos SN. Harnessing the power of enzymes for environmental stewardship. Biotechnol Adv. 2012;30:933–953. http://dx.doi.org/10.1016/j.biotechadv.2011.05.013
2. Zhang J, Babtie A, Stephanopoulos G. Metabolic engineering: Enabling technology of a bio-based economy. Curr Opin Chem Eng. 2012;1:355–362. http://dx.doi.org/10.1016/j.coche.2012.09.003
3. Vandermeulen V, Prins W, Nolte S, Van Huylenbroeck G. How to measure the size of a bio-based economy: Evidence from Flanders. Biomass Bioenerg. 2011;35:4368–4375. http://dx.doi.org/10.1016/j.biombioe.2011.08.007
4. Arancibia F. Challenging the bioeconomy: The dynamics of collective action in Argentina. Technol Soc. 2013;35:79–92. http://dx.doi.org/10.1016/j.techsoc.2013.01.008
5. Department of Science and Technology (DST). The bio-economy strategy. Pretoria: DST; 2013. Available from: http://www.dst.gov.za/images/ska/Bioeconomy%20Strategy.pdf.
6. International Energy Agency (IEA). IEA Bioenergy Task 42 on biorefineries: Co-production of fuels, chemicals, power and materials from biomass. Minutes of the Third Task Meeting; 2007 March 25–26; Copenhagen, Denmark [document on the Internet]. c2008 [cited 2015 Apr 20]. Available from: http://www.biorefinery.nl/ieabioenergy-task42/
7. South African Department of Agriculture, Forestry and Fisheries (DAFF). Pretoria: DAFF; 2013. Available from: http://www.nda.agric.za/
8. South African Mango Growers' Association [homepage on the Internet]. No date [cited 2015 Apr 20]. Available from: www.mango.co.za
9. Pomegranate Association of South Africa [homepage on the Internet]. No date [cited 2015 Apr 20]. Available from: www.sapomegranate.co.za
10. South African Cherry Growers' Association [homepage on the Internet]. No date [cited 2015 Apr 20]. Available from: www.cherries.co.za
11. SA Olive Industry Association [homepage on the Internet]. No date [cited 2015 Apr 20]. Available from www.saolive.co.za.
12. Van Dyk JS, Gama R, Morrison D, Swart S, Pletschke BI. Food processing waste: Problems, current management and prospects for utilization of the lignocellulose component through enzyme synergistic degradation. Renew Sust Energ Rev. 2013;26:521–531. http://dx.doi.org/10.1016/j.rser.2013.06.016
13. Burton SG, Mupure C, Horne KA, Jones S, Welz P. Beneficiation of agri-industrial effluents. Extraction of anti-oxidant phenolics from apple and citrus wastewaters coupled with fermentation of residual sugars to ethanol or other value-added products. WRC Report No. 1937/1/11. Pretoria: Water Research Commission; 2013.
14. Vlyssidis AG, Loizides M, Karlis PK. Integrated strategic approach for reusing olive oil extraction by-products. J Clean Prod. 2004;12:603–611. http://dx.doi.org/10.1016/S0959-6526(03)00078-7
15. Rincon B, Raposo F, Borja R, Gonzalez JM, Portillo MC, Saiz-Jimenez C. Performance and microbial communities of a continuous stirred tank anaerobic reactor treating two-phases olive mill solid wastes at low organic loading rates. J Biotechnol. 2006;121:534–543. http://dx.doi.org/10.1016/j.jbiotec.2005.08.013
16. Gonzalez JC, Medina SC, Rodriguez A, Osma JF, Alméciga-Díaz CJ, Sánchez OF. Production of *Trametes pubescens* laccase under submerged and semi-solid culture conditions on agro-industrial wastes. PLoS ONE. 2013;8:e73721. http://dx.doi.org/10.1371/journal.pone.0073721
17. Sánchez-Monedero MA, Cayuela ML, Mondini C, Serramiá N, Roig A. Potential of olive mill wastes for soil C sequestration. Waste Manage. 2008;28:767–773. http://dx.doi.org/10.1016/j.wasman.2007.09.029
18. Molina-Alcaide E, Yá-ez-Ruiz DR. Potential use of olive by-products in ruminant feeding: A review. Anim Feed Sci Tech. 2008;147:247–264. http://dx.doi.org/10.1016/j.anifeedsci.2007.09.021
19. Nasopoulou C, Stamatakis G, Demopoulos CA, Zabetakis I. Effects of olive pomace and olive pomace oil on growth performance, fatty acid composition and cardio protective properties of gilthead sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*). Food Chem. 2011;129:1108–1113. http://dx.doi.org/10.1016/j.foodchem.2011.05.086
20. Abu-Khayer MD, Chowdhury MB, Akratos CS, Vayenas DV, Pavlou S. Olive mill waste composting: A review. Int Biodeter Biodegr. 2013;85:108–119. http://dx.doi.org/10.1016/j.ibiod.2013.06.019
21. Cardoso SM, Coimbra MA, Lopes da Silva JA. Calcium mediated gelation of an olive pomace pectic extract. Carbohyd Polym. 2003;52:125–133. http://dx.doi.org/10.1016/S0144-8617(02)00299-0
22. Hamden K, Alloucheb N, Damakb M, Elfekia A. Hypoglycemic and antioxidant effects of phenolic extracts and purified hydroxytyrosol from olive mill waste in vitro and in rats. Chem-Biol Interact. 2009;180:421–432. http://dx.doi.org/10.1016/j.cbi.2009.04.002
23. Zbakh H, El Abbassi A. Potential use of olive mill wastewater in the preparation of functional beverages: A review. J Funct Food. 2012;4:53–65. http://dx.doi.org/10.1016/j.jff.2012.01.002
24. Pagnanelli F, Toro L, Veglio F. Olive mill solid residues as heavy metal sorbent material: A preliminary study. Waste Manage. 2002;22:901–907. http://dx.doi.org/10.1016/S0956-053X(02)00086-7
25. Siracusa G, La Rosa AD, Siracusa V, Trovato M. Ecocompatible use of olive husk as filler in thermoplastic composites. J Polym Environ. 2001;9:157–161. http://dx.doi.org/10.1023/A:1020465305193
26. Burton SG, Cowan DA, Garcin C, Van Schalkwyk A, Werner C. A customised bioreactor for beneficiation and bioremediation of effluents containing high value organic chemicals. WRC Report No.K5/1361. Pretoria: Water Research Commission; 2006.
27. Garcin CJ, Burton SG. Implementation of a generic membrane-based system for beneficiation and treatment of agro-industrial wastewater. WRC Report No. KV 186/07. Pretoria: Water Research Commission; 2007.
28. Garcin CJ, Harrison STL. Pilot scale treatment of table olive brines: Beneficiation, purification and water recovery for re-use. WRC Report No. 2010/1/12. Pretoria: Water Research Commission; 2012.
29. Burton SG, Garcin CR, Aucamp JH. Beneficiation of wastewaters from the South African citrus industry – A feasibility study. WRC Report No. KV 187/07. Pretoria: Water Research Commission; 2007.
30. Sinclair WB. The biochemistry and physiology of the lemon and other citrus fruits. Oakland, CA: Division of Agriculture and Natural Resources, University of California; 1984.
31. Saverini M, Catanzaro I, Sciandrello G, Avellone G, Indelicato S, Marcì G, et al. Genotoxicity of citrus wastewater in prokaryotic and eukaryotic cells and efficiency of heterogenous photocatalysis by TiO_2. J Photoch Photobio B. 2012;108:8–15. http://dx.doi.org/10.1016/j.jphotobiol.2011.12.003
32. Boluda-Aguilar M, López-Gómez A. Production of bioethanol by fermentation of lemon (*Citrus limon* L.) peel wastes pretreated with steam explosion. Ind Crop Prod. 2013;41:188–197. http://dx.doi.org/10.1016/j.indcrop.2012.04.031
33. Mamma D, Kourtoglou E, Christakopoulos P. Fungal multienzyme production on industrial by-products of the citrus-processing industry. Bioresour Technol. 2008;99:2373–2383. http://dx.doi.org/10.1016/j.biortech.2007.05.018
34. Pourbafrani M, Forgács G, Horváth IS, Niklasson C, Taherzadeh MJ. Production of biofuels, limonene and pectin from citrus wastes. Bioresour Technol. 2010;101:4246–4250. http://dx.doi.org/10.1016/j.biortech.2010.01.077
35. Göhl B. Citrus by-products for animal feed. In: Ruminant nutrition: Selected articles from the World Animal Review. Rome: FAO; 1978. Available from: http://www.fao.org/docrep/004/x6512e/X6512E08.htm
36. Deng G-F, Shen C, Xu X-R, Kuang R-D, Guo Y-J, Zeng L-S, et al. Potential of fruit wastes as natural resources of bioactive compounds. Int J Mol Sci. 2012;13:8308–8323. http://dx.doi.org/10.3390/ijms13078308
37. Rivas B, Torrado A, Torre P, Converti A, Domínguez JM. Submerged citric acid fermentation on orange peel autohydrolysate. J Agr Food Chem. 2008;56:2380–2387. http://dx.doi.org/10.1021/jf073388r
38. Bilanovic D, Shelef G, Green M. Xanthan fermentation of citrus waste. Bioresour Technol. 1994;48:169–172. http://dx.doi.org/10.1016/0960-8524(94)90205-4
39. Scerra V, Caridi A, Foti F, Sinatra MC. Influence of dairy *Penicillium* sp. on nutrient content of citrus fruit peel. Anim Feed Sci Tech. 1999;78:169–176. http://dx.doi.org/10.1016/S0377-8401(98)00264-8
40. Labaneiah MEO, Abou-Donia SA, Mohamed MS, El Zalaki EM. Utilization of citrus wastes for the production of fungal protein. J Food Technol. 1979;14:95–100. http://dx.doi.org/10.1111/j.1365-2621.1979.tb00852.x
41. Van Heerden I, Cronjé C, Swart SH, Kotzé JM. Microbial, chemical and physical aspects of citrus waste composting. Bioresour Technol. 2002;81:71–76. http://dx.doi.org/10.1016/S0960-8524(01)00058-X
42. Chalutz E, Kapulnik E, Chet I. Fermentative production of ethylene by *Penicillium digitatum* from citrus fruit peel. Eur J Appl Microbiol Biotechnol. 1983;18:293–297. http://dx.doi.org/10.1007/BF00500494

43. Orzua MC, Mussatto SI, Contreras-Esquivel JC, Rodriguez R, De la Garza H, Teixeira JA, et al. Exploitation of agro industrial wastes as immobilization carrier for solid-state fermentation. Ind Crop Prod. 2009;30:24–27. http://dx.doi.org/10.1016/j.indcrop.2009.02.001

44. Welz PJ, Ramond J-B, Cowan DA, Burton SG. Phenolic removal processes in biological sand filters, sand columns and microcosms. Bioresour Technol. 2012;119:262–269. http://dx.doi.org/10.1016/j.biortech.2012.04.087

45. Gonzalez-Centeno M, Rosello C, Simal S, Garau M, Lopez F, Femenia A. Physico-chemical properties of cell wall materials obtained from ten grape varieties and their byproducts: Grape pomaces and stems. LWT-Food Sci Technol. 2010;43:1580–1586. http://dx.doi.org/10.1016/j.lwt.2010.06.024

46. South African Wine Information Centre (SAWIS). The Winetech research output database [database on the Internet]. No date [cited 2015 Apr 20]. Available from www.sawis.co.za/winetech.php.

47. Sigge GO, Britz TJ, McLachlan T, Van Schalkwk N. Treatment of apple and wine processing wastewaters using combined UASB technology and ozonation scenarios. WRC Report No. 1364/1/06. Pretoria: Water Research Commission; 2006.

48. Burton S, Sheridan C, Law-Brown L, Le Roes M, Cowan D, Rohr L, et al. Integrated research for use in constructed wetlands for treatment of winery wastewater. WRC Report No. 1544/1/07. Pretoria: Water Research Commission; 2007.

49. Burton SG, Welz PJ, Ramond J-B, Sheridan C, Kirby B, Schueller A, et al. Health for purpose in constructed wetlands: Organic removal efficiencies and changes in microbial community dynamics associated with exposure to winery wastewater. WRC Report No. 1936/1/11. Pretoria: Water Research Commission; 2012.

50. Welz PJ, Palmer Z, Isaacs S, Kirby BM, Burton SG, Le Roes-Hill M. Adapting constructed wetlands for real world applications. WRC Project No.K5/2104. Pretoria: Water Research Commission; 2012.

51. Daroit DJ, Silveira ST, Hertz PF, Brandelli A. Production of extracellular β-glucosidase by *Monascus purpureus* on different growth substrates. Process Biochem. 2007;42:904–908. http://dx.doi.org/10.1016/j.procbio.2007.01.012

52. Fernández CM, Ramos MJ, Pérez A, Rodríguez JF. Production of biodiesel from winery waste: Extraction, refining and transesterification of grape seed oil. Bioresour Technol. 2010;101:7019–7024. http://dx.doi.org/10.1016/j.biortech.2010.04.014

53. Burg P, Zemanek P, Michalek M. Evaluating of selected parameters of composting process by composting of grape pomace. Acta U Agr Fac Silvi. 2011;59:75–80. http://dx.doi.org/10.11118/actaun201159060075

54. Sphangero M, Salem A, Robinson P. Chemical composition, including secondary metabolites, and remen fermentability of seeds and pulp of Californian (USA) and Italian grape pomaces. Anim Feed Sci Tech 2009;152:243–255. http://dx.doi.org/10.1016/j.anifeedsci.2009.04.015

55. Ping L, Pizzi A, Guo Z, Brosse N. Condensed tannins extraction from grape pomace: Characterization and utilization as wood adhesives for wood particleboard. Ind Crop Prod. 2011;34:907–914. http://dx.doi.org/10.1016/j.indcrop.2011.02.009

56. Sugumaran K, Gowthami E, Swathi B, Elakkiya S, Srivastava S, Ravikumar R, et al. Production of pullulan by *Aureobasidium pullulans* from Asian palm kernel: A novel substrate. Carbohyd Polym. 2012;92:697–703. http://dx.doi.org/10.1016/j.carbpol.2012.09.062

57. Riviera O, Moldes A, Torrado A, Dominguez J. Lactic acid and biosurfactants production from hydrolyzed distilled grape marc. Process Biochem. 2007;42:1010–1020. http://dx.doi.org/10.1016/j.procbio.2007.03.011

58. Pardo A, Perona M, Pardo J. Indoor composting of vine by-products to produce substrates for mushroom cultivation. Span J Agric Res. 2007;5:417–424. http://dx.doi.org/10.5424/sjar/2007053-260

59. Chamorro S, Goni I, Viveros A, Hervert-Hernandez D, Brenes A. Changes in polyphenolic content and antioxidant activity after thermal treatments of grape seed extract and grape pomace. Eur Food Res Technol. 2012;234:147–155. http://dx.doi.org/10.1007/s00217-011-1621-7

60. Zheng Y, Lee C, Yu C, Cheng Y-S, Simmons C, Zhang R, et al. Ensilage and bioconversion of grape pomace into fuel ethanol. J Agr Food Chem. 2012;60:11128–11134. http://dx.doi.org/10.1021/jf303509v

61. Dhillon GS, Kaur S, Brar SK. Perspective of apple processing wastes as low-cost substrates for bioproduction of high value products: A review. Renew Sust Energ Rev. 2013;27:789–805. http://dx.doi.org/10.1016/j.rser.2013.06.046

62. Kennedy M, List D, Lu Y, Newman RH, Sims IM, Bain PJS. Apple pomace and products derived from apple pomace: Uses, composition and analysis. In: Linskens HF, Jackson JF, editors. Analysis of plant waste materials Vol. 20. Berlin: Springer-Verlag; 1999. p. 75–119. http://dx.doi.org/10.1007/978-3-662-03887-1_4

63. Vendruscolo F, Albuquerque PM, Streit F, Esposito E, Ninow JL. Apple pomace: A versatile substrate for biotechnological applications. Crit Rev Biotechnol. 2008;28:1–12. http://dx.doi.org/10.1080/07388550801913840

64. Min B, Bae IY, Lee HG, Yoo S-H, Lee S. Utilization of pectin-enriched materials from apple pomace as a fat replacer in a model food system. Bioresour Technol. 2010;101:5414–5418. http://dx.doi.org/10.1016/j.biortech.2010.02.022

65. Park Y-J, Park H-R, Kim S-R, Yoon D-E, Son E-S, Kwon O-C, et al. Apple pomace increases mycelial growth of *Pleurotus ostreatus*. Afr J Microbiol Res. 2012;6:1075–1078.

66. Gullón B, Remedios Y, Alonso JL, Parajó JC. L-Lactic acid production from apple pomace by sequential hydrolysis and fermentation. Bioresour Technol. 2008;99:308–319. http://dx.doi.org/10.1016/j.biortech.2006.12.018

67. Paulsen C. Determination of the methanogenic potential of an apple processing wastewater treatment system [MSc Food Science thesis]. Stellenbosch: Stellenbosch University; 2006.

68. Mostert F. Fruit processing waste as a renewable energy source for a clean development mechanism project in South Africa [MBA thesis]. Stellenbosch: Stellenbosch University; 2010.

69. Pletschke BI, Van Dyk S, Gama R, Burton SG, Khan N, Ohlhoff C, et al. Tuneable immobilised lignocellulosic enzyme (TILE) system. WRC Project No.K5/2009. Pretoria: Water Research Commission; 2014.

70. Padam BS, Tin HS, Chye FY, Abdullah MT. Banana by-products: An under-utilized renewable food biomass with great potential. J Food Sci Technol. 2014;51(12):3527–3545. http://dx.doi.org/10.1007/s13197-012-0861-2

71. Martin AM. Bioconversion of waste materials to industrial products. London: Blackie Academic & Professional, an imprint of Thomson Science; 1998.

72. Burton S, Cohen B, Harrison S, Pather-Elias S, Stafford W, Van Hille R, Von Blottnitz H. Energy from wastewater: A feasibility study. WRC Report No. 1732/1/09. Pretoria: Water Research Commission; 2009.

73. Prior BA, Potgieter HJ. Composition of fruit and vegetable processing wastes. Water SA. 1981;7:155–157.

74. Binnie & Partners. Waste and wastewater management in the fruit and vegetable processing industry. WRC Report No. 96/1/87. Pretoria: Water Research Commission; 1987.

75. Sigge GO, Britz TJ. UASB treatment of a highly alkaline fruit-cannery lye-peeling wastewater. Water SA. 2007;33:275–278.

76. Brenn-o-kem [homepage on the Internet]. No date [cited 2015 Apr 20]. Available from www.brenn-o-kem.co.za.

77. Osma JF, Toca-Herrera JL, Rodríguez-Couto S. Cost analysis in laccase production. J Environ Manage. 2011;92:2907–2912. http://dx.doi.org/10.1016/j.jenvman.2011.06.052

78. Bansal N, Tewari R, Soni R, Soni SK. Production of cellulases from *Aspergillus niger* NS-2 in solid state fermentation on agricultural and kitchen waste residues. Waste Manage. 2012;32:1341–1346. http://dx.doi.org/10.1016/j.wasman.2012.03.006

79. Krishna C. Production of bacterial cellulases by solid state bioprocessing of banana wastes. Bioresour Technol. 1999;69:231–239. http://dx.doi.org/10.1016/S0960-8524(98)00193-X

80. Couto SR, Sanroman MA. Application of solid-state fermentation to ligninolytic enzyme production. Biochem Eng J. 2005;22:211–219. http://dx.doi.org/10.1016/j.bej.2004.09.013

81. Pandey A, Soccol CR, Mitchell D. New developments in solid state fermentation: I-bioprocesses and products. Process Biochem. 2000;35:1153–1169. http://dx.doi.org/10.1016/S0032-9592(00)00152-7

82. Zheng Z, Shetty K. Solid state production of polygalacturonase by *Lentinus edodes* using fruit processing wastes. Process Biochem. 2000;35:825–830. http://dx.doi.org/10.1016/S0032-9592(99)00143-0

83. Hesseltine CW. Microbiology of oriental fermented foods. Annu Rev Microbiol. 1983;37:575–601. http://dx.doi.org/10.1146/annurev.mi.37.100183.003043

84. De Vries RP, Visser J. *Aspergillus* enzymes involved in degradation of plant cell wall polysaccharides. Microbiol Mol Biol Rev. 2001;65:497–522. http://dx.doi.org/10.1128/MMBR.65.4.497-522.2001

85. Jin B, Van Leeuwen HJ, Patel B, Yu Q. Utilisation of starch processing wastewater for production of microbial biomass protein and fungal α-amylase by *Aspergillus oryzae*. Bioresour Technol. 1998;66:201–206. http://dx.doi.org/10.1016/S0960-8524(98)00060-1

86. García García I, Venceslada JLB, Pena PRJ, Gómez ER. Biodegradation of phenol compounds in vinasse using *Aspergillus terreus* and *Geotrichum candidum*. Water Res. 1997;31:2005–2011. http://dx.doi.org/10.1016/S0043-1354(97)00014-6

87. García García I, Jiménez PPR, Venceslada JLB, Martín Martín A, Martín Santos MA, Ramos Gómez E. Removal of phenol compounds from olive mill wastewater using *Phanerochaete chrysosporium, Aspergillus niger, Aspergillus terreus* and *Geotrichum candidum*. Process Biochem. 2000;35:751–758. http://dx.doi.org/10.1016/S0032-9592(99)00135-1

88. Hamdi M, Khadir A, Garcia JL. The use of *Aspergillus niger* for the bioconversion of olive mill waste-waters. Appl Microbiol Biot. 1991;34:828–831. http://dx.doi.org/10.1007/BF00169359

89. Vassilev N, Fenice M, Federici F, Azcon R. Olive mill waste water treatment by immobilized cells of *Aspergillus niger* and its enrichment with soluble phosphate. Process Biochem. 1997;32:617–620. http://dx.doi.org/10.1016/S0032-9592(97)00024-1

90. Rose SH, Van Zyl WH. Constitutive expression of the *Trichoderma reesei β-1,4-xylanase* gene (xyn2) and the *β-1,4-endoglucanase* gene (egl) in *Aspergillus niger* in molasses and defined glucose media. Appl Microbiol Biot. 2002;58:461–468. http://dx.doi.org/10.1007/s00253-001-0922-3

91. Rose SH, Van Zyl WH. Exploitation of *Aspergillus niger* for the heterologous production of cellulases and hemicellulases. Open Biotechnol J. 2008;2:167–175. http://dx.doi.org/10.2174/1874070700802010167

92. Bohlin C, Jönsson LJ, Roth RL, Van Zyl WH. Heterologous expression of T*rametes versicolor* laccase in *Pichia pastoris* and *Aspergillus niger*. Appl Biochem Biotech. 2006;129–132:195–214. http://dx.doi.org/10.1385/ABAB:129:1:195

93. Van Zyl PJ, Moodley V, Rose SH, Van Zyl WH. Production of the *Aspergillus aculeatus* endo-1,4-β-mannanase in *Aspergillus niger*. J Ind Microbiol Biot. 2009;36:611–617. http://dx.doi.org/10.1007/s10295-009-0551-x

94. Alriksson B, Rose SH, Van Zyl WH, Sjöde A, Nilvebrant N-O, Jönsson LJ. Cellulase production from spent lignocellulose hydrolysates with recombinant *Aspergillus niger*. Appl Environ Microb. 2009;75:2366–2374. http://dx.doi.org/10.1128/AEM.02479-08

95. Cavka AB, Alriksson B, Rose SH, Van Zyl WH, Jönsson LJ. Biorefining of wood: Combined production of ethanol and xylanase from waste fibre sludge. J Ind Microbiol Biot. 2011;38:891–899. http://dx.doi.org/10.1007/s10295-010-0856-9

96. South African Department of Energy (DoE). Renewable energy [homepage on the Internet]. c2003 [cited 2015 Apr 20]. Available from: http://www.energy.gov.za/files/renewables_frame.html

97. Abbasi T, Abbasi SA. Biomass energy and the environmental impacts associated with its production and utilization. Renew Sust Energ Rev. 2010;14:919–937. http://dx.doi.org/10.1016/j.rser.2009.11.006

98. Dodic S, Popov S, Dodic J, Rankovic J, Zavargo Z, Jevtic Mucibabic R. Bioethanol production from thick juice as intermediate of sugar beet processing. Biomass Bioenerg. 2009;33:822–827. http://dx.doi.org/10.1016/j.biombioe.2009.01.002

99. Funke T, Klein P, Meyer F. Biofuel production in South Africa. Biofuels. 2011;2:209–220. http://dx.doi.org/10.4155/bfs.11.3

100. Hang YD, Lee CY, Woodams EE, Cooley HJ. Production of alcohol from apple pomace. Appl Environ Microb. 1981;42:1128–1129.

101. Garcia-Castello E, Lora-Garcia J, Garcia-Garrido J, Rodriguez-Lopez AD. Energetic comparison for leaching waste liquid from citric juice production using both reverse osmosis and multiple-effect evaporation. Desalination. 2006;191:178–185. http://dx.doi.org/10.1016/j.desal.2005.09.012

102. Edwards M, Doran-Peterson J. Pectin-rich biomass as feedstock for fuel ethanol production. Appl Microbiol Biot. 2012;95:565–575. http://dx.doi.org/10.1007/s00253-012-4173-2

103. Widmer W, Zhou W, Grohmann K. Pretreatment effects on orange processing waste for making ethanol by simultaneous saccharification and fermentation. Bioresour Technol. 2010;101:5242–5249. http://dx.doi.org/10.1016/j.biortech.2009.12.038

104. Wilkins MR, Suryawati L, Maness NO, Chrz D. Ethanol production by *Saccharomyces cerevisiae* and *Kluyveromyces marxianus* in the presence of orange-peel oil. World J Microb Biot. 2007;23:1161–1168. http://dx.doi.org/10.1007/s11274-007-9346-2

105. Wilkins MR, Widmer WW, Grohmann K. Simultaneous saccharification and fermentation of citrus peel waste by *Saccharomyces cerevisiae* to produce ethanol. Process Biochem. 2007;42:1614–1619. http://dx.doi.org/10.1016/j.procbio.2007.09.006

106. Brown TR, Brown RC. A review of cellulosic biofuel commercial-scale projects in the United States. Biofuel Bioprod Bior. 2013;7:235–245. http://dx.doi.org/10.1002/bbb.1387

107. Balan V, Chiaramonti D, Kumar S. Review of US and EU initiatives toward development, demonstration, and commercialization of lignocellulosic biofuels. Biofuel Bioprod Bior. 2013;7:732–759. http://dx.doi.org/10.1002/bbb.1436

108. Den Haan R, Mcbride JE, La Grange DC, Lynd LR, Van Zyl WH. Functional expression of cellobiohydrolases in *Saccharomyces cerevisiae* towards one-step conversion of cellulose to ethanol. Enzyme Microb Tech. 2007;40:1291–1299. http://dx.doi.org/10.1016/j.enzmictec.2006.09.022

109. Den Haan R, Rose SH, Lynd LR, Van Zyl WH. Hydrolysis and fermentation of amorphous cellulose by recombinant *Saccharomyces cerevisiae*. Metab Eng. 2007;9:87–94. http://dx.doi.org/10.1016/j.ymben.2006.08.005

110. Den Haan R, Kroukamp H, Mert M, Bloom M, Görgens JF, Van Zyl WH. Engineering *Saccharomyces cerevisiae* for next generation ethanol production. J Chem Technol Biot. 2013;88:983–991. http://dx.doi.org/10.1002/jctb.4068

111. Van Zyl WH, Lynd LR, Den Haan R, McBride JE. Consolidated bioprocessing for bioethanol production using *Saccharomyces cerevisiae*. Adv Biochem Eng Biot. 2007;108:205–35. http://dx.doi.org/10.1007/10_2007_061

112. Van Zyl WH, Chimpangho AFA, Den Haan R, Görgens JF, Chirwa PWC. Next generation cellulosic ethanol technologies and their contribution to a sustainable Africa. Interface Focus. 2011;1:196–211. http://dx.doi.org/10.1098/rsfs.2010.0017

113. La Grange DC, Den Haan R, Van Zyl WH. Engineered cellulolytic ability into bioprocessing organisms. Appl Microbiol Biot. 2010;87:1195–1208. http://dx.doi.org/10.1007/s00253-010-2660-x

114. Ilmén M, Den Haan R, Brevnova E, McBride JE, Wiswall E, Froehlich A, et al. High level secretion of cellobiohydrolases by *Saccharomyces cerevisiae*. Biotechnol Biofuels. 2011;4:30. http://dx.doi.org/10.1186/1754-6834-4-30

115. Benjamin Y, Cheng H, Görgens JF. Evaluation of bagasse from different varieties of sugarcane by dilute acid pretreatment and enzymatic hydrolysis. Ind Crop Prod. 2013;51:7–18. http://dx.doi.org/10.1016/j.indcrop.2013.08.067

116. Diedericks D, Van Rensburg E, Görgens JF. Fractionation of sugarcane bagasse using a combined process of dilute acid and ionic liquid treatments. Appl Biochem Biotech. 2012;167:1921–1937. http://dx.doi.org/10.1007/s12010-012-9742-4

117. Diedericks D, Rensburg EV, Prado García-Aparicio M, Görgens JF. Enhancing the enzymatic digestibility of sugarcane bagasse through the application of an ionic liquid in combination with an acid catalyst. Biotechnol Progr. 2012;28:76–84. http://dx.doi.org/10.1002/btpr.711

118. Diedericks D, Van Rensburg E, Görgens JF. Enhancing sugar recovery from sugarcane bagasse by kinetic analysis of a two-step dilute acid pretreatment process. Biomass Bioenerg. 2013;57:149–160. http://dx.doi.org/10.1016/j.biombioe.2013.07.006

119. Aboyade AO, Carrier M, Meyer EL, Knoetze H, Görgens JF. Slow and pressurized co-pyrolysis of coal and agricultural residues. Energ Convers Manage. 2013;65:198–207. http://dx.doi.org/10.1016/j.enconman.2012.08.006

120. Leibbrandt NH, Aboyade AO, Knoetze JH, Görgens JF. Process efficiency of biofuel production via gasification and Fischer-Tropsch synthesis. Fuel. 2013;109:484–492. http://dx.doi.org/10.1016/j.fuel.2013.03.013

121. Amigun B, Petrie D, Görgens JF. Economic risk assessment of advanced process technologies for bioethanol production in South Africa: Monte Carlo analysis. Renew Energ. 2011;36:3178–3186. http://dx.doi.org/10.1016/j.renene.2011.03.015

122. Ambali A, Chirwa PW, Chamdimba O, Van Zyl WH. A review of sustainable development of bioenergy in Africa: An outlook for the future bioenergy industry. Sci Res Essays. 2011;6:1697–1708.

123. Van Zyl WH, Prior BA. Biofuels development in South Africa. IEA Bioenergy Task 39 Newsletter #33. 2013;April:4–10.

Spatial soil information in South Africa: Situational analysis, limitations and challenges

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Soil information is vital for a range of purposes; however, soils vary greatly over short distances, making accurate soil data difficult to obtain. Soil surveys were first carried out in the 1920s, and the first national soil map was produced in 1940. Several regional studies were done in the 1960s, with the national Land Type Survey completed in 2002. Subsequently, the transfer of soil data to digital format has allowed a wide range of interpretations, but many data are still not freely available as they are held by a number of different bodies. The need for soil data is rapidly expanding to a range of fields, including health, food security, hydrological modelling and climate change. Fortunately, advances have been made in fields such as digital soil mapping, which enables the soil surveyors to address the need. The South African Soil Science fraternity will have to adapt to the changing environment in order to comply with the growing demands for data. At a recent Soil Information Workshop, soil scientists from government, academia and industry met to concentrate efforts in meeting the current and future soil data needs. The priorities identified included: interdisciplinary collaboration; expansion of the current national soil database with advanced data acquisition, manipulation, interpretation and countrywide dissemination facilities; and policy and human capital development in newly emerging soil science and environmental fields. It is hoped that soil information can play a critical role in the establishment of a national Natural Agricultural Information System.

Introduction

Information about the distribution of the natural resources of a country is vital for a wide range of purposes, including local and regional planning, economic forecasting, food security and environmental protection. The most critical of natural resources, in terms of agricultural production, are terrain, climate and soil.

Information on terrain can easily be obtained from topo-cadastral maps, digital elevation models and other survey information. Climate information is readily accessible from sources such as the Agroclimatology Programme at the Agricultural Research Council's Institute for Soil, Climate and Water (ARC–ISCW) and the South African Weather Service. Direct assessment from near-real-time weather station data and increasing applications from modelled climate surfaces at increasing levels of detail have enabled extrapolations in time and space to be made as required. Soil information, on the other hand, is more difficult to obtain, especially at more refined levels of detail. Substantial financial investment is often necessary to obtain soil data because soils and their properties, and consequently their potential and limitations, change very substantially over short distances, and the skills and expertise necessary to accurately record, measure and map such changes are time and labour extensive.

The situation is likely to become more critical in the foreseeable future, with the continually increasing population of South Africa requiring more food, fibre and energy to be produced, against the background of potentially changing climate patterns across the country and the wider southern African region.

Accurate soil information forms an essential component of environmental baseline characterisation for any country. In this review, we provide an historical background leading to the current state of soil information in South Africa, highlight the soil information requirements of the country and outline a way forward in terms of data capture, storage and interpretation using recent technological advances.

Historical perspective

The first actions concerned with obtaining spatial soil information in South Africa were carried out by the Department of Agriculture, through the then Division of Chemistry, in the 1920s, although the first recorded soil investigation was undertaken as early as 1899.[1] Subsequently, a series of soil surveys was carried out, including areas along rivers where large dams were constructed, mainly to allow cultivation under irrigation in some of the drier parts of the South African interior. As a consequence, the information contained on these early maps is mainly concerned with a very superficial description of the soils, coupled with an irrigation suitability class, sometimes refined with a qualification such as presence of gravel or 'brak' (salts) within the soil profile. Although these surveys were usually extremely detailed in scale (often at 1:5000 to 1:7500), and were often confined to narrow strips on either side of the rivers concerned, they retain some present-day value.

The first steps in the recording of information about soils in South Africa on a wider scale were taken in the late 1930s, culminating in the publication *Soils of South Africa* by CR van der Merwe[2], who attempted to gather all existing knowledge, both first-hand and assumed, so that a national soil pattern map, at a very small scale (approximately 1:2 500 000) was produced.

With this first attempt as a starting point, the expansion and increasing mechanisation and modernisation of agriculture in South Africa during the 1950s began to recognise the need for increasing knowledge about the soils across the more productive zones of the country. The expanding sugar industry in the then Natal Province commissioned soil surveys[3] to characterise and map the distribution of soils along the southeastern seaboard, mainly in terms of their suitability for cultivation with sugarcane. Beater's[3] soil descriptions embraced the concept of 'natural soil bodies'. Shortly thereafter, a second large survey[4] was carried out in Natal, namely the *Soils of*

the Tugela Basin, in which a wider range of soils, occurring on various parent materials, was studied. The Tugela Basin study deviated from the concepts of soil series as a natural soil body by providing the first concepts of locally based soil classes that were accommodated within a formal hierarchical soil classification system. These classes would eventually become the soil series and forms of the first edition of the South African soil classification system.[5]

At the same time, a wide range of other surveys, mainly for irrigation suitability, but also including a range of selected 1:50 000 map sheets, had been carried out by the Soil and Irrigation Research Institute, further improving and expanding the soil knowledge base of South Africa. The state of spatial soil knowledge, the various scales of surveys and the possibilities and limitations thereof, were summarised for the Silver Jubilee Congress of the Soil Science Society of South Africa in 1978.[6] In addition, a range of studies in different geographical areas was carried out to help quantify the soils occurring, and by implication, naturally occurring soil bodies. These studies included the previous Transvaal[7], Free State[8] and Karoo[9] Agricultural Regions, as well as an extensive series of surveys of the former homeland areas carried out by private consultants, such as Loxton, Venn and Associates.

However, despite the increasing body of knowledge, mainly of soils occurring, there was still limited information concerning the soil properties and their distribution within many areas of South Africa. Certain regions of the country, as well as certain soil types, still remained only vaguely surveyed, so a decision was taken to initiate a countrywide soil survey that would remedy this situation.

Land Type Survey

In the early 1970s, the national Land Type Survey[10] commenced in South Africa. This huge undertaking was based on a field survey, using 1:50 000 topo-cadastral sheets as base maps, but with the aim of publishing the finished maps at 1:250 000 scale. A *land type* mapping unit, the basis of the survey, was defined as 'a homogeneous, unique combination of terrain type, soil pattern and macroclimate zone' and when the survey was completed around 30 years after its commencement, about 7070 such zones, based on some 400 000 soil observations (equivalent to approximately 1 observation per 300 ha) had been defined. The greatest advantage of the Land Type Survey was the fact that every part of the country, from the highly productive Highveld to the driest parts of the Northern Cape and the mountains of the Drakensberg, had been visited. Furthermore, a supporting database of around 2500 modal soil profiles, as well as a further 10 000 series identification samples (designed to confirm field soil diagnosis) had been created, providing quantitative data about a range of soil properties across the greater part of South Africa. As the field investigation phase of the Land Type Survey progressed, it also led to further advancements in soil classification, culminating in the publication of the second edition of the South African soil classification system.[11] The products of the Land Type Survey were initially a series of 1:250 000 scale overlay maps, printed by the Government Printer using the standard topo-cadastral map sheet framework. Each map sheet, or combination of one or more adjoining map sheets, was accompanied by a printed memoir book, which provided information on all the land types, climate zones and modal soil profiles occurring on that map (or maps).

As the Land Type Survey progressed, the information that was provided enabled several of the agricultural regions to establish systems to help with their environmental inventory and to contribute to improving agricultural production. These regions included the Highveld Region[12] and Natal Region[13].

The soil information system into the digital age

With the advent of digital computing in the early 1990s, soil maps could be digitised and the accompanying legend, text and analytical information stored digitally. Interpretation technology has advanced so that the manual processes of map interpretation have been replaced with the development of geographic information systems technology. This advancement has led to the establishment of the Soil Information System housed at ARC–ISCW. Land type field sheets were digitised and edge matched to produce a continuous coverage for South Africa. Land Type soil inventories have been fully captured in electronic formats, together with an extensive complement of soil profile descriptions and soil analyses. Additional soil map information from a variety of detailed surveys has either been digitised or image-scanned for electronic archiving. Elementary search applications for metadata have been established and a prototype data capture and soil data transfer application developed.

A limited number of soil information interpretation routines were added to the Soil Information System. Examples include:

- The soil profile information collected during the Land Type Survey has been supplemented by other descriptive and analytical data from a variety of sources[14], including soil profile analyses collected during irrigation assessment surveys, a range of ad-hoc soil investigations and two major projects commissioned by the Department of Agriculture[15,16] designed to improve the geographical distribution of soil profile data in South Africa.
- Two regional soil mapping projects at 1:50 000 scale have also been converted to electronic format, namely the Pretoria-Witwatersrand-Vereeniging peri-urban survey[17] and the Western Cape Metropolitan survey[18].
- A range of paper soil maps produced since the early years of the 20th century has been scanned and geo-referenced (but not digitised), in an effort to preserve and make available the information for future generations.
- A database of over 1500 profiles from rehabilitated soils on open-cast coal mines was established as part of a project[19] to study the effects of mining on the valuable agricultural soil resources of the Highveld.

From the 1960s until the late 1990s, the major focus was towards recording and mapping the distribution of soils and their functions. Soil profile descriptions and analyses were collected, representing point information of soil properties at site-specific locations. However, while classification classes provide generalised information on soil properties, concepts of soil property information are generally lacking. Beater[20] used the soil series concept to focus on soil property information. Generalised soil property information was developed for selected sandy soils of the North West Province[21], for textural soil properties of KwaZulu-Natal and Mpumalanga[14], and generally for the KwaZulu-Natal Coastal Belt. Future research should focus on developing innovative soil property information to complement traditional soil survey information that will become essential for future information system applications.

Applications include assessing the land capability of South Africa[22], as well as mapping chemical properties of South African soils, such as organic carbon[23], pH and heavy metals[24]. Recently, various land suitability assessments[25,26] have added to soil interpretation options. The KwaZulu-Natal Department of Agriculture and Environment has developed the BioResources Information System[13] for that province that has a strong fundamental basis in terrain, soil and climate natural resources. Other soil information systems that are operated within the forestry industry, by agricultural cooperatives and private companies, are reported to contain large volumes of soil information. These information systems do not lie in the public domain, so this information is not readily available to the general public. Mechanisms to overcome intellectual property rights so that this information can be accessed could be of mutual benefit to future land users.

There is now much scope for additional map and soil analysis capture operations. In a digital soil information age, a vast array of applications incorporating and developing soil information, together with complementary natural resource information, can be envisaged. In this paper, we set the scene for these developments in examining opportunities and suggesting frameworks where these may now become real possibilities.

The current state of soil knowledge

At a Soil Information Workshop held at Stellenbosch in February 2014, in which the participants included researchers, academics, government officials, private consultants and industry representatives, the

participants produced a resolution calling for improved availability of soil data and better interaction between role players, data users and decision-makers. The call was made for a national task force on soils information, representing the interests of various government departments, industry, the research community and land users/managers to convene regularly to develop new strategies and policy for soil information collection, storage and dissemination:

- to identify current and future soil information requirements at all spheres of government, within industry, the research community and land users and managers,
- to identify soil information gaps and opportunities for further research and collaboration,
- to prioritise activities on soil data and information depending on user needs, and
- to determine impact pathways for realising the required resources.

We further discuss the current situation with regard to these resolution points in the remainder of this paper.

Soil information requirements

There is a well-known saying, 'Knowledge is power'. While the benefits of increased knowledge may not be related to physical or political power, the increased spread and detail of soil information will have substantial benefits over a wide range of disciplines and development opportunities. In the area of future planning for agricultural production and food security in South Africa, one of the larger challenges is the threat of changing climate patterns, which may lead to altered levels of agricultural suitability under natural climate conditions. If various possible scenarios are considered and compared, the spatial distribution of soil types within any area, which can be coupled to crop production and eventually to yield, will help to quantify these possible scenarios, so that informed decisions can be taken.

Virtually every organ of state, as well as parastatal bodies, will benefit from soil information. For example, the Integrated Energy Policy that the Department of Energy is formulating has an agricultural sub-committee tasked with estimating present and future energy demand within the agricultural sector. Accurate, detailed soil information will enable a much better assessment of where soils that are able to be cultivated are located. From there, the approximate number of tractors and other implements, along with the fuel necessary to power them, can be determined.

The area of health is also related to soils. New and existing diseases related to human or livestock health are encountered, and the study of their distribution involves a range of potential factors, one of which may be soil type, usually as a potential host to organisms. Planning of virtually all types of infrastructure will benefit from soil information, whether it refers to high potential soils that should preferably not be disturbed, or swelling vertic clays that will pose a serious building hazard. The amount of knowledge, as well as the level of detail, about soils occurring, will make a difference to almost all decisions that are taken.

In light of the ever-increasing pressures on the high potential soils in South Africa, the Department of Agriculture, Forestry and Fisheries, with assistance from ARC, has prepared a draft policy for the *Protection and Development of Agricultural Land Framework Act* (PDALFA). For it to have maximum relevance, the Bill, when enacted into legislation, will require high levels of detail of soil information across large portions of South Africa. These levels of soil information are currently lacking and must be developed through existing detailed and semi-detailed information sources, and through future soil modelling technology and advanced new data capture operations. Digital soil evaluation technology offers considerable potential in this regard.

The national and international demand for data on soil organic carbon (SOC) distribution, existing stocks and potential changes is rapidly increasing as a result of the crucial role of SOC in soil fertility, food security, nutrient and water retention, biodiversity and ecosystem services. In addition, soil represents the largest store of terrestrial organic carbon, indicating that SOC could also contribute to climate change mitigation.[27] To improve decision-making towards improved soil management and a reduction in soil degradation, sufficiently detailed quantitative data sets and methodologies that enable spatial and temporal quantification of SOC levels and dynamics in soils, are required. Knowledge of the effect of changes in land use on SOC is vital to maintain the critical balance in carbon stocks.

Several global and regional initiatives are now aimed at increasing the level of soil carbon data and information available to support the harmonisation of methods, measurements and indicators for sustainable soil carbon management. At global level, these include the Global Soil Partnership, established under the custodianship of the Food and Agriculture Organization of the United Nations and the Global Soil Map.[28] At regional level, the Africa Soil Information Service (AfSIS) aims to develop continent-wide digital soil maps for sub-Saharan Africa using new types of soil analyses and statistical methods.[29] In addition, South Africa is a signatory to both the United Nations Convention to Combat Desertification[30] and the United Nations Framework Convention on Climate Change[31], under which we are obliged to report on various indicators, including changes in soil carbon. Updated national level SOC maps must therefore urgently be developed and regularly updated to contribute to existing soil carbon mapping initiatives, as well as to comply with international reporting obligations.

Soil information is important in hydrological modelling because soils act as a first-order control on the partitioning of hydrological flow paths, residence time distributions and water storage.[32,33] Soils play a major role in catchment hydrology by facilitating infiltration, controlling overland flow, redistributing water through the root zone, storing water for evapotranspiration and recharging groundwater aquifers.[34] Water is a primary agent in soil genesis, resulting in the development of soil properties containing unique signatures of the way they were formed. Interpretation of soil properties can therefore serve as an indicator of the dominant hydrological processes[35,36] and assist in the structuring and configuration of hydrological models.[37]

Hydrologists agree that soil properties and their spatial variation should be captured in hydrological models for accurate water quantity and quality predictions and estimation of the hydrologic sensitivity of the land to change[38,39], but they generally lack the skill to gather and interpret soil information[40,41]. New generation soil information could alter this perception. Soil inputs in hydrological models vary greatly between different models, but typically include water retention characteristics, hydraulic conductivities, storage ability (depth and porosity) and infiltration rates. In distributed models, the spatial distribution of these parameters is essential to ensure the efficiency of hydrological simulations. The soil hydrological parameters are often indirectly determined using pedotransfer functions. These functions exploit mathematical relations between easily measured properties, e.g. texture, and properties that are tedious and expensive to measure, e.g. water retention curves.

Soil information gaps

South African soil science has been well served through the first and second editions of the South African classification system.[5,11] The state of available soil knowledge has been excellently summarised in a recent publication[42] which combines information from the Land Type Survey with other existing knowledge to look at the distribution and properties of the major soil groups in South Africa. Discussions towards a revision of the classification system[43] including potential adaptation to the nature of diagnostic soil horizons and the structure and content of the classification system[44,45] are proceeding. The discipline now has the important advantage of access to numerous known soil profile locations, profile descriptions and analyses that, together with tacit knowledge, will certainly aid in the formulation of hypotheses.

However, despite the large volume of available knowledge on the soils occurring within South Africa, there is almost as much untapped information from commercial and semi-commercial sources that is not freely available. Information from academic sources, although in the

public domain, has generally not been incorporated into comprehensive soil information systems. These sources include:

- Agricultural support organisations, such as cooperatives, fertiliser and seed companies for which thousands of hectares of detailed soil surveys have been carried out for (mainly) commercial farmers. Much of this information has been interpreted for general or crop-specific suitability, including yield determinations.
- Commercial forestry companies, which have likewise carried out extensive soil surveys in specific areas, mainly to establish suitability for establishing forestry plantations.
- Mining companies that extract mainly coal, platinum and other heavy metals, for which the legal requirements for any potential mining activity include an environmental impact assessment, which must include a soil survey.
- Various governmental departments, both at national and provincial level. This data source applies mainly to soil surveys carried out in the pre-digital age. The storage and preservation of this information was not always effectively done, and was further adversely affected by the major changes within many government departments during the 1990s.
- Academic institutions such as universities and colleges, which could have produced spatial soil data, either in map or profile form. The same problems exist here as for some of the governmental departments. For example, we are aware of instances in which, through ignorance, valuable soil maps have been mislaid or destroyed to the detriment of the soil science discipline.
- Many and varied soil investigations have been carried out for a variety of purposes, including for agricultural potential determinations prior to construction of transport, power, residential or supply infrastructure. These maps are generally not kept in a central archive and are very difficult to trace.

The amount of soil information listed above is vast. For example, from the Land Cover database[46] it has been estimated that an area of approximately 6.62 million ha is under some form of cultivation in the three largest maize producing provinces of South Africa – the Free State, North West and Mpumalanga. This cultivation covers 5.4% of the land area of the country. If one takes a conservative estimate that half of this area might have some sort of detailed soil survey information available, that still equates to over 3 million ha. In addition, there is an estimated 1.96 million ha (1.6% of the land area) of commercial forestry plantations in South Africa[46] and it is reasonable to assume that at least 80% or more of this area will have been surveyed at some point by the forestry companies concerned.

Regarding the coal mining industry, it is a well-known, if unfortunate, fact that a large portion of the coal resources of South Africa lie under extremely productive agricultural soils on the Mpumalanga Highveld. Figures concerning the areas that have been, or are planned to be, affected by coal extraction are difficult to obtain, but a map provided by the Mpumalanga Provincial Department of Agriculture, Rural Development and Land Administration shows the widespread distribution of farms for which mining rights exist, and it is comfortably more than 75% of the arable portion of the province.

Reasons for the unavailability of soil data are varied. Mostly they concern the commercial nature of the data, the fact that it has been paid for by the landowner concerned, as well as a perceived fear that state authorities will misuse any such data to expropriate commercial farmland. While the right of private individuals to protect information needs to be understood and respected, the fact remains that any reasonably competent soil scientist will be able to use the existing available land type data, along with freely available ancillary remote sensing background information such as satellite imagery and even Google Earth. From these sources, a very plausible assessment of the areas cultivated on any particular farm can be made, and a very good indication can be derived of the soils occurring, and consequently, of the general potential of the farm.

ARC–ISCW embarked on a project to collect existing soil maps from provinces known to have soil maps and information. It is expected that much (although not all) of the provincial soil information has been archived. Certain private institutions and persons were also willing to provide soil information that has also been archived. However, soil information in numerous university theses and reports, while in the public domain, remains isolated from a central information system. The solution probably lies in the creation of efficient technology applications to directly capture and evaluate the quality of these essentially new data sources and here, cell phone and GPRS (general packet radio service) technology could prove effective. The Natural Resources Council of the UK has recently launched the *mySoil* smartphone application which allows users to download soil maps of the UK as well as upload photographs and basic soil descriptions at their location. In doing so, a database of basic soil information is being created across the UK and parts of Europe.[47]

Soil survey information held by agricultural cooperatives, private soil consultants, forestry companies and mines is subject to limitations on intellectual property rights. Innovative ways to archive these data such that they are accessible to both the private and public sectors must be established. Lastly, efficient web-based platforms to capture new soil information from public and private sources, and a culture to contribute to a recognised natural resources information system, must be strongly encouraged.

Advanced technologies for data collection and interpretation

Digital soil mapping

The explosion of new advances in the fields of information technology, satellite imagery, digital elevation models and geostatistics has enabled the establishment of various new soil survey techniques, which today is collectively known as digital soil mapping (DSM). The concept of DSM emerged in the 1970s and accelerated in the 1980s. Today, research on different DSM technologies is converging and reaching a stage at which operational systems are being implemented.[28] The industrious Global Digital Soil Map[28] project best showcases the theoretical potential of DSM. The aim of this project is to use both legacy and specifically collected soil data to create a soil map of the world's soil properties to a depth of 1 m and at a resolution of 90 m.[48] Digital soil mapping produces predictions of soil classes or continuous soil properties in a raster format at various resolutions.[49]

The foundation on which DSM rests is that soils are not distributed randomly in the landscape, but are rather the product of the environment in which they are formed.[50] If one could therefore decipher the soil–environment relationship, one could begin to predict the soil distribution from the environmental factors, which may be easier to measure than soil itself. Equation 1 shows this relationship mathematically:

$$S = f(E), \qquad \text{Equation 1}$$

where S is the soil class or property to be mapped, f is the relationship between S and E and E is the environmental factors used to map S.

McBratney et al.[51] formalised Equation 1 in the Scorpan approach as:

$$S = f\,(s, c, o, r, p, a, n), \qquad \text{Equation 2}$$

where S is the soil class or property to be mapped, s is the soil, or other properties of soil at a point, c is the climate or climatic properties at a point, o is the organisms, such as vegetation, fauna or human activity at a point, r is the relief, topography and landscape attributes, p is the parent material, a is the age, the time factor, and n is the spatial variability.

To create a digital soil map, one requires sufficient soil (point data, soil map, land type inventory) and environmental (digital elevation models, satellite images, geological map) information to decipher the soil–environment relationship.

Theoretically, with the current amount of data (soil and environmental) already in the public domain, we can potentially create very good baseline

soil maps for the entire country. ISRIC created soil class and property maps for sub-Saharan Africa at a 1-km resolution using around 12 000 observation points.[52] However, the accuracy achieved was low, between 18% and 45% for different soil properties. Using all the already available data, we should be able to improve on this map for South Africa. New data (both newly acquired legacy data and newly collected data) added to the database are necessary to periodically update and improve the baseline soil maps. The spatial estimation of error which is associated with DSM-produced maps will easily identify areas where focused projects can be launched to improve specific areas of the maps. A local DSM challenge which soil scientists in South Africa face is the often unreliable soil–landscape relationships as a result of the added complexity of ancient landscapes. Overcoming this challenge calls for the development of site-specific DSM methods which can be used with a degree of confidence.

Unfortunately, DSM in South Africa is still in the developmental stage, with few researchers and little or no commercial work being done in the field. At ARC-ISCW, two studies[53,54] have used remote sensing and the land type soil profile database to produce soil maps for areas of KwaZulu-Natal. Van Zijl et al.[55] disaggregated two land type inventories into soil association maps, also in KwaZulu-Natal. In the Free State, Zerizghy et al.[56] used expert knowledge-based DSM techniques to delineate land suitable for rainwater harvesting. Van Zijl and Le Roux[57] also used an expert knowledge approach to create a hydrological soil map in the Kruger National Park. Both Stalz[58] and Mashimbye et al.[59] mapped salt-affected soils using remote sensing. Van Zijl[60] developed a digital soil mapping protocol for large areas (1000 – 50 000 ha) with no soils data. For the soil survey fraternity in South Africa to fulfill the growing need for spatial soil data, there must be a thrust to create the human capacity with regard to DSM. This thrust may potentially be realised through projects to implement the PDALFA concepts and legislative demands.

Spectroscopic soil analysis

Traditional soil analysis is a costly and time-consuming exercise, which often limits the density of observations made as well as the number of properties that can be measured for a specific site. Near-infrared (NIR) and mid-infrared (MIR) spectroscopy is gaining popularity as a tool for soil analysis because of the ease and speed with which data can be collected both in the field and in the laboratory.[61] A recent review[62] has shown that NIR analysis can be reliably used to measure a number of soil properties, especially soil organic matter, mineralogy, texture and water content. Cation exchange capacity, nutrient content, soil colour and pH have also been measured using NIR analysis.[63-65] In Australia, NIR spectroscopy has been used to discriminate among soils of different classification orders.[66]

In South Africa, NIR spectroscopy has been used for many years in the sugarcane industry to measure soil characteristics such as texture, SOM and nitrogen[67] and to supply the data-hungry requirements of precision agriculture.[68] The Soil Fertility and Analytical Services laboratories of the KwaZulu-Natal Department of Agriculture and Environmental Affairs have set up confident MIR calibrations for organic carbon, total nitrogen and clay content, while calibrations for extractable acidity, acid saturation, pH and extractable calcium and magnesium are used for quality-control purposes.[69] Despite these localised uses, research into infrared techniques in South Africa is lagging far behind the international surge in soil spectroscopic research. Recently, handheld and portable NIR spectrometers have come onto the market and allow in-situ soil measurements. The ability to conduct in-field analyses significantly increases the spatial resolution of soil information that can be captured. With the increasing need for soil information, particularly soil carbon data, NIR spectroscopy may provide a cost-effective tool for obtaining soil information. Collaborative research efforts are required to build up soil spectral libraries for South African soils. The sample collection with associated laboratory analyses at ARC–ISCW may serve as the ideal starting point to standardise NIR measurements against traditional chemical analyses.

Natural resource information system

Using the national Land Type Survey and Agroclimatology databases as a starting point, ARC–ISCW offers a unique information source, which can supply data to increase the knowledge base on natural resources in South Africa. Such a database is a critical step towards assessing, and therefore protecting, our natural resources. However, with much information not available because of the reasons given previously, there will always be the potential to improve this information system by incorporating other data (even if some restrictions might be placed on its use in certain situations) to make the system as comprehensive as possible.

There are three groups of potential soil data which could be used to help with the establishment of a national soil database.

The first group is the already available data collected with public money. The bulk of these data lie with the ISCW and form an excellent basis for a national database. Other sources of this first group of data are the National and Provincial Departments of Agriculture and universities. Most of the soil data which these entities possess was collected with public money and an additional effort should be made to gather this information into the national database.

The second group of soil data which can be included into the database is the data held by private entities. These entities include agricultural cooperatives, soil consultancies, mines and forestry companies which have done soil surveys. It is trickier to include these data into the national database, as there are client confidentiality clauses and intellectual rights which currently prohibit the sharing of most of the data. Methods should be explored to gain access to such data which benefits all parties involved.

Lastly, there is data which are still to be collected. Private and public entities within the soil science field should be asked to contribute to the national soil database. All data collected for public entities and as much data as possible, within legal limits, collected for private entities, should be included. Innovative means, such as the soil application ('app') mentioned previously, should be used when possible. During an informal survey conducted at the recent Soil Information Workshop, all the respondents said they would use such an app if it was available. Other means of collecting data could include an online platform onto which data could be submitted and some form of incentive for data added, such as acknowledgement in a manner similar to the way that scientific articles are acknowledged.

Regarding the data recorded, a set of minimum criteria (including at least a soil classification, a location and some sort of analytical data) would need to be established, and different levels of data, depending on completeness and comprehensiveness, could be defined, so that users could obtain information about data confidence.

Impact pathways

Soil scientists will need to take the following actions to fulfill the growing need for soils data:

- Make an effort to regularly interact with other disciplines from a vast array of fields, to be able to assess the need for soils data in these fields.
- Create pathways which allow free sharing of soils data and the creation of a national soils database.
- Develop human capital in emerging soil fields such as digital soil mapping and spectroscopic soil analysis, so that soils data can effectively be turned into functional spatial soil information which fulfills the emerging soil data needs.

Conclusions

The considerable investment and existing development of the ARC–ISCW Soil and AgroClimate Information Systems provides the obvious framework for the operation of nationwide natural resource systems. These systems must become readily accessible to the South

African public and be recognised by government and the private sector as the authoritative information hub. The challenges faced in creating a new generation 'Natural Agricultural Resources Information System' are numerous and emerge from the full spectrum of disciplines in society. The challenges begin with the need for recognition of the future central role to be played by the Natural Agricultural Resources Information System towards food security, environmental sustainability and ultimately the nation's social well-being. At the technological level, the challenges begin with recognition, branding and association of the information system to an institution of scientific integrity held responsible for its creation and maintenance. The ARC–ISCW is the obvious choice as the institution to house this repository, because of its distinguished record of scientific work over more than a century of its existence.

Other technological challenges remain, mainly in further developing data capture, dissemination and model interpretation methodologies. These must be addressed through the acquisition and training of skilled scientific human capacity that is now urgently necessary to sustain the new generation of natural agricultural resource information demands. A positive approach must be devised towards structuring legal solutions to the challenging issues of intellectual property that will arise from collectively merging information residing in the public and private domains.

These issues, coupled to a substantial paradigm shift in funding models, could see the reality of a publically accepted and advanced functioning national Natural Agricultural Resource Information System for South Africa. The question remains: will there be sufficient moral fibre shown by scientists, decision-makers in the public and private sectors and politicians to structure new and innovative advances to meet these challenges for the benefit of the public at large? We believe that, with a concerted effort, the research visions described in this paper are desirable and attainable.

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Authors' contributions

G.P. produced the concept article and collated all contributions; D.T. made contributions regarding soil information systems; L.W. made contributions regarding soil carbon; G.v.Z. made contributions regarding spectroscopic soil analysis; C.C. made contributions regarding soil information; and J.v.T. made contributions regarding digital soil mapping.

References

1. De Villiers MC. Centenary report of the ARC-Institute for Soil, Climate and Water (1902-2002). Pretoria: ARC-Institute for Soil, Climate and Water; 2002.
2. Van der Merwe CR. Soil groups and sub-groups of South Africa. Science Bulletin 231. Pretoria: Department of Agriculture and Forestry; 1940.
3. Beater BE. Soils of the Sugar Belt, Part 1: Natal North Coast. Cape Town: Oxford University Press; 1957.
4. Van der Eyk JJ, MacVicar CN, De Villiers JM. Soils of the Tugela Basin. A study in subtropical Africa. Volume 15. Pietermaritzburg: Natal Town and Planning Regional Commission; 1969.
5. MacVicar CN, De Villiers JM, Loxton RF, Verster E, Lambrechts JJN, Merryweather FR, et al. Soil classification – A binomial system for South Africa. Pretoria: Department of Agricultural Technical Services; 1977.
6. Loxton RF, Thompson JG. Advances in soil science in Southern Africa 1953–1978: Soil survey and land use. In: Proceedings of the 8th Congress of SSSSA; 1978 July 11–14; Pietermaritzburg, South Africa. Technical Communication 165. Pretoria: Department of Agricultural Technical Services; 1980.
7. Verster E. Die gronde van die Transvaalstreek [The soils of the Transvaal region] [PhD thesis]. Bloemfontein: University of the Orange Free State; 1974. Afrikaans.
8. Eloff JF. Die grondhulpbronne van die Vrystaatstreek [The soil resources of the Free State region] [PhD thesis]. Stellenbosch: Stellenbosch University; 1984. Afrikaans.
9. Ellis F. Die gronde van die Karoo [The soils of the Karoo] [PhD thesis]. Stellenbosch: Stellenbosch University; 1984. Afrikaans.
10. Land Type Survey staff. 1:250 000 scale Land Type Survey of South Africa. Pretoria: ARC Institute for Soil, Climate and Water; 1972–2002.
11. Soil Classification Working Group. Soil classification – A taxonomic system for South Africa. Memoirs on the South African Natural Resources No. 15. Pretoria: ARC Institute for Soil, Climate and Water; 1991.
12. Ludick BP, Joubert J. An evaluation of the agricultural potential of the magisterial districts in the Highveld Region in terms of dryland cropping and livestock production. Technical Communication No. 203. Pretoria: Department of Agriculture and Water Supply; 1986.
13. Camp KGT. The bioresource units of KwaZulu-Natal. Cedara Report N/A/95/32. Pietermaritzburg: KZN Department of Agriculture; 1995.
14. Turner DP. Soils of KwaZulu-Natal and Mpumalanga [PhD thesis]. Pretoria: University of Pretoria; 2000.
15. Jacobs EO, Schoeman JL, Potgieter LJC, Nell JP, Oosthuizen AB, Smith HJC, et al. An agricultural resource fixed site monitoring system for South Africa: Soils (DAFF Project No: 21.1.1/07LUSM-10/ISCW). ARC-ISCW Report No. GW/A/2010/01. Pretoria: ARC Institute for Soil, Climate and Water; 2010.
16. Paterson DG, Jacobs EO, Van der Walt M. Soil point data collection project (report for DAFF). ARC-ISCW Report No. GW/A/2012/18. Pretoria: ARC Institute for Soil, Climate and Water; 2012.
17. Yager TU, Kaempffer LC, Coetzee CJ. 1:50 000 scale PWV peri-urban soil map. Pretoria: ARC Institute for Soil, Climate and Water; 1990.
18. Jacobs EO, Oosthuizen AB, Stehr BI. Soils of the Cape Metropolitan area. ARC-ISCW Report No. GW/A/99/83. Pretoria: ARC Institute for Soil, Climate and Water; 1999.
19. Nell JP, Steenekamp PI. Final report: Establishing a soil profile database for rehabilitated opencast coal mined land. ARC-ISCW Report No. GW/A/98/78. Pretoria: ARC Institute for Soil, Climate and Water; 1998.
20. Beater BE. Soil series of the Natal Sugar Belt. Durban: South African Sugar Association; 1970.
21. Schoeman JL. Natural soil bodies of the Lichtenburg, Bothaville, Viljoenskroon and Wesselsbron areas and estimates of their water-holding characteristics as derived from land type data. Technical Communication No. 129. Pretoria: Department of Agriculture and Water Supply; 1989.
22. Schoeman JL, Van der Walt M, Monnik KA, Thackrah A, Malherbe J, Le Roux RE. Development and application of a land capability classification system for South Africa. ARC-ISCW Report GW/A/2000/57. Pretoria: ARC Institute for Soil, Climate and Water; 2002.
23. Stronkhorst LD, Venter A. Investigating the soil organic carbon status in South African soils and the relationship between soil organic carbon and other soil chemical properties. ARC-ISCW Report No. GW/A/2008/24. Pretoria: ARC Institute for Soil, Climate and Water; 2008.
24. Herselman JE, Steyn CE. Predicted concentration of trace elements in South African soils. ARC-ISCW Report No. GW/A/2001/14. Pretoria: ARC Institute for Soil, Climate and Water; 2001.
25. Schoeman JL, Carstens JP, Van der Walt M. DRDLR-ARC Horticultural project: Establishment of fruit and vegetable enterprises and development of mini- and macro-agriparks in different provinces of South Africa. ARC-ISCW Report GW/A/2013/17. Pretoria: ARC Institute for Soil, Climate and Water; 2013.
26. Turner DP, Chirima JG, Paterson DG, Carstens JP, Seabi FT, Mushia N, et al. Integrated food and nutrition security initiative: Mapping of crop producing areas in the Eastern Cape Province. ARC-ISCW Report No: GW/A/2014/23. Pretoria: ARC Institute for Soil, Climate and Water; 2014.
27. Stockman U. Managing the soil-plant system to mitigate atmospheric CO2. Discussion paper for the Soil Carbon Sequestration Summit; 2011 January 31 – February 02; Sydney, Australia.
28. Sanchez PA, Ahamed S, Carré F, Hartemink AE, Hempel J, Huising J, et al. Digital soil map of the world. Science, 2009;325:680–681. http://dx.doi.org/10.1126/science.1175084
29. Africa Soil Information Service [homepage on the Internet]. c2013 [cited 2014 May 09]. Available from: http://africasoils.net
30. PRAIS. Reporting guidelines for strategic indicators (SOs 1, 2 and 3) and performance indicators. Version 1. UNCCD Reporting and review process 2012–2013. Rome: FAO; 2012.

31. UNFCC. Updated UNFCCC reporting guidelines on annual inventories following incorporation of the provisions of decision 14/CP.11. Note by the secretariat, FCCC/SBSTA/2006/9. Rome: FAO; 2006.

32. Park SJ, McSweeney K, Lowery B. Identification of the spatial distribution of soils using a process-based terrain characterization. Geoderma. 2001;103:249–272. http://dx.doi.org/10.1016/S0016-7061(01)00042-8

33. Soulsby C, Tetzlaff D. Towards simple approaches for mean residence time estimation in ungauged basins using tracers and soil distributions. J Hydrol. 2008;363:60–74. http://dx.doi.org/10.1016/j.jhydrol.2008.10.001

34. Schulze RE. Hydrology and agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modelling system. WRC Report No 63/2/84. Pretoria: Water Research Commission; 1995.

35. Ticehurst JL, Cresswell HP, McKenzie NJ, Clover MR. Interpreting soil and topographic properties to conceptualize hillslope hydrology. Geoderma. 2007;137:279–292. http://dx.doi.org/10.1016/j.geoderma.2006.06.016

36. Van Tol JJ, Le Roux PAL, Hensley M, Lorentz SA. Soil as indicator of hillslope hydrological behaviour in the Weatherley Catchment, Eastern Cape, South Africa. Water SA. 2010;36:513–520. http://dx.doi.org/10.4314/wsa.v36i5.61985

37. Van Tol JJ, Le Roux PAL, Lorentz SA, Hensley M. Hydropedological classification of South African hillslopes. Vadose Zone J. 2013;12(4), 10 pages. http://dx.doi.org/10.2136/vzj2013.01.0007

38. Lorentz SA, Bursey K, Idowu O, Pretorius C Ngeleka K. Definition and upscaling of key hydrological processes for application in models. WRC Report No. K5/1320. Pretoria: Water Research Commission; 2007.

39. Wenninger J, Uhlenbrook S, Lorentz SA, Leibundgut C. Identification of runoff generation processes using combined hydrometric, tracer and geophysical methods in a headwater catchment in South Africa. Hydrol Sci J. 2008;53:65–80. http://dx.doi.org/10.1623/hysj.53.1.65

40. Lilly A, Boorman DB, Hollis JM. The development of a hydrological classification of UK soils and the inherent scale changes. Nutr Cycl Agroecosyt. 1998;50:299–302. http://dx.doi.org/10.1023/A:1009765000837

41. Chirico GB, Medina H, Romano N. Uncertainty in predicting soil hydraulic properties at the hillslope scale with indirect methods. J Hydrol. 2007;334:405–422. http://dx.doi.org/10.1016/j.jhydrol.2006.10.024

42. Fey MV. Soils of South Africa. Cape Town: Cambridge University Press; 2010.

43. Soil Classification Working Group. Collected documentation towards a revised third edition of the South African soil classification system. ARC-ISCW Report No. GW/A/2013/19. Pretoria: ARC Institute for Soil, Climate and Water; 2013.

44. Turner DP. A revised perspective on the principles of soil classification in South Africa. S Afr J Plant Soil. 2013;30:119–120. http://dx.doi.org/10.1080/02571862.2013.804602

45. Turner DP. Perspectives on the principles and structure of the soil classification in South Africa: Discussion and practical examples. S Afr J Plant Soil. 2013;30:61–68. http://dx.doi.org/10.1080/02571862.2013.789130

46. Schoeman F, Newby TS, Thompson MW, Van den Berg EC. South African national land cover change map. ARC-ISCW Report No. GW/A/2010/47. Pretoria: ARC Institute for Soil, Climate and Water; 2010.

47. Shelley W, Lawley R, Robinson DA. Technology: Crowd-sourced soil data for Europe. Nature. 2013;496:300–310. http://dx.doi.org/10.1038/496300d

48. Minasny B, McBratney AB. Methodologies for global soil mapping. In: Boettinger JL, Howell DW, Moore AC, Hartemink AE, Kienast-Brown S, editors. Digital soil mapping: Bridging research, environmental application and operation. Dordrecht: Springer; 2010. p. 429–436. http://dx.doi.org/10.1007/978-90-481-8863-5_34

49. Thompson JA, Prescott T, Moore AC, Bell JS, Kautz D, Hempel J, et al. Regional approach to soil property mapping using legacy data and spatial disaggregation techniques. Paper presented at: 19th World Congress of Soil Science; 2010 August 1–6; Brisbane, Australia.

50. Jenny H. Factors of soil formation, a system of quantitative pedology. New York: McGraw-Hill; 1941.

51. McBratney AB, Mendoça Santos ML, Minasny B. On digital soil mapping. Geoderma. 2003;117:3–52. http://dx.doi.org/10.1016/S0016-7061(03)00223-4

52. ISRIC – World Soil Information. Soil property maps of Africa at 1 km resolution [homepage on the Internet]. c2013 [cited 2014 July 16]. Available from: http://www.isric.org/content/new-generation-soil-property-maps-africa

53. Van den Berg HM, Weepener HL. Development of spatial modelling methodologies for semi-detailed soil mapping, primarily in support of curbing soil degradation and the zoning of high potential land. ARC-ISCW Report No: GW/A/2009/01. Pretoria: ARC Institute for Soil, Climate and Water; 2009.

54. Van den Berg HM, Weepener HL, Metz M. Spatial modelling for semi detailed soil mapping in Kwazulu-Natal. Report No: GW/A/2009/33. Pretoria: ARC Institute for Soil, Climate and Water; 2009.

55. Van Zijl GM, Le Roux PAL, Turner DP. Disaggregation of land types Ea34 and Ca11 by terrain analysis, expert knowledge and GIS methods. S Afr J Plant Soil. 2013;30:123–129. http://dx.doi.org/10.1080/02571862.2013.806679

56. Zerizghy MG, Le Roux PAL, Hensley M, Van Rensburg LD. Prediction of soil distribution on two soilscapes in land type Dc17 east of Bloemfontein, South Africa. S Afr J Sci. 2013;109(11/12), Art. #2012-0021, 5 pages.

57. Van Zijl GM, Le Roux PAL. Creating a hydrological soil map for the Stevenson-Hamilton Supersite, Kruger National Park. Water SA. 2014;40:331–336. http://dx.doi.org/10.4314/wsa.v40i2.15

58. Stalz JB. Mapping potential soil salinization using rule based object-oriented image analysis [MSc thesis]. Stellenbosch: Stellenbosch University; 2007.

59. Mashimbye ZE, Cho MA, Nell JP, De Clercq WP, Van Niekerk A, Turner DP. Model-based integrated methods for quantitative estimation of soil salinity from hyperspectral remote sensing data: A case study of selected South African soils. Pedosphere. 2012;22(5):640–649. http://dx.doi.org/10.1016/S1002-0160(12)60049-6

60. Van Zijl GM. Creating a digital soil mapping protocol for southern Africa using case studies [PhD thesis]. Bloemfontein: University of the Free State; 2013.

61. Viscarra Rossel RA, Walvoort DJJ, McBratney AB, Janik LJ, Skjemstad JO. Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties. Geoderma. 2006;131:59–75. http://dx.doi.org/10.1016/j.geoderma.2005.03.007

62. Stenberg B, Viscarra Rossel RA, Mouazen AM, Wetterlind J, Donald LS. Chapter five – Visible and near infrared spectroscopy in soil science. Adv Agron. 2010;107:163–215. http://dx.doi.org/10.1016/S0065-2113(10)07005-7

63. Dunn BW, Batten GD, Beecher HG, Ciavarella S. The potential of near-infrared reflectance spectroscopy for soil analysis: A case study from the Riverine Plain of south-eastern Australia. Austr J Exp Agric. 2002;42:607–614. http://dx.doi.org/10.1071/EA01172

64. Shepherd KD, Walsh MG. Development of reflectance spectral libraries for characterization of soil properties. Soil Sci Soc Am J. 2002;66:988–998. http://dx.doi.org/10.2136/sssaj2002.9880

65. Viscarra Rossel RA, Cattle SR, Ortega A, Fouad Y. In situ measurements of soil colour, mineral composition and clay content by NIR spectroscopy. Geoderma. 2009;150:253–266. http://dx.doi.org/10.1016/j.geoderma.2009.01.025

66. Viscarra Rossel RA, Webster R. Discrimination of Australian soil horizons and classes from their visible–near infrared spectra. Eur J Soil Sci. 2011;62:637–647. http://dx.doi.org/10.1111/j.1365-2389.2011.01356.x

67. Meyer JH. Rapid simultaneous rating of soil texture, organic matter, total nitrogen and nitrogen mineralization potential by near infra-red reflectance. S Afr J Plant Soil. 1989;6:59–63. http://dx.doi.org/10.1080/02571862.1989.10634481

68. Van Vuuren JAJ, Meyer JH, Claassens AS. Potential use of near infrared reflectance monitoring in precision agriculture. Comm Soil Sci Plant Anal. 2006;37:2171–2184. http://dx.doi.org/10.1080/00103620600817382

69. Bainbridge SH, Manson AD. The use of mid-infrared spectroscopy for the routine prediction of various constituents in soil samples submitted for fertility analysis. In: Proceedings of the Combined Congress; 2009 Jan 20–22; Stellenbosch, South Africa. p. 19.

Unearthing a hidden treasure: 60 years of karst research in the Far West Rand, South Africa

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Karstified dolomitic formations situated in the Far West Rand goldfield of the Witwatersrand Basin constitute a significant groundwater resource in semi-arid South Africa and would be of strategic importance for alleviating the increasing water stress in nearby metropolitan areas. The deep-level gold mines operating below the dolomites have suffered from large volumes of dolomitic groundwater flowing into the mine voids, rendering mining both expensive and hazardous. In order to secure safe and economical mining, the overlying dolomites were dewatered. Here we review research over 60 years, conducted in three of the four major dolomitic compartments affected by dewatering. After more than six decades of research, these aquifers are arguably the most investigated karst systems in South Africa, and possibly worldwide. The data generated are, in many respects, unique, as many measurements can never be repeated, covering stochastic events such as a major water inrush into mine workings and some of the most catastrophic sinkhole developments ever recorded. Given the potential value for improving the understanding of general and local karst hydrogeology, our main goal for this paper is to alert the scientific community to the existence of this resource of mostly unpublished data and research. A no less important aim is to support a systematic collation of these studies which are in danger of being irretrievably lost as mines increasingly close down. Ecological and economic impacts of the flooding of mines in and around Johannesburg emphasise the lack of reliable historical mine data to optimally address the matter. We provide the first comprehensive, yet not exhaustive, overview on the existing studies, briefly discussing scientific content as well as obstacles for utilising the scattered, and often non-peer reviewed, information sources.

Introduction

The goldfield of the Far West Rand is a major deep-level mining area of South Africa, located approximately 50 km south west of Johannesburg (Figure 1). The gold-bearing reefs are covered, amongst others, by thick karstified dolomites, which host some of the largest groundwater resources in South Africa, supporting a range of high-yielding karst springs. Deep-level gold mining in the Far West Rand started in 1934 and soon affected the hydrological and hydrogeological environment.[1] Mining-related impacts included the dewatering of the dolomitic aquifers that caused several karst springs to dry up (Figure 1) and the diversion of streamflow from a river into a nearly 30-km-long pipeline. The impacts of mining have not only initiated numerous water-related studies, but have also created the necessity for ongoing research to develop environmentally acceptable mine closure strategies and sustainable long-term water management options.

Given the large volumes of water involved, and their proximity to water-stressed metropolitan areas affected by increasing water scarcity,[2] we believe that the systematic compilation and evaluation of existing relevant information will be crucial to understanding long-term impacts of historical mining and successfully utilising these valuable water resources in the future.

More than six decades of water-related research in the Far West Rand has generated an enormous amount of knowledge, expertise and data with great potential for developing sustainable post-mine closure strategies in the Far West Rand. The current uncontrolled rise of acidic mine water in the West, Central and East Rand regions poses severe threats to the environment, which will cause significant cost to the taxpayers. This situation illustrates the dire consequences of haphazard and unprepared mine closure, exacerbated by a lack of access to historical data and information. It is therefore imperative to prevent a similar loss of data and expertise in the Far West Rand – the largest of the remaining active goldfields of the Witwatersrand Basin. It is necessary to proactively collate all the available relevant data whilst access to underground structures is still possible and operational mining companies are still in a position to address potential gaps in order to avoid the negative consequences of closure.

Collating the large amount of knowledge proves, however, to be difficult, as much of it is spread across many role players, including the various mining companies/houses, governmental departments, municipalities, consultants and research institutions. Information held by dedicated archives and structured databases is often unavailable, whilst tracing the location of specific reports can be challenging. These difficulties are exacerbated by changes in government personnel as well as in the structure of the mining industry, which often results in existing reports and data no longer being retrievable, as is the knowledge and insight of experts who are no longer working in the field. This phenomenon is termed the 'loss of institutional memory'[1], which leads to repetition of research in the best case and loss of irreplaceable unique information in the worst case.

Another obstacle to utilising the accumulated knowledge results from the fact that much of it was generated without exposure to peer review, or other methods of quality assurance. A large proportion of the literature produced over the last six decades consists of reports drafted by private consultants, government officials and technical mine personnel. Generally driven by matters affecting day-to-day operations, some urgent and case specific, these studies have in common a strong focus on practical applicability rather than scientific rigour. Moreover, many reports are of limited circulation as they are contained in internal, unpublished or confidential documents, severely limiting public access. As a consequence, whilst undoubtedly containing particularly unique data and information, many reports

hardly satisfy strict scientific standards in terms of objectivity, quality assurance and referencing. The lack of proper referencing, in particular, frustrates tracing and verifying the sources of information. Dedicated sections explaining the methodology applied for generating the presented data are commonly absent. All this limits the ability of researchers to assess the reliability and quality of the data and information, thus reducing their scientific value. Consequently many reports have to be approached with caution in order to avoid compromising the quality of follow-up studies. Unfortunately this applies to the bulk of available consulting reports which often liberally use information and data from third parties without quoting the original sources.

In addition to raising awareness to these challenges, we aim here, for the first time, to provide a structured overview on the scope and extent of existing literature. To this end, each available study is allocated to one of six topical categories. Geographically, we focus predominantly on literature pertaining to the three currently dewatered groundwater compartments (Venterspost, Bank, Oberholzer) to which the overwhelming majority of studies refers.

As the number of documents concerned with hydrological issues in the Far West Rand runs into the thousands, this overview is not exhaustive. Ideally, this review should be followed by systematically archiving the available sources – preferably in digitised format to allow for collation in a single, centrally managed and searchable electronic database.

Topical categories of research in the Far West Rand

This review covers hydrogeological research in the Far West Rand from the mid-20th century, when industrial-scale deep-level mining, as well as large-scale dewatering of the dolomitic compartments, commenced to the present (2012). Excellent overviews on the course of events related to deep-level mining in the Far West Rand and associated hydrogeological impacts are provided by Swart et al.[3] and Winde[4]. Based on these and other sources, six major research themes were identified, into which the available studies are categorised: (1) general geology of the study area, (2) groundwater-related problems faced by the mines, (3) ground instabilities and sinkholes following the dewatering, (4) hydrogeological characterisation of dolomitic compartments, (5) mining-related water quality issues and (6) closure of mines. These categories are briefly discussed, with a focus on some of the most prominent sources.

General geology of the study area

First published reports of geophysical investigations in the Far West Rand[5,6] date back to the 1930s[7]. De Kock[7] compiled those findings as well as numerous company reports from gold mines, comprehensively addressing the geology of the Far West Rand, describing the major geological formations as well as structural geological features such as the major faults and intrusive and impermeable dykes. Trending roughly north to south, the latter form the eastern and western boundary of the groundwater compartments and thus are essential for understanding the hydrogeology of the Far West Rand.

The work of De Kock[7] provided the basis for later and more detailed studies of the area. Subsequent geological descriptions supplementing his work include those of Brink[8], the South African Committee for Stratigraphy[9], Engelbrecht[10], Robb and Robb[11] and McCarthy[12].

Groundwater-related problems faced by the mines

In many instances, hydrological research was initiated by the ingress of large volumes of groundwater from the overlying karst aquifers into the mine void.

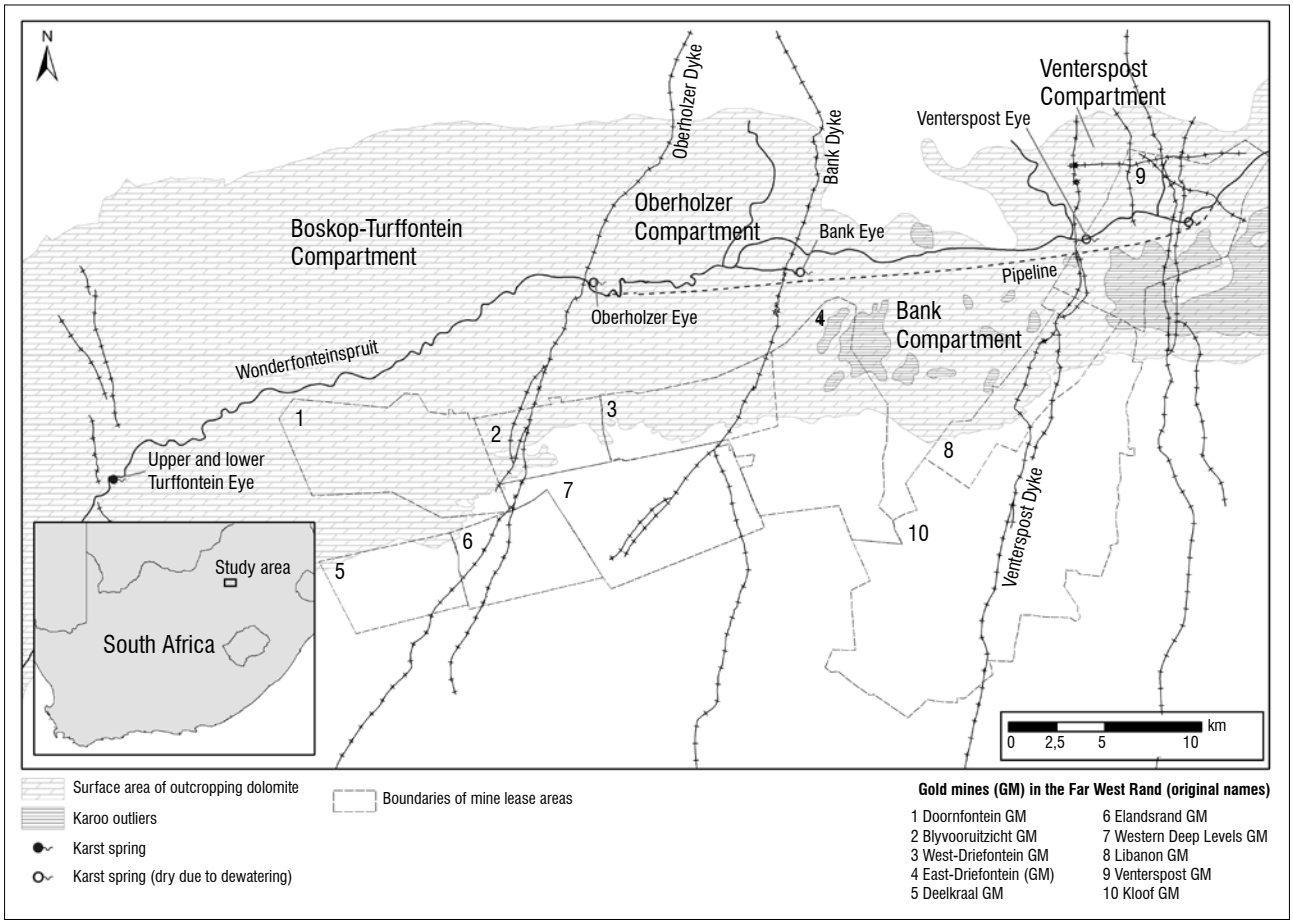

Figure 1: Locality plan and map of the central part of the Far West Rand goldfield showing the surface area of outcropping water-bearing dolomite, the position of dykes and the boundaries of mine lease areas.

In 1957, a tracer test was conducted in the area at Blyvooruitzicht Goldmine in the Oberholzer Compartment (Figure 1) which aimed to determine the rate of recirculation of water pumped from the underground mine void to the surface, followed by ingress into the mine void.[13] From this test, conclusions were drawn on the groundwater flow velocity as well as on the volume of groundwater stored in the dolomite and possible leakage through dykes. The consequences, practicability and economic viability of dewatering the groundwater compartments have been discussed in several unpublished reports.[14-17]

The most significant study on this topic was performed by the Interdepartmental Committee of Dolomitic Mine Water between 1956 and 1960 under the authority of the Minister of Water Affairs. This study thoroughly examined a range of aspects associated with the ever-increasing ingress of groundwater into the growing mine voids. The resultant 'Jordaan Final Report'[18] was a compilation of findings from several detailed studies (e.g. Enslin and Kriel[19]) that, inter alia, also investigated environmental and economic consequences of the dewatering of the two dolomitic compartments under investigation. Many hydrological data (e.g. spring flow volumes) that appear in later studies originate from the 'Jordaan Report', even though the source is not indicated in many instances. Following the recommendations of the report, legal permission to dewater the Oberholzer compartment – as defined by Wolmarans[20] – was granted to the Chamber of Mines by government after the 4-year investigation was concluded. Two of the three mines involved had already started this process well before the permission was granted, as two springs had already ceased to flow. [21]

In 1968, a massive inrush of groundwater occurred at the West-Driefontein mine (Figure 1). The event that eventually led to the dewatering of the Bank Compartment was described in detail by Cartwright[22] and Cousens and Garrett[23]. Valuable facts relating to inrush volumes during and prior to the event are to be found in an unpublished report from the Acting Secretary for Water Affairs.[24]

After official dewatering of the compartments commenced, numerous studies (see following sections) were carried out, aiming to characterise the aquifer system and adjacent geological formations, in order to respond to the various hydrogeological consequences of dewatering and resulting problems encountered during daily operations.

Ground instabilities and sinkholes following dewatering

After dewatering commenced, ground instability – in the form of subsidences and often dramatic sinkholes – rapidly developed. The consequence of lowering the water table demanded scientific attention. Early descriptions of the phenomenon exist[25,26]; later, the processes were described comprehensively by Brink[8]. Bezuidenhout and Enslin[26], Kleywegt and Enslin[27] and Kleywegt and Pike[28] evaluated data from gravimetric surveys carried out in order to delineate high-risk areas for sinkhole formation. In accordance with the serious consequences of sinkholes for the local population and infrastructure, and the associated public and political attention given to the matter, these surveys were unprecedented in terms of their level of detail and spatial scale. The findings of these surveys indicated that the formation of sinkholes depends on specific geological and hydrological conditions relating to the depth and shape of the bedrock surface[26-28], the nature and thickness of the (weathered) overburden[28], the original depth of the groundwater table[26-28] as well as the presence or absence of surface (stream) water[26-28]. Most sinkholes formed in the outcrop area of the chert-rich dolomitic formations (i.e. Monte Christo and Eccles Formations) and were often associated with fault zones, fractures and dyke edges as well as the stream bed of the Wonderfonteinspruit. Beukes[29] found a possible effect of rising water tables (termed 'rewatering') on the rate at which new sinkholes develop. Swart[30], Swart et al.[3] and Winde and Stoch[1] outlined the possible impact of sinkholes on the recharge rate of the dolomitic compartments based on historical heavy rainfall events. Although desirable in order to assess groundwater recharge of compartments under the present conditions, reliable long-term data indicating the impacts of sinkholes on recharge rates do not exist. More recent studies reviewing the history and extent of sinkhole development in the Far West Rand, without necessarily introducing new aspects or concepts, exist from De Bruyn and Bell[31] and Van Niekerk and Van der Walt[32]. A vast quantity of unpublished data (comprising some 2500 documents) on dewatering-related ground movements from 1964 to 2007 has been assembled by the State Coordinating Technical Committee. This work was and is complemented by work at the Geobasecamp of Gold Fields Ltd. in Oberholzer, where many data relating to sinkholes and ground subsidence are captured in a dedicated geographic information system (GIS).

Hydrogeological characterisation of dolomitic compartments

The hydrogeology of the dolomitic compartments, focusing on the structural geology, groundwater storage and recharge as well as the determination of hydraulic parameters, has been assessed by a range of comprehensive and detailed studies. In an early seminal study, Enslin and Kriel[19] delineated surface catchment boundaries of the dolomitic compartments and assessed monthly and annual water balances including artificial sources of recharge and discharge. Subsequent comprehensive hydrological studies exist from Brink[8], Jordaan et al.[18], Enslin[33], Enslin and Kriel[34], Fleisher[35], Vegter[36] and Foster[37].

Martini and Kavalieris[38] described the general genesis and morphology of the Transvaal dolomites, especially the caves. Processes involved in the weathering and karstification of the dolomites in the Far West Rand were described by Morgan and Brink[39] who outlined three vertical zones distinguished by their degree of karstification: a highly weathered nearly porous zone followed by a cavernous zone as well as weakly fractured to solid dolomite. The hydraulic characteristics of vertical fissures in the dolomite were described by Wolmarans and Guise-Brown[40] and Wolmarans[41]. Cross-cutting through all geological formations, these fissures transport groundwater from the dolomite into the mine voids. According to the authors, the hydraulic properties as well as the ability to conduct groundwater down to the mine voids, largely depends on the large-scale folding of the dolomite, whereas fissures in areas of synclinal folding (tension zones) generally generate more ingress water than fissures in areas of anticlinal folding (compression zones). Descriptions of the petrography, thickness and distribution, as well as the hydrology of non-dolomitic rock formations associated with the dolomitic aquifer system, can be found in De Freitas[42].

Various pumping tests have been undertaken for the hydraulic characterisation of the dolomite. Schwartz and Midgley[43] derived values of transmissivity and the storage coefficient of the Bank Compartment by applying the method of Theis[44] to data recorded during the inrush event that flooded West-Driefontein in 1968. Fleisher[35], De Freitas[42] and Bredenkamp et al.[45] describe further pumping tests evaluated by a range of methods. Results indicate a high heterogeneity of the dolomite with transmissivities ranging from a few hundred to several thousand metres squared per day. Geo Hydro Technologies[46] conducted slug tests in the Pretoria Group rocks covering the dolomite at the southern edge of the outcrop area; values of hydraulic conductivity thus obtained were generally lower than those found in the upper dolomite.

In the pumping test analyses quoted above, as well as in those conducted in similar aquifers in South Africa (e.g. van Tonder et al.[47]), it was found that the determination of the storage coefficient is problematic, as values in many cases showed a so-called distance-dependency (referring to the distance between the observation and pumping well). A possible explanation for this observation was provided by Neuman (1994, personal communication quoted in Kirchner and Van Tonder[48]).

The (effective) porosity, which was found to decline with depth, has been assessed by Enslin and Kriel[19], Enslin and Kriel[34], Fleisher[35] and Foster (unpublished data, quoted in Foster[49]). Applied methods include pumping tests as well as borehole and mine shaft log evaluation, spring flow analysis and water balance studies.

On the basis of spring flow hydrographs, groundwater recharge of compartments was described by Fleisher[35] as a two-phase system with an immediate and a delayed component. The long-term average recharge volume of compartments, often quoted as percentage of rainfall, was estimated from natural spring flow volumes[18], the Hill-method[35] and

(long-term) pumping rates of mines[50,51]. Bredenkamp[52,53] estimated recharge in two similar dolomitic compartments using chloride profiles and a ^{14}C model, respectively. The possibility of artificially recharging the aquifer via boreholes has been investigated by Enslin et al.[54] who identified possible recharge areas on the basis of data from the gravimetric survey quoted above.

Mining-related water quality issues

Groundwater quality issues relating to the problem of acid mine drainage have been addressed.[55] Pyrite, occurring in mined ore reefs, produces iron hydroxide and sulphuric acid when it comes into contact with water and oxygen. This highly toxic acidic solution may decant on the surface after flooding of abandoned mine voids. As stated by Pulles et al.[56], decanting of mine water is likely to occur to some degree in the Far West Rand after mining ceases. Although the environmental threads linked to acid mine drainage were recently under discussion for other mining areas of South Africa,[57] detailed studies of these aspects are largely lacking in the Far West Rand.

In a study jointly funded by the Water Research Commission and the Far West Rand Dolomitic Water Association, Dill et al.[58] investigated the effects on the quality of groundwater resources of the common practice of using tailings materials for the filling of sinkholes. Dill et al.[58] suggested that uranium levels of up to 300 mg/L are to be expected in leachate from such fillings. These levels indicate that tailings-filled sinkholes are a major risk for polluting groundwater.

Pollution of the environment caused by the water- and airborne transport of uranium originating to large extents from large slimes dams has been addressed by Wade et al.[59], Coetzee et al.[60], Winde[61-63], NECSA[64], Barthel[65] and IWQS[66]. These studies report on elevated concentrations of uranium in ground- and surface water[60,61,63,66,67], riverine sediments[59,60,65], soil[60,65], fish[63,64] and livestock[64]. Current research focuses on the possible associated health risks, including concentrations of uranium and processes and pathways involved in the spreading of uranium. As a major issue in this regard, Winde[67] pointed out the general lack of reliable scientific knowledge on long-term health effects of uranium, which is also reflected by the wide range of uranium limits for drinking water given by different organisations and countries.

Closure of mines

In recent years, as mining in the Far West Rand has passed its zenith, research has shifted towards the challenges of sustainable mine closure and associated hazards. Winde and Stoch[1], Usher and Scott[68] and Winde et al.[69] comprehensively address the environmental impacts of mining with special reference to mine closure strategies. A report of the Department of Water Affairs and Forestry[70] briefly assesses the future (post-mining) water supply potential of the dolomitic compartments. Winde and Stoch[71] were the first to examine the opportunities associated with mine closure by exploring the potential of the area for beneficial post-closure use of mining residuals and infrastructure.

The water quality issues mentioned above, as well as the availability of water, will be influenced by the post-mine closure management of rewatering of the compartments. Different authors have estimated the time it will take for compartments to fill up with infiltrating groundwater once the mines stop pumping. Estimates for the period for the mine void and the dewatered compartment to re-fill range from 15 years[69] to 30 years[51]. Usher and Scott[68] estimated the time it will take for the rewatering of the dolomites (but not the mine void) from groundwater balance studies at a maximum of 30 years and from numerical modelling at 21 years (only Bank Compartment). The time estimated for the rewatering of the Gemsbokfontein West compartment was 7.5 years[72] or between 5.8 and 46 years[73].

The processes of rewatering may be influenced by the formation of a mega-compartment, which could result from hydraulic linking of the previously discrete groundwater compartments of the Far West Rand.[18] This is likely to have serious implications for many features of the hydrological system such as spring flow, the rate of groundwater recharge and the resultant groundwater quality. Although the issue was already mentioned in the Jordaan Report[18] in 1960, the matter has not yet been resolved. The existing uncertainties complicate the assessment of post-mine closure scenarios with regard to aquifer conditions and the associated environmental aspects. As a result, even in investigations into other aspects, an assumption is made about the hydrogeological future by choosing one of the two opposing scenarios[58,74] (i.e. reactivation of spring flow or formation of a mega-compartment in which springs remain dry) or taking both possibilities into account[70].

The mega-compartment concept has recently been subject to opposing views. The concept has been highlighted by Usher and Scott[68] and Scott[75], the latter proposing the possibility of preventing the formation of a mega-compartment by artificially sealing the tunnels that interconnect compartments. Investigations by Gold Fields in collaboration with the Department of Water Affairs showed that this option was not economically feasible (Stoch 2014, oral communication). The mega-compartment concept was rejected by Dill et al.[58] and Swart et al.[51]. Whilst the mega-compartment concept has largely been addressed exclusively on a speculative basis, Swart et al.[51] provided the only existing study employing a scientific methodological approach (based on Darcy's Law) in order to approach the issue on a hydraulic basis. Consequently, Van Niekerk and Van der Walt[32] and Winde and Erasmus[74] propose that the existing research on the topic (i.e. hydraulic consequences of piercing of dykes) is insufficient to reach any firm conclusions.

Conclusions and recommendations

The Far West Rand is a major deep-level gold mining area in South Africa and hosts significant groundwater resources. We have identified some particularities and issues related to the literature relevant to hydrological research in the Far West Rand. Related research over the past six decades has produced a large volume of literature, which is difficult to evaluate systematically owing to a lack of a coherent, central archiving facility and a marked lack of quality-assurance procedures. By subdividing the many complex and overlapping studies into six major topical categories, an overview is provided which reduces the overwhelming complexity of the collection of relevant studies to manageable proportions. The identification of relevant studies for future researchers is hereby simplified. The number of documents obtained (amounting to a total of 765 entities) is listed in each topical category discussed in this review in Figure 2.

Water quality issues related to mining is the single largest category of the six topics covered in this review with a quarter of all documents relating to this aspect (Figure 2). Next largest is the two groundwater-related aspects addressing the hydrogeological properties of dolomite and related water flow. The closure of mines ranks last in terms of the number of relevant documents, as many mines are still active. This study highlights the need to address this aspect in more detail in future. The relatively modest number of documents relating to ground stability reflects the short-term nature of scientific attention.

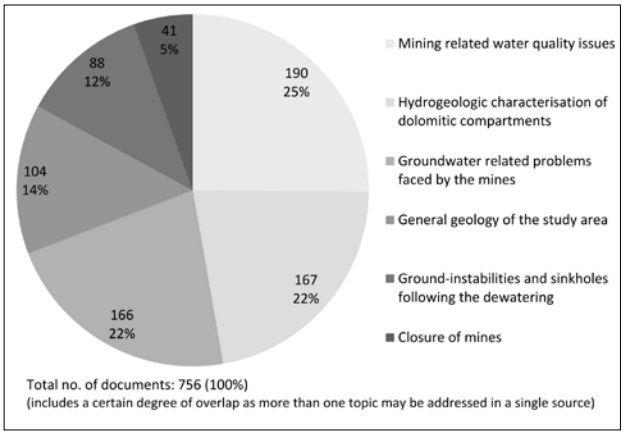

Figure 2: Number (%) of documents per category considered in this review, ranked in descending order.

Once the causes of the sudden appearance of sinkholes and ground subsidence had been understood, the number of dedicated studies on this aspect decreased. However, documents relating to routine observations of ground movement by the State Coordinating Technical Committee alone are currently estimated to number 2500, which would render this aspect by far the best covered.

The fact that much hydrological knowledge is contained in unpublished documents such as internal and confidential reports of companies is a major issue that hampers the effective utilisation of available data. Furthermore, because many documents do not meet scientific standards it is often difficult to evaluate the reliability and quality of the information. However, by putting individual studies into the context of related studies, as well as through intercomparisons, this obstacle can often be overcome, allowing the use of unique and often unreproducible data and studies.

In an effort to ameliorate the problems relating to the literature describing the Far West Rand, an initiative by the Mine Water Research Group of the North-West University (Vaal Triangle Campus) is currently underway. This initiative involves the systematic compilation of all available relevant documents into a single archive approaching some 6000 hard copies. These documents are in the process of being digitised and collated in an electronic catalogue. It is envisaged that all relevant numerical data will ultimately be extracted, georeferenced and transformed into electronic formats for the subsequent incorporation into a central GIS-supported database.

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Dedication

With sadness we learned that Dr Eliezer Joshua (Leslie) Stoch passed away on 24 August 2014. As a long-term resident he was passionate about the study area and much of what is reported in this paper is based on his vast and comprehensive collection of historical documents and was inspired by his contagious enthusiasm for this unique region. We dedicate this paper to him.

Authors' contributions

A.S. drafted the first version of the article and selected the relevant literature. F.W. provided input and background knowledge to all parts of the text and helped with structuring, editing and writing of the final version.

References

1. Winde F, Stoch EJ. Threats and opportunities for post-closure development in dolomitic gold mining areas of the West Rand and Far West Rand (South Africa) – A hydraulic view. Part 1: Mining legacy and future threats. Water SA. 2010;36(1):69–74. http://dx.doi.org/10.4314/wsa.v36i1.50908
2. United Nations Environment Programme. Geo-2000 global environmental outlook, overview. Nairobi: United Nations Environmental Programme; 1999.
3. Swart CJU, Stoch EJ, Van Jaarsveld CF, Brink ABA. The lower Wonderfontein Spruit: An exposé. Environ Geol. 2003;43(6):635–653.
4. Winde F. Karst, uranium, gold and water – Lessons from South Africa for reconciling mining activities and sustainable water use in semi-arid karst areas: A case study. In: Jones JAA, editor. Sustaining groundwater resources. Dordrecht: Springer Science+Business Media; 2011. p. 35–53.
5. Krahmann R. The geophysical magnetometric investigations on the West Witwatersrand areas between Randfontein and Potchefstroom, Transvaal. Trans Geol Soc S Afr. 1936;39:1–44.
6. Pelletier RA. Contributions to the geology of the Far West Rand. Trans Geol Soc S Afr. 1937;40:127–162.
7. De Kock WP. The geology and economic significance of the West Wits Line. In: Houghton SH, editor. The geology of some ore deposits in southern Africa, volume 1. Johannesburg: Geological Society of South Africa; 1964. p. 323–386.
8. Brink ABA. Engineering geology of South Africa, volume. 1. Pretoria: Building Publications; 1979.
9. South African Committee for Stratigraphy. Stratigraphy of South Africa. Part 1. Pretoria: Department of Mineral and Energy Affairs, Geological Survey; 1980.
10. Engelbrecht CJ. The West Wits Line. In: Antrobus ESA, editor. Witwatersrand gold – 100 Years. Johannesburg: Geological Society of South Africa; 1986. p. 199–223.
11. Robb LJ, Robb VM. Gold in the Witwatersrand Basin. In: Wilson MGC, Anhaeusser CR, editors. The mineral resources of South Africa. 6th ed. Pretoria: Council for Geosciences; 1998. p. 294–349.
12. McCarthy TS. The Witwatersrand Supergroup. In: Johnson MR, Anhaeusser CR, Thomas RJ, editors. The geology of South Africa. Johannesburg: Geological Society of South Africa, Council for Geosciences; 2006. p. 155–186.
13. National Mechanical Engineering Research Institute. Water problem at West Driefontein G.M. CO. Report No 2. Pretoria: New Consolidated Gold Fields Ltd.; 1957 [unpublished report].
14. Enslin JF. Report on the groundwater in the mining areas of Blyvooruitzicht, West Driefontein, Doornfontein and Venterspost mines and its relation to the supplies of the Oberholzer and Venterspost loop irrigation boards. Pretoria: Geological Survey; 1954 [unpublished report].
15. Interdepartmental Committee on Dolomitic Water Pumped by Mines. Depletion of water stored in Oberholzer Compartment. Interdepartmental Committee on Dolomitic Water Pumped by Mines; 1958 [unpublished report].
16. Knight K. An estimate of the total quantity of water abstracted from the Oberholzer Dolomitic compartment up to the end of 1964, the possible rate of replacing the water and the feasibility of so doing. Rand Mines Ltd; 1964 [unpublished report].
17. Irving CJ. Comment on the dewatering of the Oberholzer Dolomitic Compartment. Blyvooruitzicht Gold Mining Co Ltd; 1964 [unpublished report].
18. Jordaan JM, Enslin JF, Kriel J, Havemann A, Kent LE, Cable WH. Final report of the Interdepartmental Committee on Dolomitic Mine Water: Far West Rand. Pretoria: Department of Water Affairs and Forestry; 1960 [unpublished report].
19. Enslin JF, Kriel JP. Some results obtained from a hydrological study of a dolomitic catchment area in the Transvaal, Union of South Africa. Pretoria: Department of Water Affairs, Division of Hydrological Research; 1959.
20. Wolmarans JF. The least unsafe route, volume 1. Carletonville: Webb and Partners; 1982.
21. Stoch EJ, Winde F. Threats and opportunities for post-closure development in dolomitic gold mining areas of the West Rand and Far West Rand (South Africa) – A hydraulic view. Part 3: Planning and uncertainty – Lessons from history. Water SA. 2010;36(1):83–88. http://dx.doi.org/10.4314/wsa.v36i1.50910
22. Cartwright AP. West Driefontein – Ordeal by water. Johannesburg: Gold Fields of South Africa Ltd., JG Ince & Son Ltd.; 1969.
23. Cousens RRM, Garrett WS. The flooding at the West Driefontein Mine. S Afr Inst Min Metall. 1969;69(9):421–463.
24. Acting Secretary for Water Affairs. Far West Rand: De-watering Bank Compartment: Through West Driefontein Gold Mine: Effects on farming community: Application for urgent decision re purchase of properties and/or water rights. Pretoria: Department of Water Affairs; 1968 [unpublished report].
25. Foose RM. Sinkhole formation by groundwater withdrawal: Far West Rand, South Africa. Science. 1967;157(3792):1045–1048. http://dx.doi.org/10.1126/science.157.3792.1045
26. Bezuidenhout CA, Enslin JF. Surface subsidence and sinkholes in the dolomitic areas of the Far West Rand, Transvaal, Republic of South Africa. In: Land subsidence 1969. Proceedings of the Tokyo Symposium; 1969 Sep 17–22; Tokyo, Japan. Gentbrugge: Unesco/IAHS; 1970. p. 482–495.
27. Kleywegt RJ, Enslin JF. The application of the gravity method to the problem of ground settlement and sinkhole formation in dolomite on the Far West Rand, South Africa. In: IAEG 1973. Proceedings of the International Association of Engineering Geologists Symposium on sinkholes and subsidence – Engineering geological problems associated with soluble rocks; 1973 Sep 10–13; Hannover, Germany. Essen: Deutsche Gesellschaft für Erd- und Grundbau; 1973. p. 301–315.

28. Kleywegt RJ, Pike DR. Surface subsidence and sinkholes caused by lowering of the dolomitic water-table on the Far West Rand Gold Field of South Africa. Ann Geol Surv (S Afr). 1982;16:77–105.

29. Beukes JHT. Ground movement and the formation of sinkholes due to the partial rewatering of Venterspost Compartment 1975–1978. In: Geological survey (South Africa). Proceedings of the Seminar on the Engineering Geological Evaluation of Sites on Dolomite. Pretoria: Geological Survey; 1987. p. 86–95.

30. Swart CJU. Storm water infiltration into dewatered dolomitic compartments via sinkholes in river beds. Gold Fields Ground Stability Group. Memorandum No GF/GSG/2000/19. 2000 [unpublished report].

31. De Bruyn IA, Bell FG. The occurrence of sinkholes and subsidence depressions in the Far West Rand and Gauteng Province, South Africa, and their engineering implications. Environ Eng Geosci. 2001;7(3):281–295. http://dx.doi.org/10.2113/gseegeosci.7.3.281

32. Van Niekerk HJ, Van der Walt IJ. Dewatering of the West Rand dolomitic area by gold mining activities and subsequent ground instability. Land Degrad Dev. 2006;17(4):441–452. http://dx.doi.org/10.1002/ldr.749

33. Enslin JF. Dolomitic water supplies in the Transvaal, Republic of South Africa. Memoirs Internat Assoc Hydrogeol. 1967;8:433–476.

34. Enslin JF, Kriel JP. The assessment and possible future use of the dolomitic ground water resources of the Far West Rand, Transvaal, Republic of South Africa. In: Papers of the International Conference on Water for Peace volume 2; 1967 May 23–31; Washington DC, USA. Washington DC: US Government Printing Office; 1968. p. 908–918.

35. Fleisher JNE. The geohydrology of the dolomitic aquifers of the Malmani subgroup in the south-western Transvaal Republic of South Africa. DWAF Technical Report No GH 3169. Pretoria: Department of Water Affairs and Forestry; 1981 [unpublished report].

36. Vegter JR. Dolomitic water supplies with special reference to southern and western Transvaal. DWAF Technical Report No GH 3353. Pretoria: Department of Water Affairs and Forestry; 1984 [unpublished report].

37. Foster MBJ. The hydrogeology of dolomitic formations in the southern and western Transvaal. DWAF Technical Report No. GH 3643. Pretoria: Department of Water Affairs and Forestry; 1989 [unpublished report].

38. Martini JEJ, Kavalieris I. The karst of the Transvaal (South Africa). Int J Speleol. 1976;8(3):229–251. http://dx.doi.org/10.5038/1827-806X.8.3.1

39. Morgan DJT, Brink ABA. The Far West Rand dolomites. In: National Water Well Association, editor. Proceedings of the International Conference on Ground Water Technology; 1984 Nov 14–17; Johannesburg, South Africa. Worthington: National Water Well Association; 1984. p. 554–573.

40. Wolmarans JF, Guise-Brown FH. The water hazard in deep gold mining of the Far West Witwatersrand, South Africa. In: Asociacion Nacional de Ingenieros de Minas, Consejo Superior de Colegios de Ingenieras de Minas. Proceedings, World Congress on Water in Mining and Underground Works (SIAMOS-78); 1978 Sep 18–22; Granada, Spain. Granada: Asociacion Nacional De Ingenieros De Minas; 1978. p. 329–346.

41. Wolmarans JF. Ontwikkeling van die dolomietgebied aan die verre Wes Rand: Gebeure in perspektief [Dewatering of the dolomitic area on the Far West Rand: Events in perspective] [dissertation]. Pretoria: University of Pretoria; 1984. Afrikaans.

42. De Freitas MH. The effect of non-dolomitic rocks upon the flow of water in the Bank Compartment. London: Geology Department, Imperial College; 1974 [unpublished report].

43. Schwartz HI, Midgley DC. Evaluation of geo-hydrologic constants for the Far West Rand dolomitic formations. Civ Eng S Afr. 1975;17(2):31–36.

44. Theis CV. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. Trans Am Geophys Union. 1935;16(2):519–524. http://dx.doi.org/10.1029/TR016i002p00519

45. Bredenkamp DB, Fayazi M, Botha LJ. Interpretation of pumping test in the Gemsbokfontein East Compartment – A typical heterogeneous karst system. DWAF Technical Report No GH 3727. Pretoria: Department of Water Affairs and Forestry, Directorate of Geohydrology; 1991 [unpublished report].

46. Geo Hydro Technologies. Geohydrological investigation of the groundwater conditions at West Driefontein, a division of Driefontein Consolidated Ltd. Report No. WES\97\103. Pretoria: Geo Hydro Technologies; 1998 [unpublished report].

47. Van Tonder G, Bardenhagen I, Riemann K, Van Bosch J, Dzanga P, Xu Y. Manual on pumping test analysis in fractured-rock aquifers. WRC Report No 1116/1/02. Pretoria: Water Research Commission; 2002.

48. Kirchner J, Van Tonder GJ. Proposed guidelines for the execution, evaluation and interpretation of pumping tests in fractured-rock formations. Water SA. 1995;21(3):187–200.

49. Foster MBJ. First revision of the geohydrology of the Zuurbekom and Gemsbokfontein Compartments. DWAF Technical Report No GH 3542. Pretoria: Department of Water Affairs and Forestry; 1987 [unpublished report].

50. Foster MBJ. The groundwater resources of the Far West Rand dolomitic compartments. DWAF Technical Report No. GH 3607. Pretoria: Department of Water Affairs and Forestry; 1988 [unpublished report].

51. Swart CJU, James AR, Kleywegt RJ, Stoch EJ. The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA. Environ Geol. 2003;44(7):751–770. http://dx.doi.org/10.1007/s00254-003-0820-3

52. Bredenkamp DB. Recharge estimation based on chloride profiles. DWAF Technical Report No GH 3804. Pretoria: Department of Water Affairs and Forestry, Directorate of Geohydrology; 1993 [unpublished report].

53. Bredenkamp DB. Use of natural isotopes and groundwater quality for improved recharge and flow estimates in dolomitic aquifers. Water SA. 2007;33(1):87–94.

54. Enslin JF, Kleywegt RJ, Buekes JHT, Gordon-Welsh JF. Artificial recharge of dolomitic ground-water compartments in the Far West Rand Gold Fields of South Africa. In: International Association of Hydrological Sciences, editor. Proceedings of the Second International Symposium on Land Subsidence; 1976 Dec 13–17; Anaheim, CA, USA. Ann Arbor, MI: International Association of Hydrological Sciences; 1977. p. 495–506.

55. Durand JF. The impact of gold mining on the Witwatersrand on the rivers and karst system of Gauteng and North West Province. J Afr Earth Sci. 2012;68:24–43. http://dx.doi.org/10.1016/j.jafrearsci.2012.03.013

56. Pulles W, Banister S, Van Biljon M. The development of appropriate procedures towards and after closure of underground gold mines from a water management perspective. WRC Report No 1215/01/05. Pretoria: Water Research Commission; 2005.

57. Winde F, Stoch EJ, Erasmus E. Desktop assessment of the risk for basement structures of buildings of Standard Bank and ABSA in Central Johannesburg to be affected by rising mine water levels in the Central Basin. Final Report (Volume I of III). Potchefstroom: Mine Water Research Group, North-West University; 2011 [unpublished report]. http://dx.doi.org/10.2747/0272-3646.27.4.333

58. Dill S, Boer RH, Boshoff HJJ, James AR, Stobart BI. An Assessment of the impacts on groundwater quality associated with the backfilling of dolomitic cavities with gold mine tailings. WRC Report No 1122/1/07. Pretoria: Water Research Commission; 2007.

59. Wade PW, Woodborne S, Morris WM, Vos P, Jarvis NV. Tier 1 risk assessment of selected radionuclides in sediments of the Mooi River catchment. WRC Report No 1095/1/02. Pretoria: Water Research Commission; 2002.

60. Coetzee H, Winde F, Wade PW. An assessment of sources, pathways, mechanisms and risks of current and potential future pollution of water and sediments in gold-mining areas of the Wonderfonteinspruit catchment. WRC Report No 1214/1/06. Pretoria: Water Research Commission; 2006.

61. Winde F. Challenges for sustainable water use in dolomitic mining regions of South Africa – A case study of uranium pollution. Part I: Sources and pathways. Phys Geogr. 2006;27(4):333–347.

62. Winde F. Uranium pollution of the Wonderfonteinspruit, 1997–2008. Part 1: Uranium toxicity, regional background and mining-related sources of uranium pollution. Water SA. 2010;36(3):239–256.

63. Winde F. Uranium pollution of the Wonderfonteinspruit, 1997–2008. Part 2: Uranium in water – Concentrations, loads and associated risks. Water SA. 2010;36(3):257–278.

64. South African Nuclear Energy Corporation (NECSA). Report of radioactivity analysis of fish and chicken. Job code RA 08190, 28 Aug. 2007, for Driefontein GM. Pretoria: South African Nuclear Energy Corporation; 2007 [unpublished report].

65. Barthel R. Radiological impact assessment of mining activities in the Wonderfonteinspruit catchment area, South Africa. In: Merkel BJ, Schipek M, editors. The new uranium mining boom, challenge and lessons learned. 6th International Conference. Freiberg: Springer; 2011. p. 517–527. http://dx.doi.org/10.1007/978-3-642-22122-4_60

66. IWQS (Institute for Water Quality Studies of the Department of Water Affairs and Forestry, South Africa). Report on the radioactivity monitoring programme in the Mooi River (Wonderfonteinspruit) catchment. Report No. N/C200/00/RPQ/2399. Pretoria: Department of Water Affairs and Forestry; 1999.

67. Winde F. Uranium pollution of water resources in mined-out and active goldfields of South Africa – A case study in the Wonderfonteinspruit catchment on extent and sources of U-pollution and associated health risks. In: Water Institute of Southern Africa, International Mine Water Association. International Mine Water Conference [CD ROM]. Pretoria: Document Transformation Technologies; 2009. p. 772–781.

68. Usher BH, Scott R. Post mining impacts of gold mining on the West Rand and West Wits Line. In: Hodgson FDI, Usher BH, Scott R, Zeelie S, Cruywagen LM, De Necker E, editors. Prediction techniques and preventative measures relating to the post-operational impact of underground mines on the quality and quantity of groundwater resources. WRC Report No 699/1/01. Pretoria: Water Research Commission; 2001. p. 5.1–5.117.

69. Winde F, Stoch EJ, Erasmus E. Identification and quantification of water ingress into mine voids of the West Rand and Far West Rand goldfields (Witwatersrand Basin) with a view to long-term sustainable reduction thereof. Final report, Project No 5512. Pretoria: Council for Geoscience; 2006 [unpublished report].

70. Department of Water Affairs and Forestry. Vaal River System: Large bulk water supply reconciliation strategy. Groundwater assessment: Dolomitic aquifers. Prepared by DMM Development Consultants, Golder Associates Africa, SRK, WRP Consulting Engineers and Zitholele Consulting. DWAF Report No P RSA C000/00/4406/06. Pretoria: Department of Water Affairs and Forestry, Directorate National Water Resource Planning; 2006.

71. Winde F, Stoch EJ. Threats and opportunities for post-closure development in dolomitic gold mining areas of the West Rand and Far West Rand (South Africa) – A hydraulic view. Part 2: Opportunities. Water SA. 2010;36(1):75–82. http://dx.doi.org/10.4314/wsa.v36i1.50909

72. Van Biljon M, Krantz R. Predicted rate of rewatering the Gemsbokfontein West groundwater compartment. Report to Harmony Gold Mining Limited. Johannesburg: Rison Consulting; 2001 [unpublished report].

73. De Roer K. Hydrologic impact of rewatering of the Gemsbokfontein dolomitic western subcompartment on the Wonderfonteinspruit, South Africa [thesis]. Potchefstroom: North-West University; 2004.

74. Winde F, Erasmus E. Peatlands as filters for polluted mine water? – A case study from an uranium-contaminated karst system in South Africa. Part I: Hydrogeological setting and U fluxes. Water. 2011;3(1):291–322. http://dx.doi.org/10.3390/w3010291

75. Scott R. Investigation of the post mining impact on groundwater in the West Rand and West Wits Line mining areas. Third interim progress report to the Water Research Commission. Pretoria: Water Research Commission; 1997 [unpublished report].

Real-time measurement of outdoor worker's exposure to solar ultraviolet radiation in Pretoria, South Africa

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The city of Pretoria in South Africa receives considerable solar ultraviolet radiation (UVR) because of its low latitude (22–35°S) and relatively clear skies. Certain meteorological factors affect the amount of solar UVR that reaches the ground; the most dominant factors being stratospheric ozone, cloud cover and solar zenith angle. It is known that overexposure to solar UVR may lead to the development of adverse health conditions, the most significant being skin cancer. Outdoor workers spend a significant amount of time outside and are thus susceptible to this risk. In this case study, we estimated, for the first time, the real-time solar UVR exposure of an outdoor worker in Pretoria. Measurements were made on 27 and 28 May 2013 using a handheld ultraviolet index (UVI) meter calibrated against a science-grade biometer at the South African Weather Service in Pretoria. Personal exposure estimation was used to discern the pattern in diurnal and annual sunburn risk for the outdoor worker. Ambient UVR levels ranged from 0 UVI to 4.66 UVI and the outdoor worker's potential exposure estimates regularly exceeded 80% of these levels depending on the time of day. The risk of sunburn was evident; however, actual incidents would depend on individual skin photosensitivity and melanin content, as well as sun protection used. Further research is needed to determine the personal exposure estimations of outdoor workers in other provinces in which solar UVR levels may be equally high, or higher than those in Pretoria.

Introduction

People living in South Africa can potentially experience intense personal exposure to solar ultraviolet radiation (UVR). This potential is because of the country's low latitude (22–35°S), high altitude in the interior, annual average daytime temperature of 22 °C (thereby encouraging time spent outdoors) and high ultraviolet index (UVI) occurrences almost year-round.[1,2] The global UVI is a measure of solar UVR intended to inform the general public about UVR intensity; the index ranges from 0, which is considered low, to 11 or higher, which is considered extreme.[3,4]

Exposure to UVR is known to have both beneficial and harmful photobiological effects on humans. The most significant benefit is the endogenous production of vitamin D.[5] Vitamin D is essential for, among other processes, bone metabolism in the human body.[6] Harmful effects of UVR occur as a result of either underexposure or overexposure to UVR. Underexposure is harmful as it may result in a deficiency in vitamin D in the body.[5] Some of the main harmful effects of overexposure are damage to the skin (in the form of sunburn) and to DNA. Excess solar UVR exposure is known to be a carcinogen.

UVR is subdivided into three bands: UVA (400–315 nm), UVB (315–280 nm) and UVC (280–100 nm). UVR at wavelengths shorter than 320 nm is more photobiologically active than UVR at longer wavelengths.[7] However, radiation from 250 nm is sufficiently biologically active to cause erythema in the skin. Therefore, although UVA penetrates the human skin more deeply than UVB, because of its shorter wavelength, UVB poses a greater risk for initiation of the carcinogenic process in skin.[5]

Several factors influence the amount of solar UVR that reaches the ground. These factors include stratospheric ozone, cloud cover, sun position (determined by time of day, season, geographic latitude and solar zenith angle), altitude, surface reflection and air pollution.[3] A previous study has shown that total ozone, solar zenith angle (SZA) and cloud cover are among the dominant meteorological factors that influence the amount of UVB that reaches the ground.[8,9] It is important to determine the relationship that exists between each of these factors and solar UVR.

The main absorber in the atmosphere that determines the amount of UVR that reaches the ground is stratospheric ozone. Ozone production and destruction require solar radiation with wavelengths shorter than 240 nm (which is mainly UVC radiation).[10] Total column ozone is measured in Dobson units (DU) where 1 DU = 2.69×10^{16} mol O^3/cm^2.[11] Total column ozone is usually measured with a satellite-based instrument. A typical DU value for ozone in the mid-latitudes is found in the region of 300 DU.[12] A distinct seasonal cycle is observed at middle and high latitudes with the highest values typically occurring in spring in the southern hemisphere.[13,14] In the absence of all other factors, less ozone in the atmosphere allows for more solar UVR to reach the ground, and vice versa.[10]

Cloud cover has been found to be the second most effective shield (after stratospheric ozone) to limit the amount of solar UVR that reaches the earth's surface.[15] Cloud cover can either attenuate or enhance the amount of solar UVR reaching the ground.[10] Whether attenuation or enhancement occurs is determined by factors such as cloud location (which refers to cloud height and whether or not the cloud is covering the solar disc), percentage cover, optical thickness and liquid water content.[16] A reduction in solar UVR of 50% has been found over the USA and 70% over Sweden during overcast conditions.[17]

The intensity of the sun rays, and therefore of solar UVR, as they reach the ground is strongly dependent on SZA.[7] SZA is the angle that is formed between directly overhead and the centre of the disc of the sun (using a horizontal

coordinate system). A zenith angle of 0° means that the sun is directly overhead; this angle occurs at solar noon. When the sun is directly overhead (i.e. the SZA is smaller), all of the emitted rays are focused on a relatively small, solid area on the earth's surface. However, once the SZA starts to increase, the sun's rays are distributed over a larger area of the earth's surface, thereby decreasing the intensity of solar UVR. SZA is smaller in the summer months when the sun is higher in the sky and larger in the winter months when the sun falls lower in the sky. Therefore solar UVR is more intense during summer and less intense in winter.[7]

South Africa has a high occurrence of skin cancer, accounting for about 30% of all histologically diagnosed cancers. An important risk factor for skin cancer is skin phototype (including skin colour). Six skin phototypes have been defined according to the skin's response to solar UVR exposure. People with darker skin types have more melanin in their skin and therefore a higher degree of protection against solar UVR. People with fairer skin types have less melanin and therefore a lower degree of natural protection.[18] The Fitzpatrick classification can be used as a guide to prevent overexposure. Table 1 shows the different skin phototypes and their respective minimum standard erythemal dose values needed to elicit sunburn according to Fitzpatrick.

Outdoor workers are susceptible to overexposure to solar UVR as they spend the majority of their day outside.[23] Many previous studies (particularly in Europe, Australia and New Zealand) have measured the solar UVR exposures of outdoor workers. Larko and Diffey[24] found that outdoor workers received between 10% and 70% of ambient UVR depending on the amount of work time spent outdoors. Reducing sun exposure is not a feasible option for outdoor workers.[25] Studies among New Zealand and Australian outdoor workers found that sun protection is not seen as a priority. Poor and inconsistent sun protection measures are employed and many outdoor workers find certain measures (such as wearing hats and clothing that covers exposed areas) inconvenient to use while working. Many of the workers are not required to wear hats or use sunscreen, despite working in areas that receive high amounts of solar UVR.[26,27] It has been shown that employer-led interventions may lead to an increase in the use of sun-protective measures by outdoor workers.[28]

Potential sunburn risk among outdoor workers in South Africa based on ambient solar UVR readings has been estimated in a study.[1] The study concluded that, for almost all seasons, locations considered and six skin types, there was at least one day (but usually many more days) when outdoor workers were at risk of sunburn; however, it also was concluded that real-time measurements of outdoor workers' exposure were needed to validate these findings.

Our primary aim in this study was to measure the personal exposure to solar UVR of an outdoor worker in Pretoria. We conducted a case study in which levels of solar UVR were measured at a site where an outdoor worker was working. The results were used to determine the worker's time-stamped and average daily exposure to solar UVR. Our secondary aim was to investigate the relationship between solar UVR and the three above-mentioned meteorological factors – cloud cover, total column ozone and SZA – that influenced the amount of solar UVR that reached the ground in Pretoria in 2012 for the whole year and for each season. This investigation was done in order to understand both the static risk and the dynamic risk of overexposure to solar UVR. In this study, the static risk is the basic risk one would be exposed to on any given day. This risk is represented by the estimated exposure determined by the primary aim. The dynamic risk is the actual amount of solar UVR one is at risk of being exposed to. This risk changes according to the amount of solar UVR that reaches the ground. It is therefore influenced by the meteorological factors considered in this study. This study is the first in South Africa in which the exposure of an outdoor worker is determined using actual measurements of solar UVR. Ultimately, the results of this study will be used to develop a full-scale study to then produce recommendations for sun protective measures for outdoor workers in South Africa.

Data

Case study

The solar UVR measurements for the case study were collected using two handheld UVI meters. These instruments are available commercially and were made by the same company (name withheld). Two instruments were used just in case one of the instruments failed. The readings (in UVI) were manually captured in a logbook. Wright and Albers[29] detail the accuracy of the instruments. The recorded values were later corrected using calibration equations obtained by calibrating the UVI meters against the UVB biometer at the South African Weather Service (SAWS) in Pretoria.[29] Ambient solar UVR data for Pretoria were measured by the SAWS' UVB biometer.

Meteorological factors

Five data sets were used for the purpose of analysing the relationships between solar UVR and the three meteorological factors: cloud cover, total column ozone and SZA. These data sets were cloud cover data, sun elevation data, total column ozone data, ground-based solar UVR measurements and satellite solar UVR data. The ground-based solar UVR data and the cloud cover data were obtained from the SAWS in

Table 1: The Fitzpatrick skin phototype classification[19-22]

Skin type	Unexposed skin colour	Constitutive characteristics	History of sunburn	Ultraviolet radiation sensitivity	Continuous ultraviolet radiation exposure needed for sunburn (SED)
I	White	Fair skin, blue or light eyes and freckles	Always burns on minimal sun exposure	Extremely sensitive	2–3
II	White	Red or blonde hair, blue, hazel or brown eyes and freckles	Burns very readily	Very sensitive	2.5–3
III	White/light brown	Brown hair and blue, hazel or brown eyes	May burn on regular sun exposure with no protection	Moderately sensitive	3–5
IV	Light brown	Brown hair and dark eyes	Burns rarely	Relatively tolerant	4.5–6
V	Brown	Brown eyes and dark brown or black hair	Despite pigmentation, may burn surprisingly easily on sun exposure	Very variable	6–20
VI	Black	Brown eyes and dark brown or black hair	Rarely burns, although sunburn is difficult to detect on very pigmented skin	Relatively insensitive	6–20

SED, standard erythemal dose

Pretoria. The sun position data were obtained from the National Oceanic and Atmospheric Administration. The satellite solar UVR data and the total column ozone data were obtained from GIOVANNI, a web-based portal site that allows access to data collected by various satellites. The measurements were local noon readings taken by the OMI/Aura satellite instrument (measured in UVI and DU, respectively). All of the data covered the area in which the SAWS UVB biometer is located in Pretoria. All of the data were for 1 January 2012 to 31 December 2012. The ground-based solar UVR data set had missing values for 10 days between 3 September and 12 September. The satellite solar UVR data set had a period of 53 days between 9 September and 1 November in which no data were recorded. All the days of missing data were omitted from the respective calculations.

Methods

Case study

Site and participant selection

Pretoria was chosen as the site for this case study because in a previous study Pretoria was found to have some of the highest solar UVR levels in South Africa.[1] An outdoor worker was selected and agreed to partake in the case study. The participant had skin type VI according to the Fitzpatrick skin phototype classification. The case study was approved by the University of Pretoria Research Ethics Committee (reference EC130610-054). The participant was chosen because he met the following requirements: spends the majority of the work day outdoors, works outdoors for more than 3 days per week, and the work site is in Pretoria. The case study was conducted over 2 days with minimal cloud cover to minimise the solar UVR attenuation effect of clouds.

Instruments

Two handheld UVI meters – UVI meter 1 and UVI meter 2 – were used to measure solar UVR reaching the worker at 30-min intervals for 7 h each day. They were used in a study in which they were compared to the research-grade UVB biometer at the SAWS in Pretoria. One of the monitors, UVI meter 2, was found to be in sufficient agreement with the UVB biometer. The other monitor, UVI meter 1, overestimated the solar UVR by up to 4 UVI units. The instruments were calibrated during a previous study against the UVB biometer to ensure that their readings provided a true measure of solar UVR received.[29]

Data collection

Half-hourly readings were taken from 08:30 (South African Standard Time) when the participant began his working day until 15:30 SAST when he finished his working day. The solar UVR readings were manually recorded by one of the authors. Half-hourly readings were taken at the times corresponding to those made at half-hourly intervals at the South African Weather Service. These readings were manually recorded in a logbook and later entered into a computer database. Before these values were used in the analyses they were corrected using calibration equations. Each UVI meter had its own calibration equation as follows:

$y = 1.7508x$ (UVI meter 1) Equation 1

$y = 1.0503x$ (UVI meter 2) Equation 2

where y is the UVI-meter reading and x is the corrected value.[29]

Data analysis

The corrected values of solar UVR from the UVI meters were plotted for each case study day. The ground-based solar UVR measurements from the SAWS UVB biometer for the 2 days were overlaid on the readings of the handheld meters. A calculation was done to work out what percentage of the SAWS-measured ground-based solar UVR the UVI meters measured during the study period. This calculation gives an indication of how much solar UVR reached the site at which the outdoor worker was working, and therefore how much solar UVR the worker was exposed to during the study period. On a different set of axes, the handheld meter solar UVR readings were plotted and overlaid with skin type exposure dose (see Table 1). This comparison was done in order to assess whether the outdoor worker was exposed to a sunburn risk on the case study days. The same procedure was followed with the 2012 SAWS-measured ground-based solar UVR values in order to assess whether sunburn was a possibility for the outdoor worker on any day during 2012.

Meteorological factors

Data processing

The ground-based solar UVR data were processed in several ways. Firstly, the measured values were converted from minimal erythemal dose (MED) to standard erythemal dose (SED) by multiplying the recorded MED values by 2.1 (as 1 MED = 210 J/m^2 and 1 SED = 100 J/m^2).[3] Next, the values were converted into UVI units for easier comparison with both the satellite solar UVR values (which were measured in UVI) and cloud cover values (which are within the range of the ground-based solar UVR measurements as the maximum possible value for cloud cover is 8 octas). The following equation was used for this conversion:

$$\text{UVI} = \frac{(\text{SED} \times 100) \times 40}{1800} \quad \text{Equation 3}$$

The 12:00 values were isolated from the data set and plotted on a scatter plot in order to see the annual distribution. These daily values were grouped according to season as follows: summer (December, January, February), autumn (March, April, May), winter (June, July, August) and spring (September, October, November). The daily 12:00 values were then plotted on scatter plots in order to show the seasonal distributions.

The solar elevation angle values were converted into SZA values. This conversion was done by applying the trigonometric rule

$$\phi = (90° - \theta) \quad \text{Equation 4}$$

where ϕ = SZA and θ = solar elevation angle. The SZA values were then plotted on a scatter plot in order to see the change in SZA over Pretoria for the year 2012. This plot was overlain with the ground-based solar UVR readings in order to see the annual distribution of the two readings. The daily ground-based and satellite solar UVR values for the year 2012 were also plotted on one set of axes in order to assess how closely they relate. The cloud cover data were separated into the four seasons, then within each season they were further separated according to the number of days that had 5 octas or more of cloud cover. This separation was done in order to see the seasonal distribution of cloud cover over Pretoria.

Data analysis

Non-linear regression analyses were performed in order to show the relationship between solar UVR and each of the three meteorological factors. R^2-values were obtained from the non-linear regression analyses; values closer to 1 showing a stronger correlation between solar UVR and the meteorological factor. In order to gauge the difference between the satellite-based and ground-based solar UVR measurements, the root mean square error (RMSE) was found using the following equation:

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(S_i - G_i)^2\right]^{\frac{1}{2}}, \quad \text{Equation 5}$$

where S_i is the satellite-based value and G_i is the ground-based value.

Results and discussion

Case study results

Results of the case study are summarised in Tables 2 and 3 and Figures 1 and 2. The UVI-meter-measured solar UVR values are averages of the values measured by the two instruments used. Three categories were

used to describe where the outdoor worker was in relation to direct sunlight: sun, which describes the outdoor worker being in direct sunlight (therefore higher exposure to solar UVR); shade, which describes the outdoor worker being under partial or total shade (therefore exposed to less solar UVR); and inside, which describes the outdoor worker being indoors (therefore exposed to the least possible amount of solar UVR). It can be seen that measurements taken when the outdoor worker was either in shade or inside were lower than when he was in direct sunlight. It can also be seen in Figure 1 and Figure 2 that the UVI-meter-measured values are higher than the SAWS-measured values in the earlier hours of the day and later in the afternoon when the sun was at lower angles relative to the horizon. In the middle of the day, when the sun was further away from the horizon, the SAWS-measured values tend to be higher than or in agreement with the UVI-meter-measured values. This tendency could be an overestimation error within the UVI meters or a result of the albedo effects of the surface at the fieldwork site (dry yellowing grass) compared to the surface of the roof of the SAWS (grey concrete) where the UVB biometer is situated. The maximum solar UVR value on Day 1 exceeded 5 UVI, whereas the maximum value on Day 2 did not. There are two possible reasons for this difference. Firstly, the study period was at a time of the year when the SZA is still increasing. An increase in SZA is associated with a decrease in solar UVR. Secondly, there was more cloud cover on Day 2 than on Day 1; high-level cloud moved in at intervals throughout the day. This cloud cover could also have had an attenuating effect on the amount of solar UVR that reached the ground on Day 2.

Table 2: Ultraviolet radiation values and position of outdoor worker on Day 1 of fieldwork

Time	Handheld-meter-measured ultraviolet radiation (UVI)	Calibrated ultraviolet radiation (UVI)	Biometer-measured ultraviolet radiation† (UVI)	Position
08:30	0.5	0.29	0.61	shade
09:00	3.5	2.57	1.15	sun
09:30	4.5	3.14	1.81	sun
10:00	4.5	3.14	2.69	sun
10:30	1.5	1.05	3.56	shade
11:00	6	4.38	4.23	sun
11:30	2	1.33	4.77	shade
12:00	6	4.38	5.19	sun
12:30	6.5	4.66	5.22	sun
13:00	0.5	0.29	4.87	inside
13:30	1	0.76	4.31	inside
14:00	4	2.86	3.62	sun
14:30	4	2.86	2.80	sun
15:00	4	2.86	2.00	sun
15:30	3	2.09	1.20	sun

UVI, ultraviolet index
†Measured at the South African Weather Service in Pretoria

Table 3: Ultraviolet radiation values and position of outdoor worker on Day 2 of fieldwork

Time	Handheld-meter-measured ultraviolet radiation (UVI)	Calibrated ultraviolet radiation (UVI)	Biometer-measured ultraviolet radiation† (UVI)	Position
08:30	3	2.09	0.60	sun
09:00	4	2.86	1.14	sun
09:30	5	3.43	1.90	sun
10:00	5.5	3.90	2.75	sun
10:30	0.5	0.29	3.52	sun
11:00	6	4.19	3.96	inside
11:30	6.5	4.66	4.55	sun
12:00	6.5	4.66	4.83	sun
12:30	6.5	4.66	4.73	sun
13:00	0.5	0.26	4.59	inside
13:30	0	0	3.84	inside
14:00	5	3.62	3.67	sun
14:30	4	2.86	2.83	sun
15:00	4	2.86	2.00	sun
15:30	3	2.09	1.26	sun

UVI, ultraviolet index
†Measured at the South African Weather Service in Pretoria

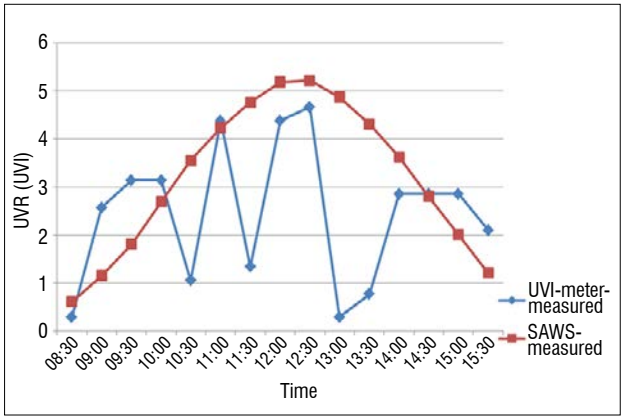

Figure 1: Solar ultraviolet radiation (UVR) on Day 1 measured as an ultraviolet index (UVI) by a handheld device on site and a biometer at the South African Weather Service (SAWS).

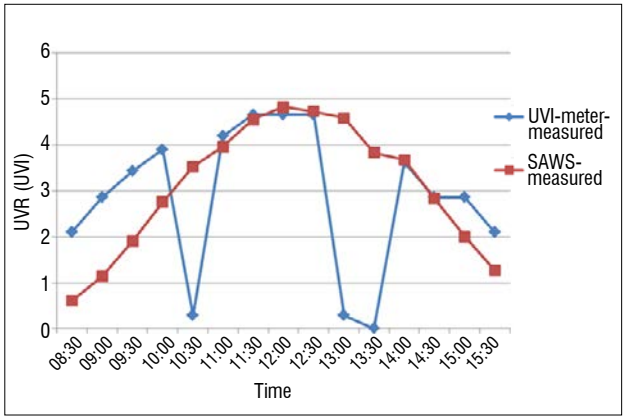

Figure 2: Solar ultraviolet radiation (UVR) on Day 2 measured as an ultraviolet index (UVI) by a handheld device on site and a biometer at the South African Weather Service (SAWS).

On both days the outdoor worker was dressed in long, royal-blue overall trousers. On both days, for the first half of the morning, i.e. from 08:30 to 10:30, the outdoor worker dressed in a royal-blue, long-sleeved overall jacket. From 10:30 until the end of his working day at 15:30, he wore a short-sleeved, navy-blue T-shirt. It is unknown whether the change from a long-sleeved to a short-sleeved shirt was his personal preference or employer-led. For the entire duration of his working day he wore a peak cap. He did not wear sunglasses at any stage. The outdoor worker's arms were therefore protected in the early hours of his working day, but were exposed for 4 h during the late morning and afternoon (except during the 1-h lunch break between 12:30 and 13:30, which he spent inside). The peak cap provided protection for his face and eyes throughout the working day, but did not shield his neck and ears.

The activities that the outdoor worker undertook on Day 1 included sweeping and tending to bushes and shrubs. These activities led to his face being bent downwards, and less exposed, for the majority of the time; however, when these activities took place in the sun, his neck and ears were more exposed. A large amount of cumulative time was also spent walking from one area to the next (as he works within a very large area). On Day 2, he spent almost his entire working day in the middle of a field (away from possible shade), thus causing his arms, neck and ears to be exposed to direct solar UVR.

There are limitations to studies involving outdoor workers. Study observation of this nature is labour intensive and difficult when numerous participants are to be observed. Self-report diaries may be used by workers to provide these data, but researchers must still verify these reports.

There are restrictions to measures for the amelioration of excess sun exposure among outdoor workers, for example, required use of specific personal protective equipment such as goggles that may or may not have UV-protective tinting. Workers may also be forced to work in full-sun conditions because of the nature of the work, thereby making practical suggestions for sun protection constrained by the workplace and nature of activities. Many of these factors may be overcome when a consultative process for addressing the problem includes the employer, employee and the Safety, Health and Environmental Quality officer, and practical, acceptable solutions are sought. Mechanisms for sun protection among outdoor workers include sunscreen; long-sleeve, cool shirts (of appropriate fabric); wide-brimmed hats or construction hard hats with a flap; and sunglasses.

A calculation was done to determine the percentage of the measured ground-based solar UVR that the UVI meters measured during the study period. It was found that 76.29% and 91.92% of the SAWS-measured solar UVR was measured by the UVI meters on Day 1 and Day 2, respectively. A higher percentage was recorded for Day 2 because, as previously mentioned, the outdoor worker spent more time in the sun on Day 2 than on Day 1. The average of these two percentages is 84.11% and can be considered the static risk of overexposure for an outdoor worker. This value was then applied to the SAWS-measured solar UVR measurements for the year 2012. There is, however, a possibility that this value is overestimated because of the possible overestimation of UVI measurements by the UVI meter. Figure 3 shows the amount of solar UVR that an outdoor worker would be exposed to in 2012 based on the static risk that was calculated above.

Figure 3 also shows the difference in the risk of sunburn for outdoor workers with different skin types in 2012. It can be seen that outdoor workers, regardless of skin type, would have been at risk of sunburn on several days in 2012. This result of 84.11% is much higher than the proposed 20% that was applied in the study by Wright et al.[1] There have been several studies in which the personal exposure risk of outdoor workers was investigated. Larko and Diffey[24] found that an outdoor worker was at risk of being exposed to between 10% and 70% of the ambient solar UVR depending on the amount of time spent outside. Another study conducted by Holman et al.[30] found that some outdoor workers were exposed to 44.85% of ambient solar UVR and also that different parts of the outdoor worker's body were exposed to different levels of solar UVR.[25,30,31] These results are within the range of our findings in the current study.

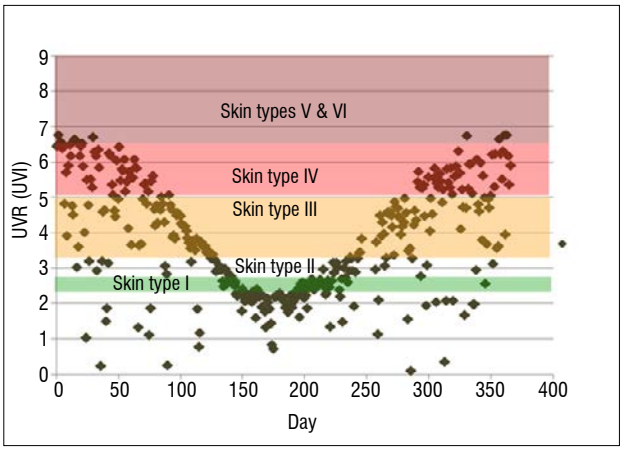

Figure 3: Sunburn thresholds over Pretoria in 2012 for various skin types using 84.11% of the solar ultraviolet radiation (UVR) measured as an ultraviolet index (UVI).

Meteorological factors

The results of the non-linear regression analysis are summarised in Table 4. All of the R^2-values are low, indicating weak correlations, which could be attributed to the fact that many meteorological factors, other than those considered in the current study, play a part in attenuating solar UVR. For all seasons, excluding summer, SZA was found to have the strongest relationship with solar UVR reaching the ground. This finding was also true for the entire year in general, which means that, of all the factors considered, sun position had the greatest effect on the amount of solar UVR that reached the ground in Pretoria in 2012. In agreement with our findings, in a study conducted in Norway, it was found that, between 1995 and 2007, the greatest seasonal UVR-controlling factor was sun position.[32] In summer, the strongest relationship with solar UVR reaching the ground was found with cloud cover. The number of days on which Pretoria had 5 or more octas of cloud cover were examined for each season. Of all the seasons in 2012, Pretoria experienced the most days with 5 or more octas of cloud cover in summer, also suggesting that cloud cover could be a major influencer in summer. This result is supported by the climatology. Typically, in summer over the northeastern interior of South Africa, synoptic conditions are favourable for cloud formation and rainfall, whereas, in winter, the presence of a strong continental anticyclone causes cloud-supressing subsidence. Therefore, there is more cloud cover during summer than during winter in Pretoria.[33]

Table 4: R^2-values for the relationships between solar ultraviolet radiation and cloud cover, total column ozone and solar zenith angle for each season of 2012 and for the entire year

2012	Cloud cover	Ozone	Solar zenith angle
All year	0.2581	0.0517	0.567
Autumn (March, April, May)	0.3294	0.0864	0.6347
Winter (June, July, August)	0.436	0.1257	0.6458
Spring (September, October, November)	0.2871	0.2502	0.4587
Summer (December, January, February)	0.3439	0.121	0.1028

It is shown in Figure 4 that solar UVR is distributed in an envelope shape, in which higher values were recorded in the summer months (December, January and February) and lower values were recorded in the winter

months (June, July and August). The SZA measurements have a bell-shaped distribution in which the lowest angles occurred in the summer months and the highest angles occurred in the winter months. These findings correspond to literature reports about the annual distribution of SZA measurements.[7] Figure 4 therefore shows that, overall, an increase in SZA is associated with a decrease in solar UVR and a decrease in SZA is associated with an increase in solar UVR at the ground. In terms of this study, lower SZA values are likely to lead to a higher dynamic risk of overexposure to solar UVR as more solar UVR reaches the ground. Therefore, of cloud cover, total column ozone and SZA, SZA is the meteorological factor that is likely to increase the dynamic risk of overexposure in all seasons except summer. Figure 4 also shows that solar UVR is strongly bounded in the upper limits, similarly to the distribution of SZA measurements.

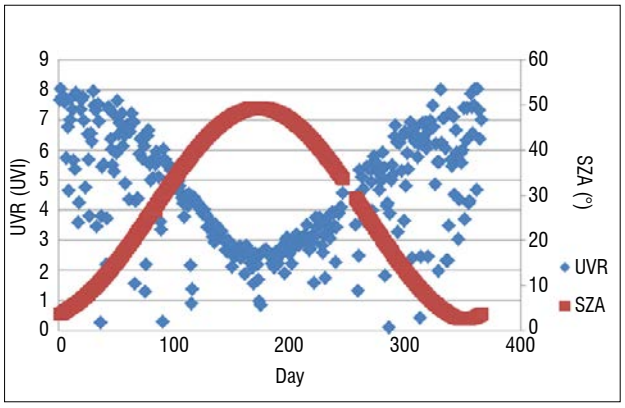

Figure 4: Distribution of solar ultraviolet radiation (UVR) and solar zenith angle (SZA) over Pretoria for the year 2012.

Figure 5 shows that ozone does not vary significantly during the year. This is also reflected in the results of the regression analysis. Research has shown that sites at lower latitudes have a small annual variation in total column ozone, while sites at high latitudes have a large annual variation in total column ozone.[32] In Oslo, Norway, which is at latitude 59° 57'N, ranges of over 250 DU between the highest and the lowest measured ozone values have been measured.[32] In the year 2012, the range between the highest and the lowest measured total column ozone values over Pretoria (which is at latitude 25° 45'S) was 75.832 DU, thus showing relatively small annual variation. That being said, the relationship between solar UVR and total column ozone for spring was the strongest of all the seasons; this finding is to be expected as relatively higher values of ozone over South Africa are expected to occur during spring.

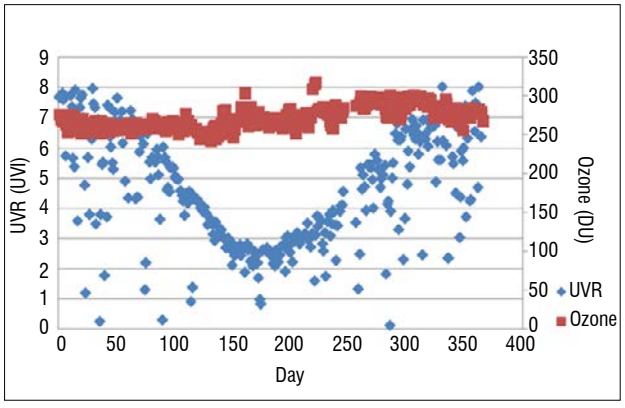

Figure 5: Distribution of solar ultraviolet radiation (UVR) and ozone over Pretoria for the year 2012.

From Figure 6 it can be seen that the shape of the distributions for the satellite-measured solar UVR and the ground-based solar UVR are very similar; on both occasions, higher values are generally observed in the summer months and lower values are seen in the winter months. However, the satellite-based values are larger than the ground-based measurements. A RMSE of 5.287 UVI was found over the whole year for the 12:00 values, which means that on average there was a difference of 5.287 UVI between the satellite-based and ground-based measurements. This large difference between the two measurements could be an indication of the strength of attenuation by the various meteorological factors. However, because change in cloud cover is not taken into account in the algorithm of the satellite values, the attenuating meteorological factor is most likely to be cloud cover. Validations between satellite-based and reference ground-based measurements done in various studies have found that, on average, the satellite overestimates the UVR by 0–30%.[34] It can also be seen in Figure 6 that there seems to be a larger difference between ground-based and satellite-based solar UVR in the summer portion rather than the winter portion of the year. Because cloud cover was found to have the strongest relationship with solar UVR in summer, this observation further substantiates the likelihood that cloud cover was the attenuating factor.

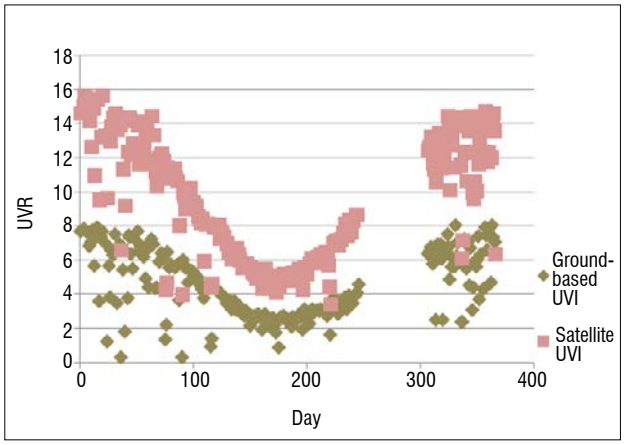

Figure 6: Satellite-based and ground-based measurements of solar ultraviolet radiation (UVR) measured as an ultraviolet index (UVI) over Pretoria for 2012.

Conclusion

In South Africa, outdoor workers may be potentially exposed to up to 84.11% of the total solar UVR that reaches the ground. Based on this figure, and considering ambient solar UVR levels measured during 2012, outdoor workers with any skin type would be at risk of sunburn on many days of the year, including during winter months. Those workers with skin types IV–VI would have greater natural protection compared with workers with skin types I–III; however, ocular exposure and the risk of cataracts and other sun exposure related eye diseases remain a concern if adequate sun protection is not used.

Each of the meteorological factors examined did reduce the amount of solar UVR reaching the ground over Pretoria and certain factors had a stronger influence in different seasons. Sun position was the main meteorological factor of the three factors considered in this study that influenced the amount of solar UVR that reached the ground overall in 2012. Cloud cover was an important meteorological factor in summer. Total column ozone did not show a noteworthy relationship with solar UVR. There was an average difference of 5.287 UVI between satellite-based and ground-based solar UVR measurements in 2012, which is likely a consequence of cloud cover attenuation.

The static risk of exposure showed that it is possible for an outdoor worker to be exposed to over 80% of the ambient solar UVR, and the dynamic risk showed that SZA and cloud cover influence the actual amount of solar UVR an outdoor worker is exposed to. Measuring the amount of solar UVR that outdoor workers may be exposed to may help in the development of sun-protective and skin cancer prevention campaigns for outdoor workers specifically; this awareness is important as outdoor workers have been identified as a susceptible group. Some

study limitations do exist when working with outdoor workers, as the nature of their work makes certain sun-protective measures impractical. However, by consulting with the employer, employee and Safety, Health and Environmental Quality officer, practical solutions can be found, which may include the use of sunscreen, long-sleeve cool shirts, wide-brimmed hats or construction hard hats with a flap and sunglasses. The results of this case study suggest that further, more comprehensive research is needed to measure a large sample of outdoor workers in different geographical areas in South Africa to best inform policy development and decision-making for occupational health. Research using electronic solar UVR dosimeters is underway.

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Authors' contributions

M.M. conducted the case study, analysed the data and wrote part of the article. C.Y.W. conceived the core concept of the project, provided the instruments for the case study, acquired the data and wrote part of the article.

References

1. Wright CY, Coetzee G, Ncongwane K. Seasonal trends in potential sunburn risk among outdoor workers in South Africa using monitored ambient solar UV radiation levels. Occ Health Southern Africa. 2011;17(6):22–29.
2. Norval M, Kellet P, Wright CY. The incidence and body site of skin cancers in the population groups of South Africa. Photoderm Photoimmunol Photomed. 2014;30(5):262–265.
3. IARC. Solar and ultraviolet radiation. IARC Monograph Eval Carcinog Risk Chem Hum. 2012;100D:35–102.
4. International Commission on Illumination (CIE). The measurement of absolute luminous intensity distributions. Vienna: CIE; 1987.
5. Lucas R, McMichael T, Smith W, Armstrong B. Solar ultraviolet radiation: Global burden of disease from solar ultraviolet radiation. Environmental Burden of Disease Series No. 13. Geneva: World Health Organization (WHO); 2006.
6. Engelsen O. The relationship between ultraviolet radiation exposure and vitamin D status. Nutrients. 2010;2:482–495. http://dx.doi.org/10.3390/nu2050482
7. Diffey BL. Sources and measurement of ultraviolet radiation. Meth.. 2002;28:4–13. http://dx.doi.org/10.1016/S1046-2023(02)00204-9
8. McKenzie EL, Mattheus WA, Johnson RV. The relationship between erythemal UV and ozone, derived from spectral irradiance measurements. Geophys Res Lett. 1991;18:2269–2272. http://dx.doi.org/10.1029/91GL02786
9. Efstathiou M, Varotsos C, Kondratyev KY. An estimation of the surface solar ultraviolet irradiance during an extreme total ozone minimum. Meteorol Atmos Phys. 1998;68:171–176. http://dx.doi.org/10.1007/BF01030208
10. Hester RE, Harrison RM, Webb AR. Ozone depletion and changes in environmental UV-B radiation. In: Issues in environmental science and technology: Causes and environmental implications of increased UV-B radiation. No. 14. Cambridge: The Royal Society of Chemistry; 2000. p. 17–36.
11. Fishman J, Watson CE, Larsen JC. The distribution of total ozone, stratospheric ozone, and tropospheric ozone at low latitudes deduced from satellite data sets. Presented at: Workshop on Tropospheric Ozone; Quadrennial Ozone Symposium; 1988 Aug 4–13; Göttingen, Germany.
12. Fishman J, Brackett VG, Fakhruzzaman K. Distribution of tropospheric ozone in the tropics from satellite and ozonesonde measurements. J Atmos Terr Phys. 1992;54(5):589–597. http://dx.doi.org/10.1016/0021-9169(92)90099-7
13. Salby ML, Garcia RR. Dynamic perturbations to the ozone layer. Phys Today. 1990;March:38–46. http://dx.doi.org/10.1063/1.881228
14. Diab RD, Barsby J, Bodeker GE, Scourfield M, Salter L. Satellite observations of total ozone above South Africa. S Afr Geog J. 1992;74:13–18. http://dx.doi.org/10.1080/03736245.1992.10586389
15. Fredrick JE, Snell HE. Tropospheric influence on solar UV radiation: The role of clouds. J Climate. 1990;3:373–381. http://dx.doi.org/10.1175/1520-0442(1990)003<0373:TIOSUR>2.0.CO;2
16. Estupi-án JG, Ramen S, Crescenti GH, Streicher JJ, Barnard WF. Effects of cloud and haze on UV-B radiation. J Geophys Res. 1996;101:16807–16816. http://dx.doi.org/10.1029/96JD01170
17. Cutchis P. A formula for comparing annual damaging ultraviolet (DUV) radiation doses at tropical and mid-latitude sites. Federal Aviation Administration Report FAA-EE 80-81. Washington DC: US Department of Transport; 1980.
18. Wright CY. Ultraviolet radiation exposure of NZ schoolchildren [thesis]. Durban: University of KwaZulu-Natal; 2006.
19. Diffey BL. Solar ultraviolet radiation effects on biological systems. Phys Med Biol. 1991;36(3):299–328. http://dx.doi.org/10.1088/0031-9155/36/3/001
20. Fitzpatrick TB. Soleil et peau [Sun and skin]. J Med Esthet. 1975;2:33–34. French.
21. Fitzpatrick TB. Skin phototypes: Evolution and present status. Paper presented at: 29th Annual Meeting of the American Society of Photobiology; 2001 July 7–12; Chicago, USA.
22. National Radiological Protection Board (NRPB). Health effects from ultraviolet radiation. Report of an advisory group on non-ionising radiation. Chilton, UK: NRPB; 2002.
23. Kimlin MG, Tenkate TD. Occupational exposure to ultraviolet radiation: The duality dilemma. Reviews on Environmental Health. 2007;22(1):1–37. http://dx.doi.org/10.1515/REVEH.2007.22.1.1
24. Larko O, Diffey BL. Natural UV-B radiation received by people with outdoor, indoor, and mixed occupations and UV-B treatment of psoriasis. Clin Exp Dermatol. 1983;8:279–285. http://dx.doi.org/10.1111/j.1365-2230.1983.tb01780.x
25. Reeder AI, Gray A, McCool JP. Occupational sun protection: Workplace culture, equipment provision and outdoor workers' characteristics. J Occup Health. 2013;55(2):84–97. http://dx.doi.org/10.1539/joh.12-0182-OA
26. McCool JP, Reeder AI, Robinson EM, Petrie KJ, Gorman DF. Non-melanoma skin cancer: Outdoor workers' perceptions of risk and sun-protection use. Wellington: Cancer Society of New Zealand; 2004.
27. Dobbinson S, Doyle C, Wakefield M. Farmers' and outdoor workers' beliefs about skin cancer and protection from summer sun: A brief report. CBRC Research Paper Series No. 18. Melbourne: Centre for Behavioural Research in Cancer, Cancer Control Research Institute, Cancer Council Victoria; 2005.
28. McCool JP, Reeder AI, Robinson EM, Petrie KJ, Gorman DF. Outdoor workers' perceptions of the risks of excess sun-exposure. J Occup Health. 2009;51:404–411. http://dx.doi.org/10.1539/joh.L9030
29. Wright CY, Albers PN. Comparison of two personal ultraviolet index monitors for sun awareness in South Africa. S Afr J Sci. 2013;109(1/2):88–91. http://dx.doi.org/10.1590/sajs.2013/0014
30. Holman CDJ, Gibson IM, Stephenson M, Armstrong BK. Ultraviolet irradiation of human body sites in relation to occupation and outdoor activity: Field studies using personal UVR dosimeters. Clin Exp Dermatol. 1983;8:269–277. http://dx.doi.org/10.1111/j.1365-2230.1983.tb01779.x
31. Gies P, Wright J. Measured solar ultraviolet radiation exposures of outdoor workers in Queensland in the building and construction industry. J Photochem Photobiol. 2003;78(4):342–348. http://dx.doi.org/10.1562/0031-8655(2003)078<0342:MSUREO>2.0.CO;2
32. Dahlback A, Bjertness E, editors. Global monitoring of atmospheric ozone and solar UV radiation. Solar Radiation and Human Health. Oslo: The Norwegian Academy of Science and Letters; 2008. p. 23–34.
33. Tyson PD, Preston-Whyte RA. The weather and climate of southern Africa. 2nd ed. Cape Town: Oxford University Press; 2000.
34. OMI Team. Ozone monitoring instrument (OMI) data user's guide. Washington DC: NASA; 2012.

Characteristics of potential gasifier fuels in selected regions of the Lake Victoria Basin

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All countries in the Lake Victoria Basin depend mostly on hydroelectric power for the provision of energy. Gasification technology has a high potential for reducing biomass energy consumption whilst increasing access to modern energy services. The key aspect for the failure of gasification operations in the Lake Victoria Basin is inadequate adaptation of gasification equipment to fuel characteristics, lack of fuel specification and inappropriate material choice. We therefore investigated the thermo-chemical characterisation of six biomass fuels, namely *Pinus caribaea*, *Calitris robusta*, *Cupressus lusitanica*, *Eucalyptus grandis, Pinus patula* and sugarcane bagasse from selected regions of the Lake Victoria Basin. Ultimate analysis was done using a Flash 2000 elemental analyser. Moisture content, ash content and volatile matter were determined in oven and muffle furnaces while heating values were determined using a Gallenkamp calorimeter. The mean percentage levels obtained indicate that all six biomass fuels had a mean range for nitrogen of 0.07±0.2–0.25±0.07%, for carbon of 40.45±0.61–48.88±0.29%, for hydrogen of 4.32±0.13–5.59±0.18% and for oxygen of 43.41±1.58–51.1±0.64%. Moisture content ranged between 25.74±1.54% and 56.69±0.52%, ash content between 0.38±0.02% and 2.94±0.14%, volatile matter between 74.68±0.49% and 82.71±0.19% and fixed carbon between 14.35±0.33% and 24.74±0.27%. Heating values ranged between 16.95±0.10 MJ/kg and 19.48±0.42 MJ/kg. The results suggest that all six biomass fuels are potential biomass gasification materials.

Introduction

Modern energy, such as electricity, is crucial in order to achieve the Millennium Development Goals of poverty reduction, improved education and environmental sustainability.[1] Currently, about one-third of the world's population, or two billion people, have only intermittent access to modern energy services. The energy sector in the Lake Victoria Basin is dominated by traditional biomass-based fuels, which contribute over 70% to the total energy consumption.[2,3] As a result of the use of poor technology (e.g. three stones and charcoal stoves), many regard biomass energy as inferior. Women and children inhale fumes while cooking indoors and spend considerable time collecting firewood.[2,4,5] Hydroelectric power and energy from petroleum products is prohibitively expensive and mostly restricted to urban areas. In order to alleviate poverty in the Lake Victoria Basin, the rural-based households (over 80%) will need access to modern energy services.[2]

Biomass in the form of trees, shrubs, agro and forest wastes, grasses and vegetables is abundant in the Lake Victoria Basin and is renewable. Fortunately, the basin is located on the equator and as a result of this proximity receives an abundant insolation averaging 4.5 kWh/m^2/day.[6] This insolation provides the necessary conducive environment for vast growth of biomass. What is really required to increase rural household energy security is to catalyse rural industrialisation. Biomass gasification for energy production is one such system.[7,8] Gasification technology involves incomplete combustion of biomass resulting in the production of combustible gases consisting of carbon monoxide, hydrogen and traces of methane.[8-12] Gasification is the most efficient way known to date of converting biomass into energy; it converts 60–90% of the energy in the biomass into energy in the gas, compared to traditional systems which utilise 10–30%.[13,14]

Method and materials

Study area

Biomass samples were obtained from the forests located in the Lake Victoria Basin in Kenya and Uganda. In Kenya, eight regions were chosen: Malava Forest in Kakamega County, Kibiri Block Forest in Vihiga County, Ombo Forest in Migori County, Kodera Forest in Rachuonyo County, Kakamega Forest in Kakamega County, Port Victoria natural forest in Busia County, Aloso Block Forest in Migori County and Sony Sugar Company in Migori County. In Uganda, samples were obtained from the Wakiso District. These forests were purposely selected because they are managed by forest services in both Kenya and Uganda.

Sampling procedure and collection

Breast-height (1.3 m from the ground) stem wood samples were collected from each species. *Cupressus lusitanica* was collected from Kakamega, Ombo, Kodera and Port Victoria Forests, *Pinus patula* was collected from Kibiri and Kodera Forests, *Pinus caribaea* from Kodera (Kenya) and Wakiso (Uganda) Forests, *Calitris robusta* from Aloso Forest and *Eucalyptus grandis* from Wakiso Forest. The samples were cut into small wood chips. Sugarcane bagasse was collected from the Sony Sugar Company and was sampled from the top, middle and bottom of the heap of sugarcane bagasse. The sugarcane bagasse samples were subsequently placed in three 50-kg gunny sacks and transported for analysis.

Determination of moisture content

Moisture content was determined in accordance with ASTM Standard D3173-87.[15] Nine replicates were obtained from each biomass sample. The sample was placed in a convection oven at 105±3 °C for 4 h, removed and cooled to room temperature in desiccators with P_2O_5 as the drying agent. The dish containing the oven-dried sample was weighed and the weight recorded. The sample was placed back into the convection oven at 105±3 °C and dried to constant weight. Percentage weight loss was taken as the moisture content of the original sample.

Ash determination

Ash determination was done in accordance with ASTM Standard D3174-97.[16] The nine dried samples (10 g) were placed into crucibles and placed in a furnace set to 575±25 °C for 4 h, after which the crucibles containing the samples were removed and cooled in desiccators. The weight of the crucible and the sample was then recorded to the nearest 0.1 mg. The ash content (%) was calculated as:

$$\text{Ash} = \frac{W_3 - W_1}{W_2 - W_1} \times 100 \qquad \text{Equation 1}$$

where W_1 is the mass of the empty dry crucible, W_2 is the mass of the dry crucible plus the dry sample of biomass and W_3 is the mass of the dry crucible plus the cooled greyish-white ash.

Volatile matter determination

Determination of volatile matter content was done in accordance with ASTM standards.[17] Approximately 10 g of the dried sample was weighed into crucibles with a closely fitting cover and placed into a muffle furnace maintained at 950±20 °C. After 7 min of heating, the crucibles were removed, cooled in desiccators and weighed. Nine samples of each feedstock were used. Volatile matter (%) was calculated as:

$$\text{Volatile matter} = 100 \times (I - F)/I, \qquad \text{Equation 2}$$

where I is the initial weight of the sample (g) and F is the final weight of the sample (g).

Calculation of percentage fixed carbon

Fixed carbon was calculated using the volatile matter and ash amount according to McKendry[18] as follows:

$$\%\ \text{FC} = 100 - (\%\ \text{VM} + \%\ \text{ash}), \qquad \text{Equation 3}$$

where FC is the fixed carbon and VM is volatile matter.

Energy content

The energy content was determined in accordance with ASTM Standard D2015-96.[19] A Gallenkamp auto bomb calorimeter (model number SG97/10/070, Fistreem International Limited, Leicestershire, UK) was used.

Higher heating values derived from theoretical equations

Equations 4–6 were used to estimate the higher heating values (HHV) of the biomass samples and the results were compared with the experimental values.

$$\text{HHV} = 0.196 \times \text{FC} + 14.119 \qquad \text{Equation 4}[20]$$

$$\text{HHV} = 0.4373 \times \text{C} - 1.6701 \qquad \text{Equation 5}[21]$$

$$\text{HHV} = -0.763 + 0.301 \times \text{C} + 0.525 \times \text{H} + 0.064 \times \text{O} \qquad \text{Equation 6}[22]$$

Ultimate analysis

The carbon, nitrogen and hydrogen contents were determined using a Flash 2000 elemental analyser (model number 31712052, Thermo Fisher Scientific, Delft, the Netherlands) according to ASTM Standard E775.[23]

Calculations for synthesis gas composition

Equations 7–9 developed by Gopal[24] were used to predict the percentage volume of CO, CO_2, and H_2:

Data analysis

Data were subjected to statistical analyses including a one-way analysis of variance (ANOVA) and Student-Newman-Keuls (SNK) test. These methods are useful in providing interdependence of the variables and significant differences.[25]

Results and discussion

Proximate analysis

A summary of the proximate analysis is presented in Table 1.

Table 1 shows that the moisture contents of the six biomass samples were significantly different ($p<0.05$, SNK test). The moisture content of wood typically varies between 10% and 60% while that of sugarcane bagasse ranges between 40% and 60%.[26,27] In this study, the moisture contents of *Pinus caribaea, Calitris robusta, Cupressus lusitanica, Eucalyptus grandis* and *Pinus patula* were in the range of 10–60%. The moisture content of sugarcane bagasse was in the range of 40–60%. Brammer and Bridgewater[28] reported that a moisture content of up to 20% and 50% is acceptable for downdraught and updraught gasifiers,

Table 1: Proximate analysis of the biomass fuels

Fuel type	% Moisture	% Ash content	% Volatile matter	% Fixed carbon
Pinus caribaea	56.69±0.32^{d}	0.38±0.02^{a}	76.98±0.61^{b}	22.64±0.63^{d}
Calitris robusta	48.64±0.28^{c}	0.54±0.02^{a}	78.79±0.61^{b}	20.67±0.63^{b}
Cupressus lusitanica	39.11±3.24^{b}	0.58±0.05^{a}	74.68±0.49^{a}	24.74±0.54^{e}
Eucalyptus grandis	48.59±0.43^{c}	0.42±0.02^{a}	78.24±0.25^{b}	21.34±0.27^{bc}
Pinus patula	25.74±1.54^{a}	0.39±0.05^{a}	77.57±0.23^{b}	22.04±0.28^{cd}
Sugarcane bagasse	36.47±0.32^{b}	2.94±0.14^{b}	77.57±0.23^{b}	14.35±0.33^{a}
p-value	< 0.0001	< 0.0001	< 0.0001	<0.001

Values shown are mean±s.e., n=9.

Mean values followed by the same small letter(s) within the same column are not significantly different from one another (one-way ANOVA, SNK test, α=0.05).

respectively, whereas fluidised bed gasifiers have been reported to gasify materials with moisture contents of up to 70%.[29]

Sugarcane bagasse showed significantly higher levels of ash compared with *Pinus caribaea, Calitris robusta, Cupressus lusitanica, Eucalyptus grandis* and *Pinus patula*. All six biomass feedstocks qualified for use in biomass gasification as they had an ash content less than 5%.[30] All the biomass feedstocks investigated can be used in downdraught gasifiers as they contained less than 6% ash[31,32] and sugarcane bagasse can be used in updraught gasifiers as the minimum ash content was 1.4% and the maximum was 25%.[31,32]

Sugarcane bagasse had a higher percentage mean of volatile matter than did *Cupressus lusitanica*. The percentage of volatile matter of *Pinus caribaea, Calitris robusta, Eucalyptus grandis* and *Pinus patula* did not differ significantly from one another ($p>0.05$, SNK test). Woods typically have a volatile matter of 72–78%.[33,34]

Cupressus lusitanica had a higher fixed carbon content than sugarcane bagasse. Sugarcane bagasse had the lowest fixed carbon content. The fixed carbon contents of *Pinus caribaea* and *Pinus patula* did not differ statistically ($p>0.05$, SNK test). According to McKendry[18], wood has a fixed carbon content of about 20%. Anjireddy and Sastry[35] showed that sugarcane bagasse had a fixed carbon content of 15.8%.

Ultimate analysis

A summary of the ultimate analyses is presented in Table 2.

Table 2 shows the percentage weight of nitrogen of the six biomass feedstocks; the mean percentages of nitrogen did not differ significantly ($p>0.05$, SNK test). According to Jenkins et al.[36], all biomass material contains 0.2–1% nitrogen. To avoid corrosion and emission of NO_x to the atmosphere during combustion, according to Obernberger et al.[37], all biomass material must contain less than 0.6% nitrogen. Our six biomass samples contained less than 0.6% nitrogen, which qualifies them as suitable feedstock for gasification processes.

There was a significant difference in the percentage weight of carbon among the six biomass fuels ($p<0.05$, SNK test). The percentage mean carbon contents of *Cupressus lusitanica*, *Calitris robusta* and *Pinus patula* were significantly higher than that of sugarcane bagasse. According to Demirbas[13] and BTG[38], the carbon content of typical biomass must range from 42% to 54%. The six biomass fuels were within this range.

Table 2 shows the percentage weight of hydrogen of the six biomass samples. The hydrogen contents of *Pinus caribaea*, *Calitris robusta*, *Cupressus lusitanica*, *Eucalyptus grandis* and *Pinus patula* were not significantly different from one another, but sugarcane bagasse had a significantly lower percentage of hydrogen ($p<0.05$, SNK test).

Turn et al.[39] reported 4.98% hydrogen for bagasse and Cheremisnoff[40] found that typical woods have about 6% hydrogen. BTG[38] reported hydrogen in the range of 5.5–6.2%. These reports are in agreement with our results.

The mean percentage oxygen of *Pinus caribaea, Eucalyptus grandis* and sugarcane bagasse were significantly higher than that of *Pinus patula* ($p<0.05$, SNK test; Table 2). The mean percentage oxygen of *Calitris robusta* and *Cupressus lusitanica* was not significantly different ($p>0.05$, SNK test). Raveendran et al.[41] reported an oxygen percentage

Table 2: Ultimate analysis of the biomass fuels

Fuel type	% Nitrogen	% Carbon	% Hydrogen	% Oxygen
Pinus caribaea	0.25±0.07	45.57±0.26	5.44±0.22^{b}	48.36±0.35^{c}
Calitris robusta	0.18±0.01	47.26±0.21^{bc}	5.56±0.17^{b}	46.46±0.27^{b}
Cupressus lusitanica	0.07±0.02	48.88±0.29^{c}	5.17±0.34^{b}	45.46±0.45^{b}
Eucalyptus grandis	0.17±0.02	45.50±0.35^{b}	5.55±0.13^{b}	48.39±0.37^{c}
Pinus patula	0.22±0.04	47.84±1.57^{bc}	5.59±0.18^{b}	43.41±1.58^{a}
Sugarcane bagasse	0.23±0.04	40.45±0.61^{a}	4.32±0.13^{a}	51.1±0.64^{c}
p-value	< 0.056	< 0.0001	< 0.0003	< 0.001

Values shown are mean±s.e., n=*9.*
Mean values followed by the same small letter(s) within the same column are not significantly different from one another (one-way ANOVA, SNK test, α=0.05).

Table 3: The energy content of the biomass fuels

Fuel type	Measured heat value (MJ/kg)	Predicted higher heating value (MJ/kg)		
		Demirbas[20]	Tilman[21]	Jenkins and Ebeling[22]
Pinus caribaea	18.61±0.12^{b}	18.56±0.52^{b}	18.26±0.11^{b}	18.93±0.12^{b}
Calitris robusta	18.39±0.08^{b}	18.17±0.55^{b}	18.99±0.09^{c}	19.39±0.11^{b}
Cupressus lusitanica	17.44±0.04^{a}	18.97±0.41^{b}	19.70±0.13^{c}	19.60±0.16^{b}
Eucalyptus grandis	19.13±0.13^{c}	18.30±0.23^{b}	18.23±0.15^{c}	18.97±0.09^{b}
Pinus patula	19.48±0.42^{c}	18.44±0.23^{b}	19.25±0.69^{c}	19.54±0.41^{b}
Sugarcane bagasse	16.95±0.10^{a}	16.93±0.39^{a}	16.02±0.26^{a}	17.20±0.17^{a}
p-value	< 0.0001	< 0.001	< 0.001	< 0.001

Values shown are mean±s.e., n=*9.*
Mean values followed by the same small letter(s) within the same column are not significantly different from one another (one-way ANOVA, SNK test, α=0.05).

of 47.1%, which is similar to our results. BTG[38] showed that typical biomass materials have an oxygen percentage of 40–51%. The results from this study therefore are in agreement with those of previous studies.

Heating values

The energy content of the biomass feedstocks is presented in Table 3.

Table 3 shows a significant difference in the energy contents of the six biomass fuels ($p<0.05$, SNK test). *Pinus patula* and *Cupressus lusitanica* had higher energy contents than *Eucalyptus grandis* and sugarcane bagasse. The energy contents of *Pinus caribaea* and *Calitris robusta* did not differ significantly. Nonde[42] reported heating values of wood fuels of between 18 MJ/kg and 20 MJ/kg. Howlett and Gamache[43] also reported values of 17.7–21.0 MJ/kg for foliage materials. These values are within the range of our results. The measured heating values were also in agreement with the predicted values. The heating value determines the suitability of biomass for pyrolysis, carbonisation, liquefaction and gasification. The heating value is a function of the chemical composition, in particular, the carbon content. Variation in the heating values among different species and different plant components shows differences in the chemical composition, which is used to demonstrate the quality of the fuel.

Predicted synthesis gas

The predicted synthesis gas composition is presented in Table 4.

The predicted synthesis gas composition from the gasification of *Eucalyptus grandis* was 16.52±0.43% H_2 and 25.13±0.65% CO. These values were slightly higher than those reported by Gopal[24] who found 16.1% H_2 and 24.0% CO. For sugarcane bagasse, the predicted composition was 15.04±0.54% H_2 and 24.47±0.88% CO, which is similar to those reported by Gopal[24] who found 15.4% H_2 and 23.4% CO. The Energy and Resources Institute[44] found that typical biomass produces 18–22% CO and 13–19% H_2. Sharma[45] concluded that feedstocks which produced 15% CO and 13% H_2 were considered acceptable for gasification.

Table 5 gives a comparison of selected properties of the selected biomass feedstocks in the Lake Victoria region.

Cupressus lusitanica from the Ombo Forest had a higher moisture content than that from the Kodera Forest ($p<0.05$, *t*-test). *Pinus patula* from the Kodera Forest had a higher moisture content than that from the Kibiri Forest. *Cupressus lusitanica* from the Kakamega Forest had a significantly higher percentage of nitrogen than that from the Kodera, Ombo and Port Victoria Forests ($p<0.05$, SNK test). There was no significant difference in the percentage of nitrogen in *Pinus caribaea* from the Kodera and Wakiso Forests ($p>0.05$, *t*-test). This variation in the percentage of nitrogen among the regions and species is mainly because of differences in environmental factors, nutrients and water.[46]

There also were significant differences in the percentage of carbon in *Cupressus lusitanica* ($p<0.04$, SNK test). The percentage of carbon in *Cupressus lusitanica* from the Kakamega, Ombo and Port Victoria

Table 4: The predicted synthesis gas composition of the biomass fuels

Biomass fuel	% CO_2	% H_2	% CO
Pinus caribaea	11.03±0.10	16.42±0.68	25.31±1.05
Calitris robusta	10.42±0.08	16.29±0.51	25.45±0.80
Cupressus lusitanica	9.79±0.11	15.92±1.06	26.66±1.78
Eucalyptus grandis	11.06±0.12	16.52±0.43	25.13±0.65
Pinus patula	10.30±0.51	15.43±0.91	24.39±1.43
Sugarcane bagasse	13.02±0.26	15.04±0.54	24.47±0.88

Values shown are mean±s.e., n=*9.*

Table 5: Comparison of selected properties of the biomass from different regions within the Lake Victoria Basin

Species	Region	% Moisture	% Nitrogen	% Carbon	% Hydrogen
Cupressus lusitanica	Ombo	47.95±0.25	0.05±0.03[a]	49.99±0.39[b]	5.73±0.26[b]
	Kodera	34.69±4.54	0.02±0.01[a]	47.96±0.75[a]	6.56±0.29[b]
	Kakamega		0.16±0.00[b]	49.09±0.16[ab]	4.28±0.33[a]
	Port Victoria		0.04±0.01[a]	48.46±0.00[ab]	4.11±0.49[a]
		***p*=0.01**	***p*=0.01**	***p*=0.048**	***p*=0.003**
Pinus patula	Kibiri	23.20±0.12(0.006)	0.05±0.00	46.81±0.43	5.18±0.31
	Kodera	30.85±2.28	0.31±0.02	45.26±0.23	5.80±0.18
		***p*=0.006**	***p*<0.0001**	***p*=0.283**	***p*=0.111**
Pinus caribaea	Kodera		0.16±0.04	46.81±0.43	5.67±0.09
	Wakiso		0.27±0.08	45.26±0.23	5.38±0.28
			***p*=0.516**	***p*=0.009**	***p*=0.622**

Mean values followed by the same small letter(s) within the same column are not significantly different from one another (one-way ANOVA, SNK test, $\alpha=0.05$).

Forests was significantly higher than that from the Kodera Forest. There was also a significant difference in the percentage of carbon in *Pinus caribaea* from Kodera and Wakiso Forests ($p<0.05$, *t*-test). The differences in the percentage of carbon among different regions can be attributed to soil physiology.[46] The percentage of hydrogen in *Cupressus lusitanica* from Kodera and Ombo Forests was significantly higher than those from Kakamega and Port Victoria Forests ($p<0.05$, SNK test).

Conclusion and recommendations

The six biomass fuels had low ash content, low nitrogen content and high energy content and are therefore suitable for gasification. Significant variations were also observed in the selected thermo-chemical properties of the biomass from different regions within the Lake Victoria Basin. The predicted synthesis gas composition of the biomass fuels was more than 15% CO and 13% H_2. It is recommended that an actual gasification can be carried out to compare the amount of synthesis gas generated with that estimated from the thermodynamic equilibrium model.

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Authors' contributions

G.O.M. wrote the manuscript; C.O.O. was the project leader; P.M., S.B.T., S.B. and R.B.J. collected the samples for analysis.

References

1. Modi V, McDade S, Lallement D, Saghir J. Energy and the Millennium Development Goals. New York: Energy Sector Management Assistance Programme, United Nations Development Programme, UN Millennium Project and World Bank; 2006.
2. East Africa Community (EAC). East Africa Community regional strategy on scaling-up access to modern energy services in the East African Community [document on the Internet]. c2009 [cited 2011 Oct 21]. Available from: http://www.eac.int/energy/index.php?option=com_docman&task=doc_download&gid=14&Itemid=70
3. Ministry for Planning and National Development (MPND). Integrated assessment of the energy policy with focus on the transport and household energy sectors. Nairobi: MPND; 2006.
4. Bailis R, Ezzati M, Kammen DM. Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa. Science. 2005;308:98–103. http://dx.doi.org/10.1126/science.1106881
5. Reddy AKN, Williams RH, Johansson TP. New opportunities in energy demand, supply and systems. In: Amulya K, editor. Energy after Rio – Prospects and challenges. New York: UNDP; 1997. p. 63–108.
6. Ministry of Energy and Mineral Development (MEMD). Energy efficiency and renewable energy directory. 2nd ed. Kampala: MEMD; 2005.
7. Keyun D. State of the art of the utilization of agricultural residues and other biomass and identification of priority projects in China in agricultural biomass for sustainable rural development. Bangkok: ESCAP; 1993.
8. Nouni MR, Mullick SC, Kandpal TC. Biomass gasifier projects for decentralized power supply in India: A financial evaluation. Energ Policy. 2007;35:1373–1385. http://dx.doi.org/10.1016/j.enpol.2006.03.016
9. Ravindranath NH, Somashek HI, Dasappa S, Jaysheela Reddy CN. Sustainable biomass power for rural India: Case study of biomass gasifier for village electrification. Curr Sci India. 2004;87:56–89.
10. Adnan M, Murat D, Colin R, Howarth M, Ling J, Teoman A. Combustible gas production from sewage sludge with a downdraft gasifier. Energ Convers Manage. 2001;42:157–172. http://dx.doi.org/10.1016/S0196-8904(00)00053-4
11. Dasappa S, Paul PJ, Mukunda HS, Rajan NKS, Sridhar G, Sridhar HV. Biomass gasification technology – A route to meet energy needs. Curr Sci India. 2004;87:908–916.
12. Stassen HEM. Small-scale biomass gasifiers for heat and power: A global review. World Bank Technical Paper Series. Washington DC: UNDP ESMAP; 1995. http://dx.doi.org/10.1596/0-8213-3371-2
13. Richey CB. Downdraft channel biomass gasifier. US Patent 4, 452, 611, 1984.
14. Demirbas A. Combustion characteristics of different biomass fuels. Prog Energ Combust. 2004;30:219–230. http://dx.doi.org/10.1016/j.pecs.2003.10.004
15. Reed TB, Das A. Handbook of biomass downdraft gasifier engine systems. Golden, CO: SERI; 1998.
16. American Society for Testing Materials (ASTM). Standard test method for moisture in the analysis sample of coal and coke. Standards D3173-87. In: Annual book of ASTM standards, Section 5, Vol. 05.05. West Conshohocken, PA: ASTM; 1998. p. 301–302.
17. American Society for Testing Materials (ASTM). Standard test method for ash in the analysis sample of coal and coke. Standards D3174-97 In: Annual book of ASTM standards, Section 5, Vol. 05.05. West Conshohocken, PA: ASTM; 1998. p. 303–305.
18. American Society for Testing Materials (ASTM). Standard classification of coal by rank. Standards D388-99. Philadelphia, PA: ASTM; 1999.
19. McKendry P. Energy production from biomass (part 3): Gasification technologies. Bioresour Technol. 2002;83:37–63. http://dx.doi.org/10.1016/S0960-8524(01)00118-3
20. American Society for Testing Materials (ASTM). Standard test method for gross calorific value of coal and coke by the adiabatic bomb calorimeter. Standard D2015-96. In: Annual book of ASTM standards, Section 5, Vol. 05.05. West Conshohocken, PA: ASTM; 1998. p. 239–247.
21. Demirbas A. Calculation of higher heating values of biomass fuels. Fuel. 1997;76:431–434.
22. Tilman DA. Wood as an energy resource. New York: Academic Press; 1978.
23. Jenkins BM, Ebeling JM. Correlations of physical and chemical properties of terrestrial biomass with conversion. In: Proceedings of the IGT symposium: Energy from Biomass and Waste IX; 1985 Jan 28 – Feb 01; Lake Buena Vista, FL, USA. Chicago, IL: IGT; 1985. p. 371.
24. American Society for Testing Materials (ASTM). Standard test method for elemental analysis. Standards E775–8. In: Annual book of ASTM standards, Section 5, Vol. 05.05. West Conshohocken, PA: ASTM; 1998. p. 306–308.
25. Gopal G. Parametric study of a commercial-scale biomass downdraft: Experimental and equilibrium modeling [Master's dissertation]. Auburn, AL: Auburn University; 2010.
26. Miller JC, Miller J. Statistics for analytical chemistry. 2nd ed. Chichester: Ellis Harwood Ltd; 1988.
27. Quaak P, Knoef H, Stassen H. Energy from biomass. A review of combustion and gasification technologies. World Bank Technical Paper No. 422. Washington DC: World Bank; 1999.
28. Faaij A, Doorn JV, Curvers T, Waldheim L, Olsson E, Wijk AV, et al. Characteristics and availability of biomass waste and residues in the Netherlands for gasification. Biomass Bioenerg. 1997;2:225–240. http://dx.doi.org/10.1016/S0961-9534(97)00003-2
29. Brammer JG, Bridgewater AV. Drying technologies for an integrated gasification bio-energy plant. Renew Sust Energ Rev. 1999;3:243–289. http://dx.doi.org/10.1016/S1364-0321(99)00008-8
30. Holmberg H, Ahtila P. Comparison of drying cost in biofuel drying between multi-stage and single-stage drying. Biomass Bioenerg. 2004;26:515–530. http://dx.doi.org/10.1016/j.biombioe.2003.09.007
31. Food and Agricultural Organization of the United Nations (FAO). Wood gas as engine fuel. FAO Forest Paper 72. Rome: Mechanical Wood Products Branch, Forest Industries Division, FAO; 1986.
32. Van Swaay WPM, Van dee Aarsen FG, Bridgewater AV, Heesink ABM. A review of biomass gasification. A report to the European Community. Paris: DGXII JOULE program; 1994.
33. BTG (Biomass Technology Group). BTG: Energy from biomass. A review of combustion and gasification technologies. World Bank Technical Paper No. 422. Washington DC: World Bank; 1995.

34. Food and Agriculture Organization of the United Nations (FAO). Wood gas as engine fuel. Rome: FAO; 1986. Available from: http://www.fao.org/3/a-t0512e.pdf

35. Turare C. Biomass gasification – Technology and utilization. Glucksburg, Germany: ARTES Institute, University of Flensburg; 2002.

36. Anjireddy B, Sastry R. Biomass gasification processes in downdraft fixed bed reactors: A review. Int J Chem Eng Appl. 2011;6:425–431.

37. Jenkins BM, Baxter LL, Miles TR. Combustion properties of biomass. Fuel Process Technol. 1998;54:17–46. http://dx.doi.org/10.1016/S0378-3820(97)00059-3

38. Obernberger I, Brunner T, Bärnthaler G. Chemical properties of solid biofuels – Significance and impact. Biomass Bioenerg. 2006;14:30973–30982.

39. BTG (Biomass Technology Group). Thermochemical conversion of biomass to energy. Vienna: UNIDO; 1987.

40. Turn SQ, Keffer V, Staackmann M. Analysis of Hawaii biomass energy resources for distributed energy applications. Prepared for the State of Hawaii, Department of Business, Economic Development and Tourism. Honolulu: Natural Energy Institute; 2002.

41. Cheremisnoff PN. Waste incineration handbook. Oxford: Butterworth-Heinemann; 1992.

42. Raveendran K, Ganesh A, Khilar KC. Influence of mineral matter on biomass pyrolysis characteristics. Fuel. 1995;74:1812–1822. http://dx.doi.org/10.1016/0016-2361(95)80013-8

43. Nonde E. Forest research utilization: A Powerpoint presentation on Kaputa bio gasifier project. Lusaka: Forest Department; 2009.

44. Howlett K, Gamache A. Forest and mill residues as potential sources of biomass. Report 7347. Maclean, VA: The Mitre Corporation/Metek Division; 1997.

45. The Energy and Resources Institute (TERI). RETs II theme – Thermal applications of biomass gasifier in SMiEs. Project Report No. 2005BE28. New Delhi: TERI; 2006.

46. Sharma KA. Equilibrium modeling of global reduction reactions for a downdraft (biomass) gasifier. Energ Convers Manage. 2011;49:832–842. http://dx.doi.org/10.1016/j.enconman.2007.06.025

47. Michigan Forest Forever Teacher Guide. Plant physiology [homepage on the Internet]. c1998 [cited 2012 Oct 10]. Available from: from http://www.mfftg.com/plantphysiology

Particle boards produced from cassava stalks: Evaluation of physical and mechanical properties

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We investigated the potential use of cassava stalks for the production of bonded particle boards. Particle boards were produced from cassava stalks using urea-formaldehyde as a binder. Water absorption and thickness swelling tests were carried out to determine dimensional stability of the boards while modulus of rupture and modulus of elasticity tests were carried out to assess the mechanical strength of the boards. Particle boards produced using an adhesive–cassava stalk ratio of 3:1 gave the best results in terms of the lowest mean values of water absorption (20%) and thickness swelling (6.26%), as well as the highest values of modulus of rupture (4×10^6 N/m^2) and modulus of elasticity (2366.74×10^6 N/m^2). The particle boards produced met the ANSI/A208.1-1999 standard for general-purpose boards. The results of analyses of variance carried out revealed that the adhesive–cassava stalk ratio had a marked influence ($p<0.05$) on the physical properties (water absorption and thickness swelling) but not on the mechanical properties (modulus of rupture and modulus of elasticity).

Introduction

The start of the manufacture of modern particle boards can be traced back to the early 19th century.[1] In Nigeria and throughout the world, the panel/board industry has experienced continuous growth in recent years, using wood mainly obtained from forest resources.[2,3] The use of wood and wood-based panels/boards was estimated to be 2.866 million m^3 and 0.121 million m^3, respectively, in the early 1990s. These values are expected to rise to 4.704 million m^3 and 0.688 million m^3, respectively, within the next 20 years.[4,5] The increased demand for wood and wood-based panel products in Nigeria has placed a significant pressure on current forest resources, which has consequently led to an increase in the price of wood.[1,6] This demand has led to the need to find alternative raw materials for the production of boards and panels. One solution to this problem, as identified by researchers, is the use as an alternative of agricultural residues such as the stalks of most cereal crops, rice husks, coconut fibres (coir), bagasse, maize cobs, peanut shells, cassava stalks, etc. These agricultural residues are typically left on the farm after the target crops have been harvested. Nigeria is the world's largest producer of cassava, with an annual production capacity of 45 million tonnes.[7] Agbro and Ogie[8] reported that cassava has the highest output of residues generated in Nigeria and its estimated value is about 29 million metric tonnes per annum. In most underdeveloped and developing countries, these residues have very limited reuse capacity and they are typically inappropriately discarded or openly burnt.[2,9-11]

The improper disposal of these wastes has many negative environmental consequences. For instance, burning these wastes leads to increased levels of carbon dioxide in the atmosphere, which contributes to global warming. These wastes can also cause blockage of drains which consequently results in flooding. Accumulated wastes release offensive odours, thereby contributing to air pollution, and also serve as a breeding ground for mosquitoes and flies which spread several diseases. Waste products also add to space problems in landfills, as they remain in landfills until they are biodegraded.[12] The use of these materials offers potential benefits both environmentally and socio-economically. They are cheap, abundantly available, resource oriented when handled appropriately and the environmental problems associated with inappropriate disposal are eliminated.[13,14]

Numerous studies on the use of these wastes have been carried out in many parts of the world, including Nigeria. Most of these studies were focused on determining the suitability of these wastes for the manufacture of composites.[1,11] Some of the agro-wastes studied so far include rice husk[10], rattan[15], pine[11], wood wastes[16], wheat straw[17], cotton straw[18], sunflower stalks[1], and date palm leaves[19].

Particle board is a composite panel product traditionally produced from wood and wood wastes such as shavings, flakes, wafers, chips, sawdust, strands and wood wool.[11,20] Particle board is commonly used in structural applications such as flooring, wall bracing, ceiling boards, furniture, partitioning and cladding.[11,21,22] Synthetic resins are used to bond the agro-wastes together and other additives can be added to improve some of its properties. Resin-bonded panels are typically lighter, and thus have the potential to replace cement-bonded panels and concrete constructions like prefabricated walls and partitions.[20] Several types of resins are commonly used, although urea-formaldehyde is the cheapest and easiest to use.

We investigated the potential use of cassava stalks for the production of bonded particle boards in this study. Our objective was to evaluate the physical and mechanical properties of cassava stalk bonded particle board. A manufacturing process such as this one has the potential to reduce the pressure on forest resources and at the same time provide solutions to the problems of agricultural waste disposal in Nigeria.

Materials and methods

Material collection and pretreatment

Cassava stalks were obtained from the Asaba cassava mill located in the Delta State of Nigeria. The urea-formaldehyde adhesive used as a binder was obtained from the Chemical Engineering Laboratory, University of Benin, Edo State, Nigeria. The cassava stalks were milled using a hammer mill and then sifted using standard sieves

to obtain particles in the size range 0.85–2.0 mm. The milled cassava stalks were transferred into hot water at a constant temperature of 85 °C to extract inhibitory sugar compounds such as glucose, hemicelluloses and lignin.[3] This extraction was done in order to ensure proper setting of the boards. The extracted materials were separately air dried to attain approximately 12% moisture content before use.

Particle board formation and testing

The milled cassava stalks were mixed thoroughly with the urea-formaldehyde adhesive based on the experimental design specified in Table 1 until a uniform lump-free matrix was obtained. After mixing, the material was put in a mat-forming box, with dimensions 0.35 m×0.35 m×0.006 m. A manual press machine was used to make a pre-pressing at 0.78 $\times 10^6$ N/m^2. The box was then put in a hydraulic press and the boards were made by using an 8-min press closing time at a pressure of 1.23 $\times 10^6$ N/m^2. The mat-forming box was covered with a polythene sheet prior to board formation to prevent the boards from sticking onto the box.

The nominal dimensions and density of the boards produced were 0.35 m×0.35 m×0.006 m and 1000 kg/m^3, respectively. Three boards were produced for each treatment. About 20 mm of the edge of each board was trimmed off the samples using a buzz saw. The boards were subsequently put in a climatisation chamber at a temperature of 20±2 °C and a relative humidity of 65±2% for 21 days. They were thereafter subjected to physical tests – thickness swelling and water absorption tests – and mechanical tests – modulus of rupture and modulus of elasticity tests – in accordance with the procedures stipulated in ASTM D1037 and DIN 52362, respectively.[23,24]

Table 1: Experimental design for the manufacture of particle boards

Treatment (adhesive–cassava stalk ratio)	Adhesive		Material	
	Type	%	Type	%
T1 (2:1)	Urea-formaldehyde	66.7	Cassava stalks	33.3
T2 (2.5:1)		71.4		28.6
T3 (3:1)		75.0		25.0

Statistical analysis

The experimental design used in this work was a 3 x 1 factorial experiment in completely randomised design resulting in three treatments as shown in Table 1. The factors considered were material type (cassava stalks) and adhesive–cassava stalk ratio (by mass) (2:1, 2.5:1 and 3:1). The following properties were evaluated: water absorption after 24 h, thickness swelling after 24 h, modulus of elasticity and modulus of rupture. An analysis of variance (ANOVA) was performed and a 5% probability level was used to test the significance of treatment means.

Results and discussion

Effect of material variables on physical properties of the boards

The dimensional stability of the boards was assessed through water absorption and thickness swelling tests. Figure 1 shows the values of water absorption of particle boards produced from cassava stalks using different adhesive–cassava stalk ratios. The water absorption ranged from 20% to 43.12%. The highest water absorption was obtained for particle boards produced using an adhesive–cassava stalk ratio of 2:1, while the lowest water absorption was obtained for particle boards produced using an adhesive–cassava stalk ratio of 3:1. The relatively high values obtained when the 2:1 ratio was used could be because of the difficulty in compression and the presence of voids in the boards which allowed the boards to take in water.[3,25] Generally, the values obtained were similar to those reported by Mendes et al.[22] for particle boards produced from sugar cane bagasse using urea-formaldehyde as a binder. The results presented in Figure 1 show that the boards produced from an adhesive–cassava stalk ratio of 3:1 were more resistant to the permeation of water, and hence had the potential to perform better than others in very humid environments or when the boards came into contact with water or moisture. The resistance to the permeation of water observed in the case of the boards which had an adhesive–cassava stalk ratio of 3:1 is an indication of dimensional stability.

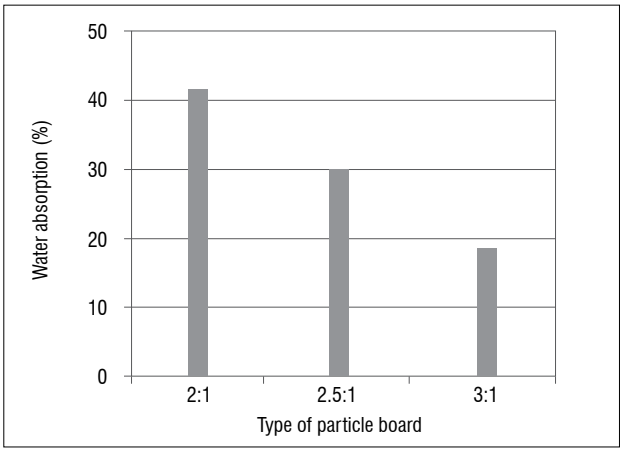

Figure 1: Percentage water absorption of particle board produced using different adhesive–cassava stalk ratios (2:1, 2.5:1 and 3:1).

Table 2: Analysis of variance of the effect of material variables on water absorption

Source	d.f.	Type III sum of squares	Mean square	F	*p*-value
Adhesive–cassava stalk ratio	2	364.38	182.19	55.10	0.004*
Error	12	39.68	3.31		
Total	14	404.06			

*$p < 0.05$

There was a significant difference in water absorption after 24 h among the samples, as indicated by the ANOVA results presented in Table 2. The adhesive–cassava stalk ratio therefore significantly influenced the water absorption property of the particle boards.

Figure 2 shows the values of thickness swelling for particle boards produced from cassava stalks using different adhesive–cassava stalk ratios. The values of thickness swelling ranged from 6.26% to 24.54%. Copur et al.[26] and Mendes et al.[22] reported similar values for thickness swelling for boards produced from hazelnut husk and cassava bagasse, respectively. The highest value of thickness swelling was obtained for particle boards produced using an adhesive–cassava stalk ratio of 2:1 while the lowest thickness swelling was obtained for particle boards produced using an adhesive–cassava stalk ratio of 3:1. Small values of thickness swelling are indicative of dimensional stability; hence the boards produced using the 3:1 ratio would be expected to perform better than the others. It has been reported that the thickness swelling is affected by the presence of void spaces in the boards in the same way as water absorption, as these spaces enhance the absorption of water by the boards which leads to internal swelling.[3,27] The results presented are also in agreement with those reported by Murakami et al.[27] and Adedeji[21] who observed that by increasing the adhesive content of the boards, the dimensional stability of the boards can be enhanced. The American National Standard Institute specifies a maximum thickness swelling of 8% for general-purpose particle boards (standard ANSI/A208.1-1999).

The results obtained in this study, as presented in Figure 2, show that all the boards produced met the thickness swelling requirement specified by the American National Standard Institute (ANSI/A208.1-1999) for general-use boards.[28]

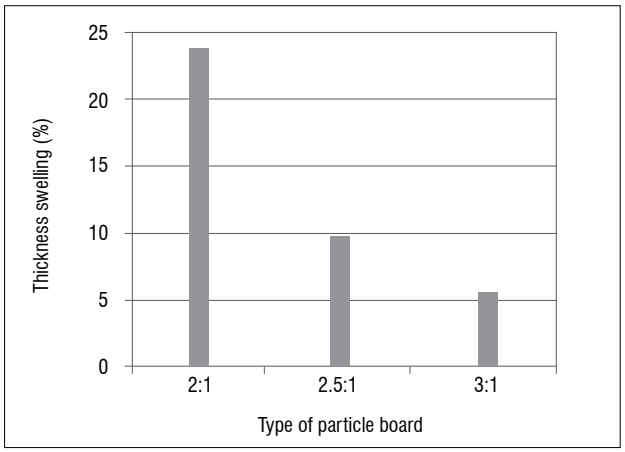

Figure 2: Thickness swelling of particle board produced using different adhesive–cassava stalk ratios (2:1, 2.5:1 and 3:1).

Table 3: Analysis of variance of the effect of material variables on thickness swelling

Source	d.f.	Type III sum of squares	Mean square	F	*p*-value
Adhesive–cassava stalk ratio	2	919	459.58	17.61	<0.0001*
Error	12	313.10	26.09		
Total	14	1232.15			

*$p<0.05$

The adhesive–cassava stalk ratio had a significant effect on the thickness swelling of the boards (Table 5; ANOVA, $p<0.05$).

Effect of material variables on mechanical properties of the boards

The mean values of modulus of rupture of the different boards tested are presented in Figure 3. The highest value of modulus of rupture (4.0×10^6 N/m^2) was obtained for particle boards produced using an adhesive–cassava stalk ratio of 3:1 while the lowest modulus of rupture (2.56×10^6 N/m^2) was obtained for particle boards produced using an adhesive–cassava stalk ratio of 2:1. The relatively high values of modulus of rupture recorded could be as a result of the random distribution of the particles in the boards.[3] This finding indicates that the boards are mechanically stable and can resist deformation under load. The adhesive–cassava stalk ratio did not significantly influence the modulus of rupture of the boards at the 5% probability level, as shown in Table 4. The American National Standard Institute standard ANSI/A208.1-1999 specifies a minimum modulus of rupture of 3×10^6 N/m^2 for general-purpose particle boards. The results obtained in this study show that the boards produced using an adhesive–cassava stalk ratio of 2.5:1 and 3:1 met the requirements specified by the American National Standard Institute for general-use particle boards (ANSI/A208.1-1999).[28] However, the boards produced using an adhesive–cassava stalk ratio of 2:1 did not meet the requirement.

Table 4: Analysis of variance of the effect of materials variables on modulus of rupture

Source	d.f.	Type III sum of squares	Mean square	F	*p*-value
Adhesive–cassava stalk ratio	2	2.42	1.21	13.68	0.341^{ns}
Error	12	1.06	0.09		
Total	14	3.48			

ns, $p>0.05$

Figure 4 shows the values of modulus of elasticity of the particle boards. The values ranged from 1075×10^6 N/m^2 to 2367×10^6 N/m^2. The highest modulus of elasticity was obtained for particle boards with an adhesive–cassava stalk ratio of 3:1 while the lowest modulus of elasticity was obtained for particle boards with an adhesive–cassava stalk ratio of 2:1. The results presented are also in agreement with those reported by Bamisaye[10]. The minimum acceptable value of modulus of elasticity as specified by the American National Standard Institute standard ANSI/A208.1-1999 is 550×10^6 N/m^2. The results obtained show that all the boards produced met this minimum requirement of the American National Standard Institute for general-use particle boards.

The adhesive–cassava stalk ratio did not significantly influence the modulus of elasticity of the boards (Table 5; ANOVA, $p>0.05$).

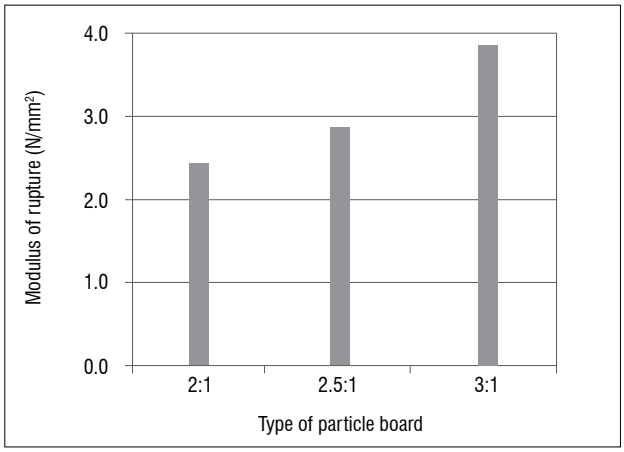

Figure 3: Modulus of rupture of particle board produced using different adhesive–cassava stalk ratios (2:1, 2.5:1 and 3:1).

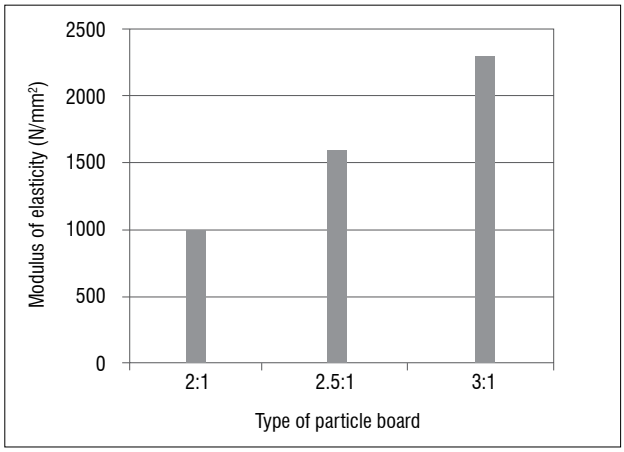

Figure 4: Modulus of elasticity of particle board produced using different adhesive–cassava stalk ratios (2:1, 2.5:1 and 3:1).

Table 5: Analysis of variance of the effect of materials variables on modulus of elasticity

Source	d.f.	Type III sum of squares	Mean square	F	*p*-value
Adhesive–cassava stalk ratio	2	4182754	2091377.15	8.82	0.541^{ns}
Error	12	2846191	237182.58		
Total	14	7028945			

ns, **p***>0.05*

Conclusions

We investigated the potential use of cassava stalks for the production of particle boards using urea-formaldehyde as a binder. The following conclusions can be drawn:

- Particle boards can be produced from cassava stalks using urea-formaldehyde as a binder.
- Particle boards produced using an adhesive–cassava stalk ratio of 3:1 are more dimensionally stable as evident in their smaller values of water absorption and thickness swelling compared with the other samples.
- Particle boards produced using an adhesive–cassava stalk ratio of 3:1 have higher mechanical strengths as evident in the higher values of modulus of rupture and modulus of elasticity compared with the other samples.
- Particle boards that satisfy the ANSI/A208.1-1999 standard can be produced from cassava stalks using urea-formaldehyde as a binder.
- ANOVA results show that the adhesive–cassava stalk ratio significantly influenced the water absorption and thickness swelling but not the modulus of rupture and modulus of elasticity.

Authors' contributions

F.A.A. and N.A.A. designed the study and K.C.B. performed the experiments. N.A.A. and K.C.B. managed the literature searches and N.A.A. wrote the first draft of the manuscript. F.A.A. provided analytical advice and corrected the manuscript. All authors read and approved the final manuscript.

References

1. Bektas I, Guler C, Kalaycioğlu H, Mengeloglu F, Nacar M. The manufacture of particleboards using sunflower stalks (*Helianthus annuus* l.) and poplar wood (*Populus alba* L.). J Compos Mater. 2005;39(5):467–473. http://dx.doi.org/10.1177/0021998305047098
2. Garay RM, MacDonald F, Acevedo ML, Calderón B, Araya JE. Particleboard made with crop residues mixed with wood from *Pinus radiata*. BioResources. 2009;4(4):1396–1408.
3. Sotannde OA, Oluwadare AO, Ogedoh O, Adeogun PF. Evaluation of cement-bonded particle board produced from *Afzelia africana* wood residues. J Eng Sci Technol. 2012;6(7):732–743.
4. Aruofor RO. Review and improvement of data related to wood products in Nigeria An output of the EC-FAO Partnership Programme (1998-2001) [document on the Internet]. c2000 [cited 2013 Dec 01]. Available from: ftp://ftp.fao.org/docrep/fao/004/X6762E/X6762E00.pdf.
5. Sotannde OA, Oluyege AO, Adeogun PF, Maina SB. Variation in wood density, grain orientation and anisotropic shrinkage of plantation grown *Azadirachta indica*. J Appl Sci Res. 2010;6(11):1855–1861.
6. Kayode J. Conservation implication of timber supply pattern in Ekiti State, Nigeria. Res J Forestry. 2007;1(2):86–90. http://dx.doi.org/10.3923/rjf.2007.86.90
7. FAO. Food outlook: Global market analysis. Rome: Food and Agriculture Organisation; 2009. p. 28.
8. Agbro EB, Ogie NA. A comprehensive review of biomass resources and biofuel production potential in Nigeria. Res J Eng Appl Sci. 2012;1(3):149–155.
9. Aisien FA, Hymore FK, Ebewele RO. Comparative absorption of crude oil from fresh and marine water using recycled rubber. J Environ Eng. 2006;132(9):1078–1081. http://dx.doi.org/10.1061/(ASCE)0733-9372(2006)132:9(1078)
10. Bamisaye JA. Cement bonded particle board production from rice husk in southwestern Nigeria. J Eng Appl Sci. 2007;2(1):183–185.
11. Erakhrumen AA, Areghan SE, Ogunleye MB, Larinde SL, Odeyale OO. Selected physico-mechanical properties of cement-bonded particleboard made from pine (*Pinus caribaea* M.) sawdust-coir (*Cocos nucifera* L.) mixture. Scientific Res Essays. 2008;3(5):197–203.
12. Aisien FA, Amenaghawon NA, Onyekezine FD. Roofing sheets produced from cassava stalks and corn cobs: evaluation of physical and mechanical properties. Int J Scientific Res Know. 2013;1(12):521–527. http://dx.doi.org/10.12983/ijsrk-2013-p521-527
13. Duku MH, Gu S, Hagan EB. A comprehensive review of biomass resources and biofuels potential in Ghana. Renew Sust Energ Rev. 2011;15(1):404–415. http://dx.doi.org/10.1016/j.rser.2010.09.033
14. Amenaghawon NA, Aisien FA, Ogbeide SE. Bioethanol production from pretreated cassava bagasse using combined acid and enzymatic hydrolysis. University Benin J Sci Technol. 2013;1(2):48–53.
15. Olorunnisola AO. Effects of particle geometry and chemical accelerator on strength properties of rattan-cement composites. Afr J Sci Technol Sci (Eng Series). 2007;8(1):22–27.
16. Fabiyi JS, Oyagade AO. Utilisation of wood residue as means of reducing poverty among rural communities. In: Akindele SO, Popoola L, editors. Community forestry and stakeholders' participation in sustainable development: Proceedings of the 29th Annual Conference of the Forestry Association of Nigeria; 2003 September 6–11; Calabar, Cross River State, Nigeria. Calabar: Forestry Association of Nigeria; 2003. p. 64–71.
17. Cooper PA, Balatinecz JJ. Looking beyond 2005: Product developments required. Paper presented at: Global Panel Based Conference; 2005 October 18–19; Kuala Lumpur, Malaysia.
18. El Mously HI, Megahed MM, Rakha MM. Agricultural residues for particleboard production. Paper presented at: A Case on Cotton Stalks Conference: Mechanical Design & Production; 1999 February 15–17; Cairo, Egypt.
19. Tayseer AM, El Mously HI, Megahed MM. A new lumber-like product from date palm leaves' midribs. Paper presented at: Euromat-97 Conference; 1997 April 21–23; Maastricht, Holland.
20. Yimsamerjit P, Surin P, Wong-on J. Mechanical and physical properties of green particle board produce from corncob and starch binder composite. In: Proceedings of the PSU-UNS International Conference on Engineering and Environment – ICEE-2007; 2007 May 10–11; Phuket, Thailand.
21. Adedeji YMD. Sustainable housing in developing nations: The use of agro-waste composite panels for walls. Built Human Environ Rev. 2011;4:36–47.
22. Mendes RF, Mendes LM, Júnior JBG, Santos RCD, Bufalino L. The adhesive effect on the properties of particleboards made from sugar cane bagasse generated in the distiller. Revista de Ciências Agrárias. 2009;32(2):209–218.
23. ASTM. ASTM D 1037-93 Standard methods for evaluating properties of wood-based fiber and particle panel materials. Philadelphia, PA: American Society for Testing and Material; 1995.
24. Normen Fur Holzfaserplaten, Spanplatten, Sperrholz – DIN 52362. Testing of wood chipboards bending test, determination of bending strength. Berlin: Beuth; 1982. p. 39–40. German.
25. Lee AWC. Physical and mechanical properties of cement bonded southern pine excelsior board. Forest Products J. 1984;34(4):30–34.
26. Copur Y, Guler C, Akgul M, Tascioglu C. Some chemical properties of hazelnut husk and its suitability for particle board production. Build Environ. 2007;42(7):2568–2572. http://dx.doi.org/10.1016/j.buildenv.2006.07.011
27. Murakami K, Ueda M, Matsuda H, Zhang M, Kawasaki T, Kawai S. Manufacture and properties of three-layered particleboards with oriented face strands of veneers. I. Effects of face strand/core article ratios. Resin types and resin contents on the board properties. J Japan Wood Res Soc. 1999;45(5):395–402.
28. American National Standard Institute (ANSI). Particle board ANSI A208.1-1999 Table A. Washington DC: ANSI; 1999. p.7

Monitoring and evaluating astronomy outreach programmes: Challenges and solutions

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A number of tools exist to guide the monitoring and evaluation of science, technology, engineering and mathematics (STEM) education and outreach programmes. Fewer tools exist for evaluating astronomy outreach programmes. In this paper we try to overcome this limitation by presenting a monitoring and evaluation framework developed for the International Astronomical Union's Office of Astronomy for Development (OAD). The mandate of the OAD is to stimulate sustainable development at an international level and to expand astronomy education and outreach globally. The broad assumptions of this programme are that astronomy has the potential to contribute to human development by means of the transferable nature of its science discoveries, as well as its potential to activate feelings of wonderment, inspiration and awareness of the universe. As a result, the programme potentially embodies a far broader mix of outcomes than conventionally considered in STEM evaluation approaches. Towards this aim, we operationalise our monitoring and evaluation approach by first outlining programme theories for three key OAD programmes: a programme for universities and research, another one for schools, and one for public outreach. We then identify outcomes, indicators and measures for each one of these programmes. We conclude with suggestions for evaluating the global impact of astronomy for development.

Introduction

What does gazing at the stars and putting a man on the moon have to do with monitoring and evaluation?

The answer lies in a spate of recent discussions around evaluation of science, technology, engineering and mathematics (STEM) interventions. At the 27th Annual Conference of the American Evaluation Association in 2013, the STEM Topical Interest Group emerged as a fully fledged area of interest and sponsored 23 different sessions. Apart from presentations dealing with evaluations of STEM education, delegates affiliated to the National Aeronautics and Space Administration (NASA) presented a paper entitled 'Measuring Inspiration' to describe their agency-wide approach to advance high-quality STEM education.[1] In their presentation, they highlighted the need for rigorous and thorough performance assessment of astronomy outreach programmes, which they defined as evaluation approaches that include both an assessment of how well the programmes are being implemented (process evaluation) and whether they are achieving their aims (outcome assessment). Ideally, these assessments should be based on plausible theories on how the programme is supposed to work (i.e. a programme theory), and use reliable and valid data collection instruments.[1]

In 2011, the International Astronomical Union's (IAU) Office of Astronomy for Development (OAD) was opened at the South African Astronomical Observatory in Cape Town with the mandate to stimulate development at an international level and expand astronomy education and outreach globally. The formative and emergent nature of the programme meant that simple, focused and very practical monitoring and evaluation approaches were needed. In this article, we describe the method we used to develop a programme monitoring and evaluation (M&E) framework for the OAD.

Astronomy for development

The IAU is an international astronomical organisation of more than 10 000 professional astronomers from more than 90 countries. Its mission is to promote and safeguard the science of astronomy in all its aspects through international cooperation. The International Year of Astronomy (2009) inspired the IAU to 'commit to even more ambitious programmes of educating the world to the beauty of the Universe and the sense of common humanity that derives from it'[2(p.3)]. The IAU's vision, through the establishment of the OAD, was to promote human development by means of astronomy outreach. Outreach activities were focused around three core programme areas: (1) universities and research, (2) children and schools and (3) the public.

The OAD's vision that astronomy has the potential to lead to positive human development was underscored by a number of hypotheses or core assumptions. The first of these was that because astronomy has triggered curiosity and a certain form of fascination throughout cultures, continents and generations, it has the ability to reach out to as broad an audience as possible. This reach, in turn, enables astronomy to plant the seeds for a sense of common heritage and a shared, overarching (or superordinate) sense of humanity – building blocks for a generally more tolerant society.

A second hypothesis was that astronomy has the potential to contribute to human development by means of the transferable nature of its developments and discoveries. In support of this assumption, the OAD cites a number of technologies and skills developed for astronomical research that are now applied in industry, the medical field, and in devices that one uses on a daily basis.[3] A few examples of these are the charge-coupled devices (better known as CCDs) that one finds in digital cameras and cellular phones; the transfer of technology developed for astronomy

into medical imaging instrumentation; and the application of adaptive optics technology in the high-precision laser industry and medicine.

A final assumption was that astronomy as a science has the potential to positively build the economic, institutional and human capital of participating countries and institutions. For example, according to Schilizzi et al.[4], the square kilometre array radio telescope's influence will be widely felt in astroparticle physics and cosmology, fundamental physics, galactic and extragalactic astronomy, solar system science and astrobiology. A report from Promoting Africa European Research Infrastructure Partnerships (PAERIP)[5] – a European Union–Africa partnership – elaborates on the positive socio-economic impact of a large astronomical project such as the Southern African Large Telescope (SALT). Via the SALT collateral benefits programme, the building of SALT is believed to have generated employment, skills and human-capacity building, science awareness in the surrounding communities, as well as the development of teacher-training and higher-education programmes. More broadly, a recent article in *Nature*[6] highlights the importance of supporting science and ways of using it for capacity building.

Evaluating astronomy for development

A key question for the OAD was the extent to which their assumptions about impact (outlined above) were plausible, and could be substantiated by empirical evidence stemming from their outreach activities. For this reason, OAD early on identified the need for their outreach activities to be underscored by a robust impact evaluation platform.

But evaluators are not able to determine impact with certainty, only with varying degrees of confidence.[7] Degrees of confidence in turn are dependent to a large extent on the research design utilised for estimating programme effects, how distal the outcomes of interest are, and how mature the programme of interest is. The OAD is not a mature programme, and the outcome of interest – human development – is both distal and difficult to define. If evaluators could, for example, compare participation in scientific research within countries where astronomy for development programmes were implemented with participation in countries where no programmes were implemented, one could theoretically estimate the effect difference with relative certainty. However, implementing such a design might call for randomised field experiments or the selection of carefully matched comparison sites to enable a quasi-experimental design. This scenario presents challenges in terms of time, cost, accurate data and cooperation.

A less robust approach is the measure of 'perceptions' of impact. This measure consists of gathering anecdotal testimonies of how a project is perceived to have affected the lives of its target audience, and thus contributed to the intended outcomes. The data can be in the form of narratives, pictures or short films. Although this approach may be satisfying to some audiences, the true measure of impact is likely to remain as an elusive end goal.

In light of these difficulties, we made a strategic decision when defining our M&E approach to not focus on measuring distal impacts; that is, testing the OAD's pre-suppositions relating to human development outcomes. Rather, the decision was made to place initial emphasis on ensuring effective implementation and short-term outcome attainment for public, educational and university outreach programmes. The rationale behind this decision was that if the OAD's outreach activities were not being implemented effectively or achieving even their short-term aims, more distal impact pathways – whether plausible or not – are unlikely to ever be realised. In our paper, we therefore restrict our M&E approach to an assessment of the design, implementation and short-term outcomes of the OAD's astronomy outreach programmes.

For our purposes, we understand programme evaluation to be defined as 'the use of social science research methods to systematically investigate the effectiveness of social intervention programs in ways that are adapted to their political and organizational environments and are designed to inform social action in ways to improve social conditions'[7(p.431)], and programme monitoring as 'the systematic documentation of aspects of program performance that are indicative as to whether the program is functioning as intended'[7(p.171)]. An M&E approach is thus an approach that uses social science research methods to systematically document programme performance and functioning with a view to inferring the extent to which the programme is improving the social conditions of target beneficiaries. Typically, programme monitoring will focus on the continuous measurement of programme implementation and outcomes, whereas evaluation efforts can be more broad-based in that they might also assess, for example, the design of the programme, the need for the programme, and the cost-effectiveness or efficiency of the programme.

Challenges in evaluating astronomy outreach programmes

In developed countries, aspects of astronomy are frequently integrated into formal school curricula in an effort to inspire and interest students in science[8], and numerous studies exist in which researchers have examined how learners' conceptual models of astronomical phenomena might best be moved towards more scientific notions[8-10]. In contrast, the benefits of integrating astronomy into informal public, educational and university outreach programmes are less clear. Although there have been calls for M&E approaches that specifically enhance the design and delivery of astronomy outreach,[11] most of these programmes have been viewed in terms of the degree to which they contribute to STEM development, and have been evaluated accordingly.

Educational STEM programmes are relatively straightforward to evaluate and a number of resources are available in the literature.[12-14] Short- and medium-term outcomes typically are defined in terms of so-called 'STEM activation', which usually includes curiosity towards STEM, awareness of scientific principles, self-efficacy in STEM, and belief in the importance of the scientific enterprise. Long-term outcomes usually relate to competence, knowledge and mastery of STEM-relevant skills.[12] For tertiary-level STEM programmes, increased collaboration with university scientists may be an important additional outcome.[15]

While astronomy outreach programmes share many objectives with STEM programmes, there are a number of other, less understood areas through which we hypothesised that astronomy programmes may hold unique benefits. In astronomy we are dealing with a science that explores the universe and celestial objects within it. For this reason, it is an inspirational science that has the potential to evoke feelings of wonderment and a yearning to understand our origins. Our fascination with the universe may even result in a sense of oneness that contradicts and undermines those national and cultural boundaries that separate us. For these reasons, we felt that astronomy outreach potentially embodies a far broader mix of outcomes than those conventionally considered in most STEM evaluation approaches.[12] And while some evaluation frameworks for assessing learning outcomes (such as the Generic Learning Outcomes framework[16]) acknowledge constructs such as enjoyment, creativity and inspiration in their conceptual frameworks, in order to operationalise our M&E framework, we were faced with the challenge of providing indicators and measures for such outcomes.

Approaches to astronomy outreach evaluation have for the most part failed to reflect this complexity. In one example from Hawaii, the Imoloa Astronomy Center in Mauna Kea claimed a role in the mitigation of cultural differences between astronomers and the Hawaiian community. This role, however, was never formally assessed by means of an empirical M&E approach.[17] The well-known European Universe Awareness programme also makes it clear that project goals include the somewhat abstract outcome of changes in intergroup attitudes, but no guidelines as to how these domains might be measured are provided in their evaluation manual.[18] Rather, evaluation tends to be directed solely at the level of astronomy awareness, knowledge, understanding and skills,[19,20] for example, correctly identifying a galaxy (knowledge) or using a telescope (skills). A final example is provided in the evaluation approach of the Sol programme run by NASA for underrepresented communities.[21] In the evaluation of the pilot of this programme, outcomes were expressed solely in terms of students' positive opinions and knowledge of STEM fields and careers (not specifically astronomy), as well as performance in science and mathematics classes. For this evaluation, generic survey tools relating to general STEM activation were adapted by the M&E team.

Although guidelines on evaluating attitude and behaviour change related to informal science programmes are available in the literature,[22] they are fairly broad and will need to be adapted and developed in more depth for specific astronomy-related projects.

Empirical evidence for the effects of astronomy outreach programmes

Overall, there is a lack of empirical evidence as to the effects of astronomy outreach programmes on human development. Although studies make it clear that astronomy frequently rates higher in the public mind than other science subjects on the basis of it encapsulating abstract concepts such as 'remoteness', 'unknownness', and 'excitement of discovery'[23(p.225)], whether these sentiments can be useful to human development is less definite. Indeed, it is not even clear if educational astronomy programmes are even effective in inspiring lasting interest in astronomy, let alone broader areas of science and development.

One study examined the experience of 655 10- and 11-year-olds in the United Kingdom who took part in a simulated space trip.[24] Although a quarter of the children were inspired by the visit to become scientists, half showed no significant changes and some even showed negative changes in their attitude. A later study[25] used a pre-test, multiple post-test design to assess the lasting effects of a space centre visit on elementary school children's attitudes towards science and astronomy. Although over 90% of students who visited the centre were highly excited by astronomy after completing the visit (a quarter expressed a desire to become astronauts one day), there was no evidence of the visit having a statistically significant effect on children's enthusiasm for science. Improvements in children's views about science and being scientists in future were also marginal, and over a period of a few months declined to the point that the final post-test means were only slightly higher than the pre-visit means.

Studies of astronomy training at a tertiary level have shown similar trends. One evaluation tracked three cohorts of over 400 Mexican students enrolled in a semester-long introductory astronomy course.[26] Although students typically progressed well in terms of conceptual subject mastery, there was little to no significant change over each semester in students' positive attitudes about astronomy specifically, and science generally. Teachers' attitudes may be even harder to influence than students. Ucar and Demircioglu[27], for example, reported that a semester-long astronomy course did not change teacher attitudes toward astronomy, and that only marginal gains were evident after even a full 4-year programme.

Given these challenges, the value added by exposing learners, students and the public to astronomy (as opposed to STEM outreach more generally) needs to be carefully considered.[25] Research has suggested that, like any extracurricular science outreach programme, informal astronomy outreach programmes – especially those targeted at children – require skilful facilitation and careful integration of content into school curricula if attitudes and learning are to be positively influenced.[25,28,29] And while more formal, tertiary-level programmes may be effective in facilitating conceptual mastery of astronomy principles,[30] considerable work needs to be done if students are to be inspired to pursue STEM subjects generally (and astronomy career paths specifically) as a result of completing these courses. For programmes such as the OAD's, where a lack of facilities and resources in developing countries might understandably limit programme quality, these challenges should be taken particularly seriously. There is therefore a clear need for simple yet effective formative M&E systems that are properly aligned to the programme's impact theory.

A programme theory for the astronomy outreach programmes

We used a theory-based approach to develop our M&E framework.[7,31-36] The approach involves the evaluators interacting with the programme stakeholders to draw out their programme theory until the stakeholders 'find little to criticize in the description'[7]. M&E can then be focused on ensuring that benchmark processes and outcomes in the programme's stated theory are being met.

A programme theory can be simply defined as 'a plausible and sensible model of how a programme is supposed to work'[34(p.5)], or more specifically as 'the set of assumptions about the manner in which a program is related to the social benefits it is expected to produce and the strategy and tactics the program has adopted to achieve its goals and impacts'[7(p.432)]. Rossi et al.[7] go on to define two components of programme theory – the programme's process theory, which outines the assumptions and expectations about how the programme is expected to operate, and the impact theory, which describes the cause-and-effect sequences brought about by programme activities which lead to programme impact. This distinction is similar to the distinction between action and change theory made by Chen[33], who describes programme theory as a set of stakeholders' prescriptive assumptions on what actions are required to solve a problem (i.e. an action theory), as well as descriptive assumptions about why the problem will respond to the actions (i.e. a change theory).

We started to build our M&E framework by developing a high-level model for the three programmes of the OAD (universities and research, children and schools, and public outreach). This model is depicted as a variable-oriented programme theory in Figure 1.

The assumption underlying this programme is: if programme activities for universities and research, children and schools, and the public are

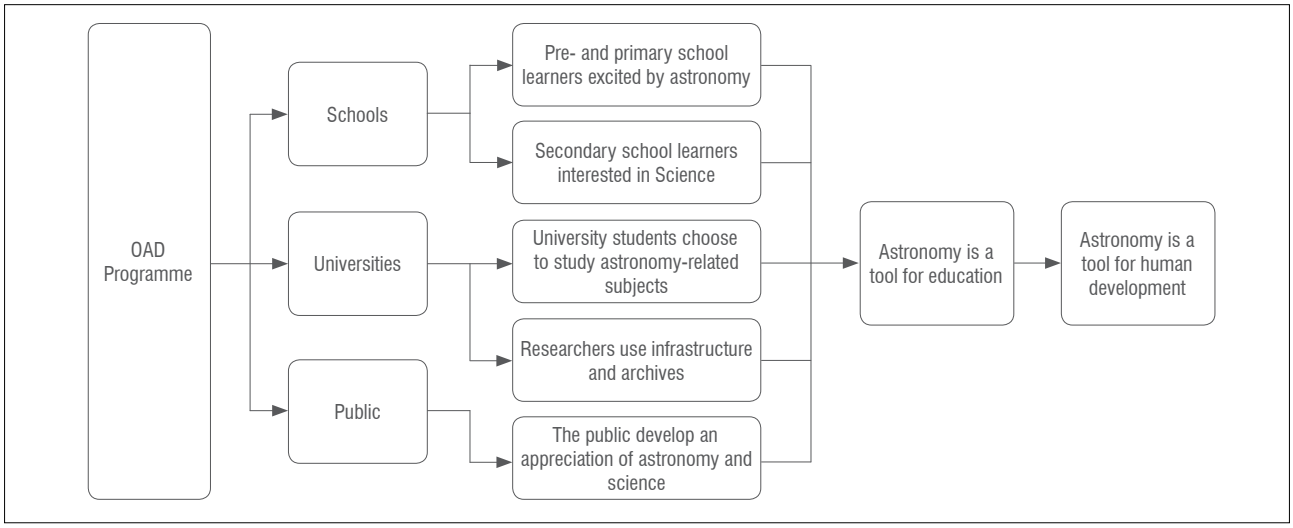


Figure 1: High-level variable-oriented programme theory for the Office of Astronomy for Development (OAD).

offered as intended and at the right intensity, astronomy will serve as a tool for education, and, in the long run, as a tool for human development.

Thereafter, we expanded the programme theories for each one of the three different programmes. We then added tables detailing the process and outcome indicators and measures to assess whether benchmark processes and outcomes are being achieved as planned. Based on these tables, we then developed data collection templates. This final step is specifically important for developing countries for which data collection and management may not be the norm. The templates also serve to ensure comparable data across projects, countries and continents. The OAD will require that programme managers use data from these templates when submitting regular progress reports. The templates will be available to programme managers in online or hard copy format, depending on technological standards within the relevant country. For the sake of brevity, the templates are not included here, but are available from the corresponding author and the OAD website.[35] However, the three surveys included appear in the data collection templates.

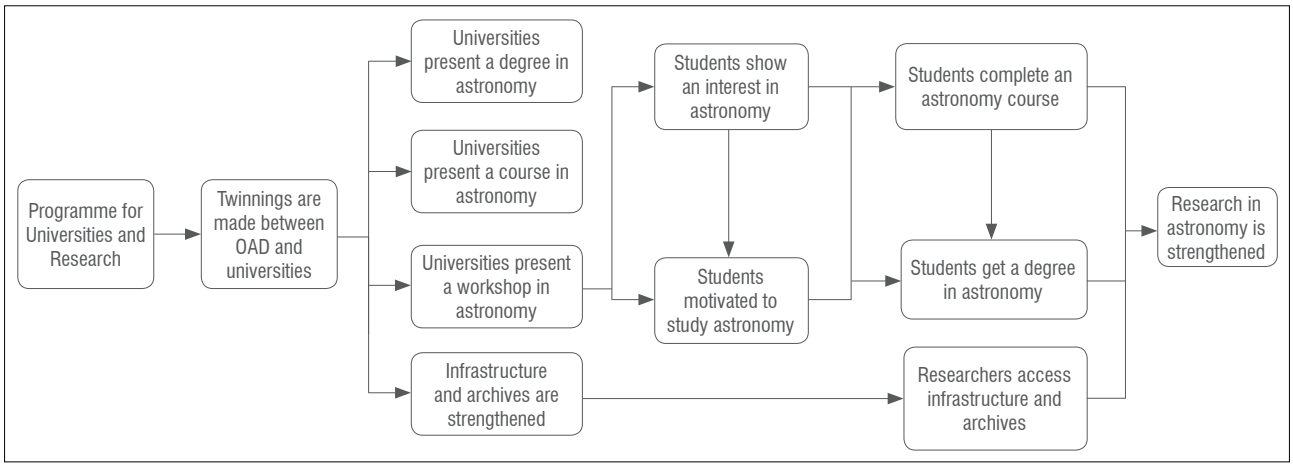
Programme theory for the Universities and Research Programme

This programme can be considered a core programme of the OAD. Its goal is to create cohorts of graduates and researchers, in astronomy specifically and in science generally. The programme theory is depicted in Figure 2.

Here the assumption is, that given the relevant offering at a university, students will become motivated to follow this field of study. As a result of this motivation, students will be more likely to study astronomy-related subjects and/or pursue a degree in astronomy.

The intervention involves twinning between universities, particularly in developing countries.[2] Typically, twinning involves mentorship of emerging researchers and students by senior international researchers, and the presentation of one or more workshops at a university that is not yet offering astronomy degrees or astronomy-related subjects. The programme also encourages researchers in astronomy and astronomy-related subjects to establish and access astronomy infrastructure and archives.

Data monitoring for this programme focuses on both process and outcome monitoring. Process monitoring primarily involves tracking the amount, type and quality of university twinning, as well as workshop presentations. For most of these indicators, programme records would typically serve as measures. Developing indicators and measures for the quality and strength of inter-institutional collaboration proved more challenging. We considered proxy indicators such as email correspondence (measure: correspondence frequency), but ultimately opted to use the presence of a memorandum of understanding as a measure for twinning amount and



OAD, Office of Astronomy for Development

Figure 2: Programme theory for the Programme for Universities and Research.

Table 1: Process and outcome indicators and measures for the Programme for Universities and Research

Process/Outcome	Indicators	Measures	Data source
Twinnings made (process)	Amount, type, quality of twinning	Number and type of connections, signed Memorandum of Understanding, participant satisfaction, etc.	Organisational records, communication reports, participant feedback ratings
Workshops presented (process)	Amount, type, quality of workshops presented	Number and type of workshops, participant satisfaction, etc.	
Universities present degrees/courses in astronomy (outcome)	Astronomy degrees and courses	Number of new courses/degrees etc.	Annual university survey
Students show an interest in astronomy and astronomy-related subjects (outcome)	Student attitude	Student ratings on items in workshop participant survey	Workshop participant survey
Students choose to study astronomy and astronomy-related subjects (outcome)	Astronomy degree and subject uptake	Students registered for target subjects/degrees	Annual university survey, workshop report
Researchers access astronomy archives and services (outcome)	Access to Astronomy Database Services	Number of people accessing, type of access	Annual university survey
Astronomy-related research increases (outcome)	Astronomy-related journal publications	Number, type of publication, etc.	Annual university survey

type. Participant satisfaction surveys were used to measure twinning quality. In contrast, outcome monitoring for this programme focused mainly on updating university records in order to track coverage in terms of astronomy and science graduates (Table 1).

We assumed that studying astronomy or science indicated an interest in these subjects and decided not to measure interest in astronomy for this programme. Where workshops in astronomy are presented at universities that do not offer courses or degrees in astronomy, the quality of the workshop presentation and the intention of workshop delegates to pursue a degree in astronomy or science is measured by means of a short survey. Items for this survey are presented in Table 2.

From Table 2, it is clear that many of the survey statements are quite blunt in nature, and do not include mechanisms for potentially increasing validity such as negatively worded statements. This bluntness was intentional. The global nature of the OAD programme meant that simple tools were needed that are unlikely to pose significant challenges to translation and analysis. Moreover, because respondents in some target countries are likely to be less familiar with surveys than their counterparts, the surveys needed to be both brief and direct in nature. Indeed, at this stage of the process of evaluating astronomy for development we are more concerned with whether these surveys are applicable to a specific target population across a wide range of socio-economic and educational contexts than with their content and construct validity. At a later stage, the psychometric properties of the surveys will need to be tested more rigorously.

Table 2: Participant survey to measure student attitude towards astronomy

1	I want to learn more about astronomy
2	I think I may become an astronomer one day
3	Astronomy is relevant to what I experience in my life
4	Astronomy is useful for making the world a better place
5	Attending this workshop has made it more likely that I will study astronomy at university
6	Attending this workshop has changed my perspective on how useful physics is as a subject
7	There is no astronomy at my university, but I would like to study physics

Response ranges from 1 (strongly disagree) to 4 (strongly agree), except for Item 7.

Programme theory for the Children and Schools Programme

The main goal of this programme is to activate excitement for astronomy in primary school children and to foster interest in science in secondary school children. However, several researchers have found that teachers often lack even the most basic scientific understanding of astronomical concepts,[36,37] which suggests the need for improved training at this level. In light of these considerations, the OAD programme was disaggregated to two levels of programme beneficiaries: teachers (the direct recipients of OAD support) and learners (the secondary beneficiaries). The relevant programme theory is depicted in Figure 3.

The assumptions underlying this programme theory are: if relevant teachers are qualified (trained) to present and implement the programmes for schools as intended, the children who receive these programmes will be inspired by them; and older children will become interested in science.

In order to collect comparable data for process and outcome monitoring, we created a comprehensive list of indicators and suggested measures. A simplified version of this list is presented in Table 3. From Table 3, we can see that the outcome 'inspired by astronomy' is expressed at two levels of specificity: excitement in astronomy and identification with a superordinate grouping. Here, superordinate grouping identification is defined in terms of a sense of common humanity that transcends common sub-groupings such as national identity or ethnicity. These levels of specificity were developed with consideration to the OAD's strategic plan,[8] as well as the personal experience of OAD staff during the first few years of project implementation. Excitement in astronomy might be measured by items relating to interest in astronomy and motivation to learn more about astronomy. In contrast, the outcome 'interest in science' is interpreted in terms of STEM activation. For our purposes, measures for STEM activation include items relating to interest in STEM, belief in the importance of STEM, and motivation to study STEM.

Two surveys are mentioned in Table 3: the primary and the secondary student surveys. When developing the primary school survey items, we had to keep in mind that in many developing countries primary school attendance is low and science often is not taught at this level. On the other hand, in many developed countries, children are taught science in sophisticated laboratories and start developing aspirations for careers as scientists at a young age. Because the OAD's mandate aims to establish impact within a global community that includes the developing world, measureable outcomes needed to be suitable for both developed and developing countries.

One of the most significant challenges was the lack of appropriate tools to guide the collection of M&E data in developing country contexts. While some STEM researchers have called for sensitivity to diversity, equality and cultural concerns in STEM programme evaluation[38,39] the majority of STEM programmes do not consider these elements to be important

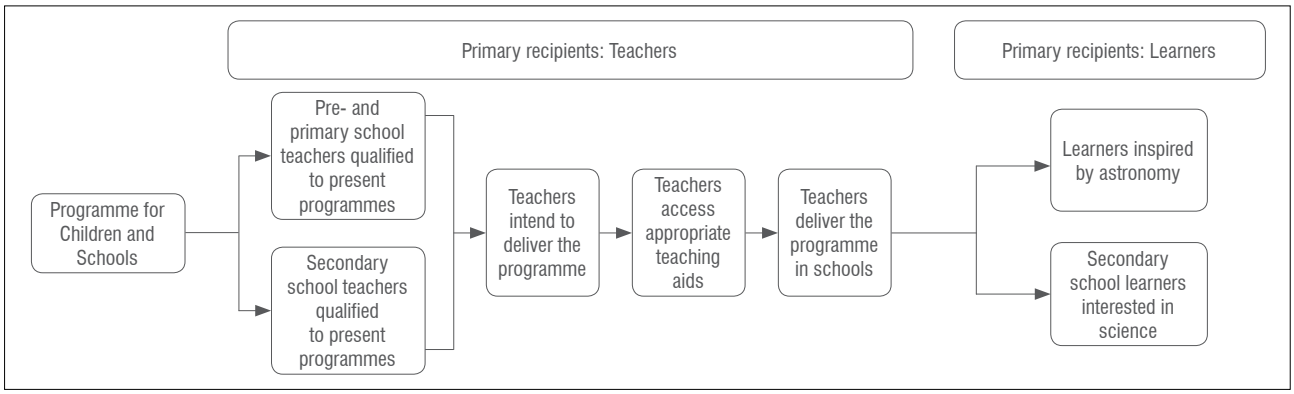


Figure 3: Programme theory for the Programme for Children and Schools.

to programme outcomes. Indeed, most researchers who work in this field have focused on race/ethnic disparity of minorities in developed countries,[40,41] and there is marked absence of debate around adaption of STEM instruments to the developing world. In one study, for example, the effects of astronomy outreach programmes on children were measured by adapting existing scales that probe children's science enthusiasm as well as beliefs as to the value of science to society. Because science is not always offered (at least in practice) at the elementary level in some developing countries, measuring outcomes in terms of, for example, science enthusiasm and outlook on science,[25] seemed implausible. Other tools, such as the Survey of Attitudes towards Astronomy tool developed by Zeilik et al.[26], have only been applied to university-level students.[26,42] In contrast, tools more suitable for children of elementary school going age, such as the Space Interest Scale referred to by Jarvis and Pell[25], seemed too narrowly targeted at specific types of astronomy outreach (in this case a visit to a high technology simulation space centre).

Similar problems were encountered when developing the secondary school survey. Although we came across well-constructed and comprehensive surveys aimed at probing changes in attitudes towards STEM,[43] only a few of the items in these surveys seemed suitable for developing countries. Other tools we reviewed were problematic in

Table 3: Process and outcome indicators and measures for the Programme for Children and Schools

Process/Outcome	Indicators	Measures	Data sources
Teachers qualified (process)	Teacher training outputs	Number trained, type trained, nationality, etc.	Teacher training report
	Teacher training quality	Average facilitator ratings, certification, teacher assessment, etc.	Teacher survey
Teachers equipped (process)	Access to learning aids	Teachers using equipment, type and quantity of equipment available, etc.	Teacher survey
Students exposed to suitable learning aids (process)	Use of learning aids in classes	Amount, type and quality of learning aids used	Classroom report
Teachers intend to deliver the programme (outcome)	Intent	Teachers' self-reported intent to teach astronomy	Teacher survey
Teachers deliver the programme (outcome)	Behaviour	Number of classes taught etc.	Classroom report
Learners inspired by astronomy (outcome)	Excitement	Interest in astronomy, motivation to learn about astronomy	Primary school survey
	Superordinate group identification	Awareness, identification, absorption	Primary and secondary student surveys
Secondary school learners interested in science (outcome)	STEM activation	Interest in STEM, belief in importance of STEM, motivation to study STEM	Secondary student survey

Table 4: Surveys for children participating in astronomy outreach

Primary school student survey (for children aged 8 to 12 years)	
1	I find astronomy interesting
2	I like astronomy
3	I sometimes cannot stop thinking about the things we are taught in astronomy
4	I am excited to talk to my friends and family about what I learn in astronomy
5	I would like to read more about astronomy on my own, outside of class
6	When I look at the sky, I forget about the bad things that worry me
7	Learning about astronomy has shown me that I am part of a very big world
8	Learning about astronomy has opened my mind to other people who share my interest
Secondary school student survey (for children aged 13 to 18 years)	
1	I find science interesting
2	I like science
3	Learning science is important for understanding my place in the world
4	Learning science has changed my ideas about how the world works
5	Learning science will help me get a good job
6	I want to learn more about science
7	Learning about science showed me that I live in a very big world
8	Learning science has opened my mind to other people who share my interest
9	Learning about astronomy in science class was exciting

Response ranges from 1 (strongly disagree) to 4 (strongly agree), except for Item 9.

that they focused too much on specific STEM areas such as science or mathematics,[44,45] making them more suitable for the evaluation of structured programmes solely focused on these areas of STEM activation. For both primary and secondary school children, we struggled to identify items that captured identification with a superordinate group at the level of universal citizenship, rather than, for example, superordinate groups at the level of nationality or ethnicity.[46] Given these challenges, after much discussion and research, we developed the surveys in Table 4 for primary school students into those for secondary school students.

Programme theory for the Public Outreach Programme

The main goal of this programme is to inspire, entertain and introduce adults to the accessible science of astronomy. The programme theory is shown in Figure 4.

The assumptions of the OAD underlying this programme are that the public will appreciate astronomy if this programme is delivered by competent presenters. Here data monitoring is concerned with coverage of the public, the quality of the public presentation, and the attitudes of the audience towards astronomy and science (Table 5).

The items for the participant survey for this programme are presented in Table 6.

Interpreting outcomes

The surveys and instruments presented in this paper are intended to measure the extent to which the OAD's astronomy outreach activities are bringing about desirable changes in programme beneficiaries. Because these changes are seen as stepping stones towards the OAD's long-term strategic goal of astronomy for development, monitoring indicators of progress towards these benchmark intermediate outcomes is important. But how should the OAD interpret the monitoring data? And how should data be used more generally to guide programme improvement?

In programme evaluation, failure of a programme to achieve its outcomes is usually taken to imply one of two things: implementation

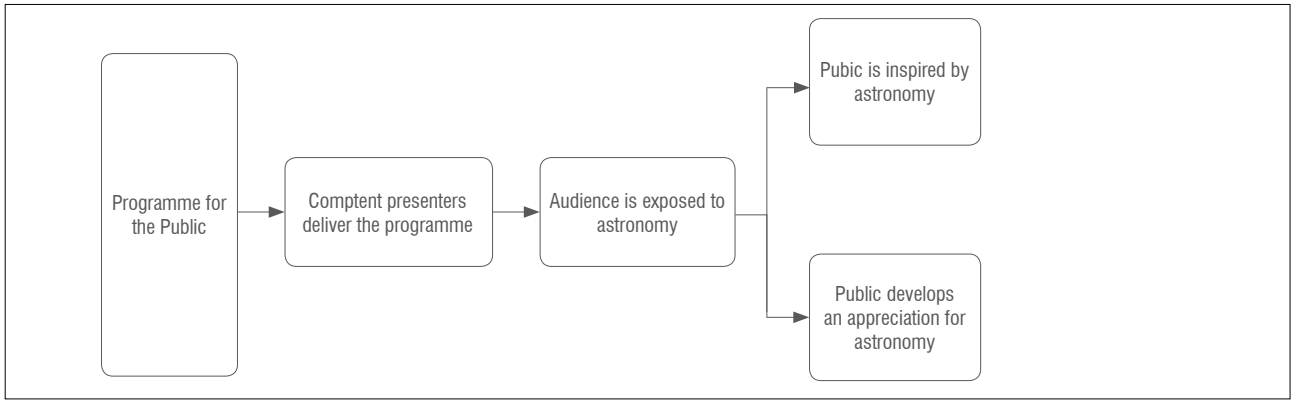


Figure 4: Programme theory for the Programme for the Public.

Table 5: Process and outcome indicators and measures for the Programme for the Public

Process/Outcome	Indicators	Measures	Data sources
Competent presenters deliver programme (process)	Amount, type and calibre of lecturers and lectures	Lecture outputs, audience lecturer ratings, etc.	Lecturer and lecture reports, participant survey
Public exposed to astronomy (process)	Use of small telescopes/planetariums	Proportion of lectures in which a small telescope or planetarium is used	Lecture report
Public develops an appreciation of astronomy (outcome)	Astronomy activation	Participants' self-reported change in astronomy activation	Participant survey

Table 6: Public participant survey for public's attitude towards astronomy and an astronomy lecture

1	The course presenter was enthusiastic about astronomy
2	The course presenter demonstrated a high level of astronomy expertise
3	This presentation has increased my interest in astronomy
4	I can't stop thinking about astronomy
5	I want to learn more about astronomy
6	I think astronomy is useful to help me understand science
7	Astronomy is relevant to what I experience in my life
8	I think astronomy is useful to make the world a better place

Response ranges from 1 (strongly disagree) to 4 (strongly agree).

failure or theory failure. Corrective action taken by the programme will vary considerably depending on the type of failure that is implicated. As Rossi et al.[7] explain, implementation failure usually suggests that there has been poor service delivery on the part of the programme, and/or inadequate service utilisation on the part of the participants. Shortcomings in service delivery might be because activities were not delivered at the right intensity, resources were insufficient, or the amount, type and quality of interventions were inadequate. Service utilisation failure on the other hand might mean that beneficiaries have not responded to the programme in the manner intended, or that the wrong beneficiaries were targeted in the first place. The programme may also have had insufficient reach. Whereas corrective action in the former instance would usually centre efforts to improve service delivery, corrective action for a service utilisation failure is likely to focus on effort to improve the coverage, targeting and uptake of outreach programmes.

The second potential reason for a failure to achieve outcomes might be that the programme theory itself is implausible. Thus, if an implementation failure is not suggested by the M&E data, a theory failure must be considered likely. Even a very well delivered programme with an implausible theory can never be expected to bring about outcomes – because the logic linking actions to outcomes is fundamentally flawed. For us, the implications of a theory failure are potentially far more significant than those for an implementation failure, because in the case of theory failure, the strategic goals of the programme in relation to project activities might need to be reassessed and potentially revised.

Understanding process

From the above it is apparent that understanding process is critical to interpreting outcomes, because a good understanding of service delivery and utilisation can aid in distinguishing between a theory and implementation failure. However, our review of the astronomy outreach programme evaluation literature shows that indicators of implementation are seldom reported, making failure to achieve outcomes difficult to interpret. In the M&E framework presented here, we were therefore careful to incorporate process monitoring indicators and measures in an attempt to address this oversight. The fixed indicators and measures outlined in our M&E framework are, however, quite limited in nature and may occasionally need to be supplemented by more detailed process evaluations. Process evaluations, while similar to process monitoring in their scope and application, are typically tailored to specific projects and structured around key evaluation questions.

The next challenge: Measuring impact

In this article we have outlined an approach for monitoring and evaluating changes in the status of programme implementation and outcomes over time. Using this framework, regular measures taken over time are likely to provide valuable data suitable for formative programme improvement. The first priority of the OAD is therefore to test and apply the M&E framework to its global project sites. The objective will be to acquire as much quality data as possible and receive useful feedback on the framework's usability and relevance. This process of testing and revision can be tracked on the OAD website, from where the latest M&E framework and tools can also be downloaded.[35]

The framework does not, however, allow for establishing a programme effect or the 'proportion of an outcome change that can be attributed uniquely to the programme as opposed to the influence of some other factor'[6(p.206)]. In order to make this assessment, an impact evaluation with some form of control group would be needed. While the OAD has committed to reporting on the impact of their programmes for the period 2010–2020, a move towards more rigorous impact evaluation approaches for 'astronomy for development' will pose considerable challenges – many of which we have highlighted in this paper. In order to justify such a study, we would need to carefully consider their reasons for wanting to establish impact, and the way in which impact data would ultimately be used. Moreover, we would need to acknowledge that impact is unlikely to be achieved if there is implementation or theory failure.

In this paper, we have hoped to illustrate how the careful M&E of a programme's implementation and intermediate outcomes can greatly assist in determining the plausibility of the programme theory. Without a plausible programme theory, attempting to gauge by empirical means as to whether a programme has brought about desirable long-term impacts is unlikely to prove a useful exercise. And if implementation is flawed, even short-term outcomes are unlikely to be realised. For these reasons, focusing on operationalising a simple M&E framework such as the one presented in this paper has numerous advantages. Should the framework indicate that the OAD's outreach initiatives are both theoretically and operationally sound, the next challenge would be to progress towards a more rigorous assessment of impact.

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Authors' contributions

S.C. wrote the manuscript and was responsible for the evaluation design. L.C. is a PhD student working with the OAD; she provided comments on the manuscript, wrote key sections on the role of astronomy in science, technology and development, and gave input on the evaluation design. J-C.M. is the programme manager for IAU OAD; he gave comments on the manuscript, gave input on the evaluation design and supervised L.C. K.G. is the OAD director; he gave comments on the manuscript, wrote key sections on the mandate and organisational structure of the OAD, contributed to the evaluation design, provided overall project oversight, and supervised L.C. J.L-P. is the corresponding author and project leader; she wrote the first outline of the manuscript, gave input on the subsequent drafts, was responsible for the evaluation design, and supervised S.C.

References

1. Shaffer PM, Whitney VW, Wills L, Senghore F, Matthews MJ. Measuring inspiration: Planning for NASA education's performance measurement and evaluation. In: 27th Annual Conference of the American Evaluation Association; 2013 Oct 16–18; Washington DC, USA. Washington DC: American Evaluation Association; 2013. p. 246–255.
2. International Astronomical Union (IAU). Astronomy for development: Building from the IYA 2009 – Strategic plan for 2012–2020. Cape Town: IAU; 2010.
3. Rosenberg M, Russo P. Why is astronomy important? International Astronomical Union 2013. Available from: http://www.iau.org/public/themes/why_is_astronomy_important/
4. Schilizzi RT, Dewdney PEF, Lazio JW. The Square Kilometre Array. Ground-based and airborne telescopes II. Proc SPIE. 2008;7012(1I):1–13.
5. Promoting Africa European Research Infrastructure Partnerships (PAERIP). An analysis of the socio-economic impact of African-European research infrastructure cooperation. PAERIP; 2012. Available from: http://www.paerip.org/sites/www.paerip.org/files/PAERIP%20report%203.3%2015092012.pdf
6. Poh L. Research policy: How to build science capacity. Nature. 2012;490(7420):331–334. http://dx.doi.org/10.1038/490331a
7. Rossi PH, Lipsey MW, Freeman HE. Evaluation: A systematic approach. 7th ed.Thousand Oaks, CA: Sage Publications; 2004. Lelliott A, Rollnick M. Big ideas: A review of astronomy education research 1974–2008. Int J Sci Educ. 2009;32(13):1771–1799.
8. Diakidoy I-AN, Kendeou P. Facilitating conceptual change in astronomy: A comparison of the effectiveness of two instructional approaches. Learn Instruct. 2001;11(1):1–20. http://dx.doi.org/10.1016/S0959-4752(00)00011-6
9. Hannust T, Kikas E. Children's knowledge of astronomy and its change in the course of learning. Early Child Res Quart. 2007;22(1):89–104. http://dx.doi.org/10.1016/j.ecresq.2006.11.001
10. Stroud N, Groome M, Connolly R, Sheppard K. Toward a methodology for informal astronomy education research. Astron Edu Rev. 2006;5(2):146–158. http://dx.doi.org/10.3847/AER2006023

11. Malyn-Smith J, Cedrone D. A program director's guide to evaluating STEM education programs: Lessons learned from local, state, and national initiatives [document on the Internet]. c2013 [cited2014 May 27]. Available from: http://stelar.edc.org/sites/stelar.edc.org/files/A_Program_Directors_Guide_to_Evaluating_STEM_Eduation_Programs_links_updated.pdf

12. Frechtling JA. User-friendly handbook for project evaluation: Science Mathematics, Engineering and Technology education. Arlington, VA: The National Science Foundation; 1993.

13. Osborne J, Simon S, Collins S. Attitudes towards science: A review of the literature and its implications. Int J Sci Educ. 2003;25(9):1049–1079. http://dx.doi.org/10.1080/0950069032000032199

14. George-Jackson CE, Rincon B. Increasing sustainability of stem intervention programs through evaluation [document on the Internet]. c2013 [cited 2014 May 27]. Available from: http://rube.asq.org/edu/2012/02/engineering/increasing-sustainability-of-stem-intervention-programs-through-evaluation.pdf.

15. United Kingdom Museums, Libraries and Archives Council (MLA). Generic learning outcomes [homepage on the Internet]. c2014 [cited 2014 Dec 08]. Available from: http://inspiringlearningforall.gov.uk

16. Ciotti JI. Museums and planetariums: Bridging the gap between Hawaiian culture and astronomy through informal education – A case study [document on the Internet]. c2010 [cited 2014 June 26]. Available from: http://forumonpublicpolicy.com/spring2010.vol2010/spring2010archive/ciotti.pdf.

17. Arisa E, Fabregat J, Ros RM. EU-UNAWE Project: Inspiring every child with our wonderful cosmos. Highlights Span Astrophysics VII. 2013;1:959–961.

18. Burtnyk K. Impact of observatory visitor centres on the public's understanding of astronomy. Publ Astron Soc Aust. 2000;17:275–281. http://dx.doi.org/10.1071/AS00043

19. Prather EE, Cormier S, Wallace CS, Lintott C, Jordan Raddick M, Smith A. Measuring the conceptual understandings of citizen scientists participating in Zooniverse projects: A first approach. Astron Edu Rev. 2013;12(1):010109. http://dx.doi.org/10.3847/AER2013002

20. Rhodes H, Neishi K, Velez M, Mendez J, Martinez A. The SoI pilot national evaluation: Findings and recommendations. Cambridge, MA: Abt Associates; 2011.

21. Friedman AJ, editor. Framework for evaluating impacts of informal science education projects: Report from a National Science Foundation workshop. Arlington, VA: National Science Foundation; 2008. Available from: http://www.aura-astronomy.org/news/EPO/eval_framework.pdf

22. Jarman R, McAleese L. Physics for the star-gazer: Pupils' attitudes to astronomy in the Northern Ireland science curriculum. Phys Educ. 1999;31(4):223–226. http://dx.doi.org/10.1088/0031-9120/31/4/020

23. Jarvis T, Pell A. Effect of the challenger experience on elementary children's attitudes to science. J Res Sci Teach. 2002;39(10):979–1000. http://dx.doi.org/10.1002/tea.10055

24. Jarvis T, Pell A. Factors influencing elementary school children's attitudes toward science before, during, and after a visit to the UK National Space Centre. J Res Sci Teach. 2005;42(1):53–83. http://dx.doi.org/10.1002/tea.20045

25. Zeilik M, Schau C, Mattern N. Conceptual astronomy. II. Replicating conceptual gains, probing attitude changes across three semesters. Am J Phys. 1999;67(10):923–927. http://dx.doi.org/10.1119/1.19151

26. Ucar S, Demircioglu T. Changes in preservice teacher attitudes toward astronomy within a semester-long astronomy instruction and four-year-long teacher training programme. J Sci Educ Teach. 2011;20(1):65–73. http://dx.doi.org/10.1007/s10956-010-9234-7

27. Falk JH, Koran JJ, Dierking LD. The things of science: Assessing the learning potential of science museums. Sci Educ. 1986;70(5):503–508. http://dx.doi.org/10.1002/sce.3730700504

28. Şentürk E, Özdemir ÖF. The effect of science centres on students' attitudes towards science. Int J Sci Educ. 2012;4(1):1–24. http://dx.doi.org/10.1080/21548455.2012.726754

29. Prather EE, Slater TF, Adams JP, Bailey JM, Jones LV, Dostal JA. Research on a lecture-tutorial approach to teaching introductory astronomy for non–science majors. Astron Edu Rev. 2004;3(2):122–123. http://dx.doi.org/10.3847/AER2004019

30. Coryn CLS, Noakes LA, Westine CD, Schröter DC. A systematic review of theory-driven evaluation practice from 1990 to 2009. Am J Eval. 2011;32(2):199–226. http://dx.doi.org/10.1177/1098214010389321

31. Weiss CH. Theory-based evaluation: Past, present, and future. New Dir Eval. 1997;1997(76):41–55. http://dx.doi.org/10.1002/ev.1086

32. Chen HT. Theory-driven evaluations. New York: Sage; 1990.

33. Bickman L. Using program theory in evaluation. In: Bickman L, editor. New directions for program evaluation, no 33. San Francisco, CA: Jossey-Bass; 1987. p. 5–18.

34. Office of Astronomy for Development (OAD). Monitoring and evaluation framework of the OAD [homepage on the Internet]. c2014 [cited 2015 Apr 27]. Available from: http://www.astro4dev.org/funded-projects-2014/me-framework/

35. Atwood VA, Atwood RK. Preservice elementary teachers' conceptions of what causes night and day. School Sci Math. 1995;95(6):290–294. http://dx.doi.org/10.1111/j.1949-8594.1995.tb15785.x

36. Mant J. A survey of British primary school teachers' understanding of the Earth's place in the universe. Educ Res. 1995;37(1):3–19. http://dx.doi.org/10.1080/0013188950370101

37. Greene JC, DeStefano L,Burgon H, Hall J. An educative, values-engaged approach to evaluating STEM educational programs. New Dir Eval. 2006;109:53–71. http://dx.doi.org/10.1002/ev.178

38. Zeyer A, Çetin-Dindar A, Zain M, Jurišević M, Devetak I, Odermatt F. Systemizing: A cross-cultural constant for motivation to learn science. J Res Sci Teach. 2014;50(9):1047–1067. http://dx.doi.org/10.1002/tea.21101

39. Clewell BC, Cosentino de Cohen C, Tsui L, Deterding N. Revitalizing the nation's talent pool in STEM: Science, technology, engineering and math [document on the Internet]. c2006 [cited 2014 May 27]. Available from: http://www.urban.org/UploadedPDF/311299_revitalizing_stem.pdf

40. Tsui L. Effective strategies to increase diversity in STEM fields: A review of the research literature. J Negro Educ. 2007;76(4):555–581.

41. Bektasli B. The effect of media on preservice science teachers attitudes towards astronomy and achievement in astronomy class. Turk Online J Ed Tech. 2013;12(1):139–146.

42. Hartry A, Snow J. A toolkit for evaluating small-scale science, technology, engineering, and mathematics (STEM) programs: Big mistake/bad idea? Or a way to ensure small organizations have access to high-quality evaluations? In: 27th Annual Conference of the American Evaluation Association; 2013 Oct 16–18; Washington DC, USA. Washington DC: American Evaluation Association; 2013. p. 142–160.

43. Germann PJ. Development of the attitude toward science in school assessment and its use to investigate the relationship between science achievement and attitude toward science in school. J Res Sci Teach. 1988;25(8):689–703. http://dx.doi.org/10.1002/tea.3660250807

44. Kind P, Jones K, Barmby P. Developing attitudes towards science measures. Int J Sci Educ. 2007;29(7):871–893. http://dx.doi.org/10.1080/09500690600909091

45. Stone CH, Crisp RJ. Superordinate and subgroup identification as predictors of intergroup evaluation in common ingroup contexts. Group Process Intergr Relat. 2007;10(4):493–513. http://dx.doi.org/10.1177/1368430207081537

A Rasch analysis of a Grade 12 test written by mathematics teachers

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There is much concern in South Africa about the low levels of mathematics achievement amongst learners. Aligned to this issue is that of mathematics teachers' proficiency in mathematics. The purpose of this study was to explore mathematics teachers' proficiency in the mathematics that they teach. A sample of 253 teachers' responses to a shortened Grade 12 examination was analysed using the Rasch model. When the teachers' proficiency and item location are represented on one scale, as is the case in Rasch measurement theory, it is expected that the teachers should be located beyond the difficulty level of the items as they teach the content to their learners. However, in this study, the teachers' proficiency was located close to the mean of the item locations. Furthermore, the levels of almost one-third of the group were below that of all the Level 3 and Level 4 items in the test. If such a result holds across other groups of teachers, it may explain why higher levels of passes in mathematics are not achieved. A second aim of this study was to illustrate how the application of the Rasch model can be used to contribute to a more informative and fair assessment. In line with Rasch measurement theory, the test was subjected to various analyses and the results were used to improve the fit of the items and the test.

Introduction

There have been many initiatives in South Africa since 1994 to improve the quality of education in the country, particularly in mathematics education. The interventions have sought to address concerns about the low level of mathematical skills in the country, which have been revealed by both international and national studies.[1-3]

Many studies point to mathematics teachers' poor content knowledge as one reason for low levels of learners' mathematics achievement.[4-6] Hugo et al.[7] reported on a KwaZulu-Natal study which found that none of the Grade 6 teachers were able to achieve 100% for the test on the curriculum that they were teaching, while 24% of the respondents achieved less than 50% on the test. On average, only 47% produced correct responses to each test item. Spaull[4], in his analysis of the Southern and Eastern Africa Consortium for Monitoring Educational Quality (SAQMEQ) III results, revealed that the top 5% of Grade 6 *learners* (559 students) scored higher marks on the same mathematics test than the bottom 12.5% of Grade 6 *educators* (62 teachers) in the sample. There have been no similar studies about the content knowledge of mathematics teachers who teach in the Further Education and Training (FET) band which represents the final three years of schooling (Grades 10–12). One aspect of a larger study[8] that was set up to investigate the content knowledge of Grade 12 mathematics teachers from a group of 253 practising mathematics teachers from the province of KwaZulu-Natal is reported on here. The corresponding research questions that guide this study are: (1) What does a Rasch analysis reveal about the mathematical proficiency of a sample of FET mathematics teachers in aspects of the mathematics they teach? (2) How can an application of the Rasch model to an assessment instrument contribute to improved scoring rubrics?

Rasch measurement theory

Note that with Rasch measurement theory (RMT) there is an assumption that for the construct of interest there exists a latent trait in the learner that may be gauged through the operationalisation of the construct through items. The latent trait is conceived as a single dimension or scale along which items can be located in term of their difficulty.[9] With RMT, learner ability, denoted by β_n, and item difficulty, denoted δ_i, may be represented on the same scale. Rasch analysis is then the formal testing of an outcome scale against a mathematical model developed by Rasch[9].

The term 'measurement' is often used loosely in the assessment of social and educational constructs. By drawing on measurement in the physical sciences, and a classical theory of measurement, we note that the property of invariance across the scale of measurement is required.[10] For example, the measure of the height of a population at two different sites should not differ, nor should the means of measuring (system of units) change for different objects. Rasch analysis is the process of examining the extent to which the responses from a scale approach the pattern required to satisfy axioms of measurement in order to construct measurement.[11] In RMT, and in conformity with classical measurement theory, the requirement is that the data fit the model, rather than that the statistical model is adapted to fit the data. With RMT, the first step in approximating measurement is to define the construct being measured. The next step is to invoke a probabilistic process, a transformation that constructs natural units of measurement that are independent of both the construct and the persons being measured. This procedure involves converting a raw score percentage into its success-to-failure odds and then to its natural logarithm.[12] Similarly for items, the percentage of correct responses for the item is calculated and converted to a logarithm of the correct-to-incorrect odds for the item. This log-odds transformation of raw data is a first approximation of the Rasch measurement scale. Thereafter these estimations are then subjected to a series of iterations by the computer, allowing the student ability and item difficulty to be located on a common continuum so that a genuine interval scale using logits is produced.[12]

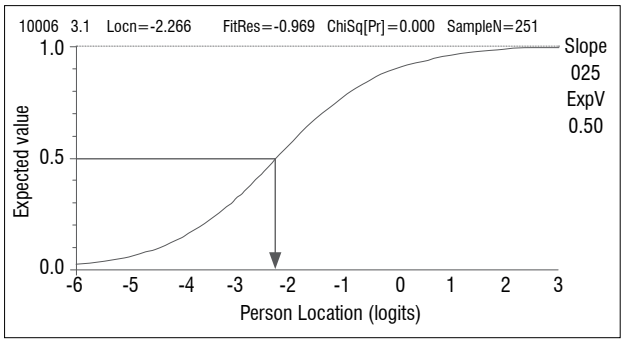
The Rasch simple logistic model for dichotomous items is given in Equation 1.[13] In RMT, the equation which relates the ability of learners and the difficulty of items is given by the logistic function:

$$P\{X_{vi}= 1\} = \frac{e^{\beta_v - \delta_i}}{1+e^{\beta_v - \delta_i}} \qquad \text{Equation 1}$$

This function expresses the probability of a person v, with ability β_v responding successfully on a dichotomous item i, with two ordered categories, designated as 0 and 1. Here P is the probability of a correct answer; X_{vi} is the item score variable allocated to a response of person v, on dichotomous item i; and δ_i is the difficulty of item i.

Applying Equation 1, we can see that if a person v is placed at the same location on the scale as an item labelled i, then $\beta_v = \delta_i$, that is, $\beta_v - \delta_i = 0$, and the probability in Equation 1 is thus equal to 0.5 or 50%. Thus, any person will have a 50% chance of achieving a correct response to an item whose difficulty level is at the same location as the person's ability level. If an item difficulty is above a person's ability location, then the person has a less than 50% chance of obtaining a correct response on that item, while for an item whose difficulty level is below that of the person's ability, the person would have a greater than 50% chance of producing the correct response. Figure 1 illustrates this relationship for a single item.

The item characteristic curve (ICC) depicted in Figure 1 represents the alignment of item difficulty and person ability. Learners are represented on the horizontal axis from low proficiency (to the left, towards -6) to high proficiency (to the right towards +1). The probability of a correct response is represented by the vertical axis (from 0 to 1). The person located at -2.266 logits has a 0.5 probability of answering this item correctly.



Learners are represented on the horizontal axis, from low proficiency (left) to high proficiency (right). The probability of a correct response is represented by the vertical axis (from 0 to 1).

Figure 1: Item characteristic curve for an item located at -2.266 logits, representing a 0.5 probability of a correct answer.

As ability varies, the probability of a correct response to the item also varies. The probability that a person with low proficiency will respond correctly is correspondingly low, approaching 0 asymptotically as ability decreases. Symmetrically, the probability that a person with high proficiency will respond correctly is correspondingly high, and approaches 1 asymptotically as proficiency increases.

Figure 2 shows both the probability of responding correctly and incorrectly, where:

$$P\{X_{vi}= 0\} = 1 - \frac{e^{\beta_v - \delta_i}}{1+e^{\beta_v - \delta_i}} = \frac{1}{1+e^{\beta_v - \delta_i}} \qquad \text{Equation 2}$$

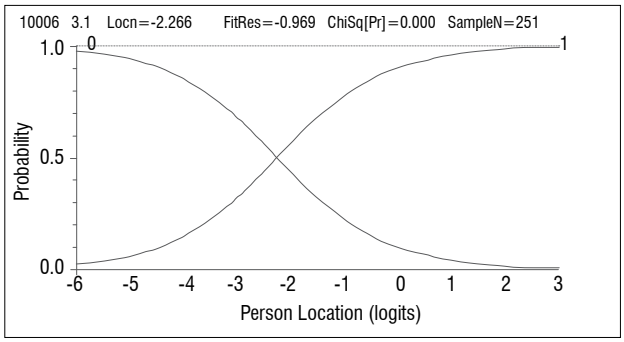


Figure 2: Category probability curve showing the probabilities of scores 0 and 1 on a single item as a function of proficiency.

The location of the item is identified as the point on the ability scale where the probability curves of 0 and 1 intersect. At this point, the probability of a response of either 0 or 1 is equally likely. Because it is a dichotomous item, there is a probability of 0.5 of either response. The probability of a correct response decreases as proficiency decreases, and increases as proficiency increases, around this point. The item shown in Figure 2 has a location of -2.266 logits.

The simple logistic model was developed by Rasch[9] for the analysis of dichotomously scored test items. Many assessment programmes, however, require greater precision or more information than a simple right/wrong scoring system allows from any particular item. In these cases, polytomously scored items with several levels of performance may be required. Rasch's[9] formulation of the model for polytomously scored items is an extension of the simple logistic model. Instead of dealing with dichotomous items with two response categories, and possible scores of 0 and 1 only, it provides a model for test items with more than two response categories, with possible scores of 0,1,2,….,m. Andrich[14] derived a model which gives the probability of a person with ability β_v being classified in a category x in a test item of difficulty δ_i, with $m+1$ ordered categories as:

$$P\{Xvi= 1\} = \frac{e^{(x\beta_v - \delta_i) - \Sigma_{k=1}^{x}\tau_k)}}{\Sigma_{x=0}^{m} e^{(x\beta_v - \delta_i) - \Sigma_{k=1}^{x}\tau_k)}} \qquad \text{Equation 3}$$

where $x \in \{1,2, \ldots,m\}$ and τ_x are the thresholds. In Equation 3 the threshold parameters are not subscripted by i, indicating they are assumed identical across items, making it possible to estimate one set of thresholds which hold for all the items.[13] If thresholds are different across items, the model takes the form of Equation 4:

$$P\{X_{vi}= 1\} = \frac{e^{(x\beta_v - \delta_i) - \Sigma_{k=1}^{x}\tau_{ki})}}{\Sigma_{x=0}^{mi} e^{(x\beta_v - \delta_i) - \Sigma_{k=1}^{x}\tau_{ki})}} \qquad \text{Equation 4}$$

The model of Equation 3 has become known as the ratings scale model and the model of Equation 4 has become known as the partial credit model. Here the partial credit model is used because it is less restrictive and allows the distances between the response categories to emerge from the data rather than being imposed on the data and also because each of the items had a different number of categories. The term 'threshold' defines the transition between two adjacent categories, for example between scoring 0 and 1 (τ_1), or scoring between 1 and 2 (τ_2). Figure 3 shows the category curves for Item 1.3

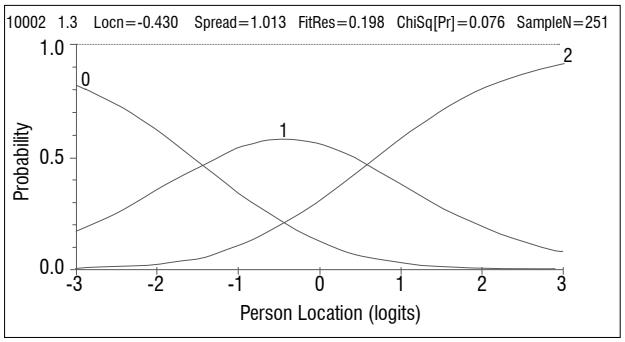


Figure 3: Category curves for Item 1.3

In Figure 3, there are three category curves corresponding to the probabilities of obtaining a score of 0, 1 or 2. The thresholds, and the categories they define, are naturally ordered in the sense that the threshold defining the two higher categories of achievement is of greater difficulty than the threshold defining the two lower categories of achievement. The first threshold (τ_1), which represents the point where a score of 1 becomes more likely than a score of 0, is about -1.5 logits. The second threshold, where a score of 2 becomes more likely than a score of 1, is approximately 0.6 logits. These thresholds show that progressively more ability is required to score a 1 than a 0 and a 2 than a 1 on this item.

Method

In this study, the data collection instrument was a shortened form of the National Senior Certificate March 2011 supplementary examination written by Grade 12 mathematics students (see Appendix 1 in the online supplementary material). The instrument was shortened to seven questions because of time constraints. The topics of the different questions that appeared in our data collection instrument are summarised in Table 1 while those that were excluded were arithmetic and geometric sequences, simultaneous equations, exponential functions, financial mathematics and cubic graphs.

Table 1: Details of the research instrument

Question	Description	Number of sub-questions	Maximum mark
1	Quadratic equations and inequalities	2	8
2	Patterns	3	9
3	Hyperbolic function	5	11
4	Parabolic function	6	15
5	Finding derivatives using rules	2	6
6	Optimisation	2	8
7	Linear programming	4	18
Total			75

The instrument was administered to the teachers under test conditions, and teachers who consented were given 2 h to write the test. The participants were given detailed feedback about their performance in the test so that they could improve on their weak areas. The teachers were from different districts in KwaZulu-Natal and were enrolled in an Advanced Certificate in Education programme, which is designed for upgrading the skills of teachers who have a 3-year diploma from a teaching college. However, approximately 20% of the group were already fully qualified teachers. A condition for selection into the programme is that a teacher must be teaching mathematics at the FET level at that time. Of the group of approximately 350 teachers, there were 286 who agreed to participate in this study. The teachers' responses were then marked by two experts who had many years of experience in marking matric examination papers. Marks were then captured for each item. The items were categorised into the assessment taxonomy levels[15] by three mathematics education experts, including the author, who coordinated the programme[8]. The data were then cleaned and anomalies and inconsistencies were removed with respect to missing details or missing records. The total number of records analysed was 253.

Sample size

The general rule for the construction and development of test instruments is that the learner count is about 10 times the maximum score count.[16] In this analysis, the test consisted of 24 items which were made up initially of 75 marks in total, that is 75 thresholds. In that situation, a sample size of 253 is small, because the recommended sample size should be 10–20 persons per threshold, which would be at least 750 persons. However, with the rescoring process, the number of thresholds considered was 42, which means, although closer, the sample size is still smaller than the recommended size of 420 persons.

The results of the Rasch analysis

A requirement of RMT is that the data fit the model, in order to claim measurement within the model's framework. The properties of Rasch measurement apply only to the extent to which the data fit the model's demanding requirement.[12] When the data fits a Rasch model, suitable transformation of the raw total scores for persons and raw frequencies of score categories of each item will enable calculation of estimates for both learner ability parameters and all item thresholds and average difficulty levels.[17] All these estimates may then be legitimately represented and located on the same scale or linear dimension,[17] from which inferences can be made based on an interpretation within the context. The fit statistics are used to help detect discrepancies between the Rasch model prescriptions and the data that is collected in practice, and these are first considered in this section. This step is followed by a report on the individual item analysis, and the post-hoc changes that were made to the scoring. Tests for differential item functioning or item bias are then reported. DIF can also affect fit to the model and occurs when different groups within the sample respond in a different manner to an individual item. As recommended by Tennant and Conaghan[11], it was also necessary to check for response dependency and multidimensionality in the items, which, if present, are a breach in the assumption of local independence of items. The final test statistics are then presented, followed by a discussion of the person–item map.

Initial analysis

Rasch analysis can be undertaken with software such as WINSTEPS, RUM2030, and ConQuest. Each reports findings in slightly different ways, but with a main focus on testing whether the response pattern observed in the data is close to the theoretical pattern predicted by the model. RUMM2030 was used in this study. This software reports fit statistics in terms of item and person fit residual statistics which are an indication of the differences between their actual and expected responses. RUMM2030 also reports on item–trait interaction chi-square, which reflects the property of invariance across the trait.

From the initial Rasch analysis, the summary statistics (Table 2), person–item location distribution (Figure 4) and person–item threshold distribution (Figure 5) were generated. Table 2 presents the initial summary statistics, which shows the item mean as 0 (as set by the model) and the person mean as 0.4557, which is slightly above zero, showing that generally the students found the test comfortable. The standard deviation for the item location is 1.0577, which is just above the ideal value of 1 while the standard deviation of the person location is 0.8049, which is less than 1, suggesting that the distribution of the person locations is clustered together.

The mean of the item fit residual (-0.2018) is close to zero. The standard deviation of the item fit residual is 1.5987, larger than 1, which means that the fit varies more than expected. Similarly, the mean of the person fit residual is approximately -0.2 and the standard deviation of the person fit residual is 0.8741, which is slightly smaller than 1, showing that the

distribution of the person fit residuals is slightly more clustered than the ideal situation.

In terms of reliability, in RUM2030 an estimate of the internal consistency reliability of the scale is the person separation index. The statistic of the person separation index in Table 2 is very good – over 0.9, which is higher than the minimum of 0.85 advised by Tennant and Conaghan[11]. This shows that the estimation of the person's ability is consistent across the model. In this case the figure is 0.9007 which indicates that the persons have been separated well by the test. The item trait interaction figures have a chi-square value of 213.897 with a probability value of 0.000, which is significant and means that the hierarchical ordering of the items may vary across the trait.

Person–item location distribution

The person–item location distribution (PILD) and the person–item threshold distribution were then generated. The item locations range from -2.389 to about 1.082 logits. The person locations are estimated between -1.905 and about 2.728 (with a mean of 0.456), with two people obtaining extreme scores (full marks) being estimated at 3.499 logits. The fact that the person location is higher than the mean of the item location, suggests that this Grade 12 test was slightly easy for this particular group of teachers.

For polytomous items, as is the case in this test, a person–item threshold distribution is useful to better understand the spread of the item thresholds. Figure 5 illustrates that the thresholds range from below -2 to above 3, showing a much wider distribution than the items themselves.

Individual item analysis

The Rasch analysis may indicate that the scoring rubric of items is working as required by the model in order and contributing to the measure of learner proficiency or it may identify items where the scoring rubric is not working in an ordinal way. The graphical analysis provided by the ICC (see Figure 1) and the category probability curves (see Figures 2 and 3) can be used to check item functioning.

In a Rasch analysis test of fit, the learners are placed into class intervals and the average ability of each class is calculated – in this study there were four class intervals. The mean ability of the four groups becomes the horizontal coordinate of points in the diagrams and the vertical coordinates depict the probability of answering correctly.[18]

When the theoretical curve (the expected frequencies) and the observed proportions (the empirically established average of the actual item scores in the four chosen groups) are in alignment, we assume fit to the model, as depicted by the ICC in the right-hand side of Figure 6. On the other hand, a substantial deviation of the observed proportions from the theoretical curve signals some sort of misfit between the data and the model (for example, the first ICC on the left-hand side of Figure 6). There are four categorisations that describe how the observed proportions might relate to the theoretical expectation; these categorisations are described in detail with examples in an article by Long et al.[18]

Each of the 24 items was checked for the item fit statistics, ICC, as well as the functioning of the categories. Based on these diagnostic procedures, some items were rescored if such a rescoring was supported by the qualitative analysis, as described in the discussion following Figure 7. Appendix 2 in the online supplementary material provides a summary of the processes that were followed and the decisions that were taken for each of the items.

Appendix 2 indicates that the initial analysis identified Items 14, 19 and 24 as having misfit statistics, outside the recommended limits of -2.5 to 2.5 logits.[12,13] The ICC and category probability curves for each item were checked, and, if a rescoring was suggested by the analysis and the rescoring was supported by the qualitative analysis, then the item was rescored. The details of this process are described in Appendix 2. This rescoring process resulted in improved fit residual statistics for the misfit items. However, the fit residual statistic for Item 5 (-3.162) was outside the generally acceptable interval of between –2.5 and 2.5. This item was rescored again, resulting in a better fit residual statistic of 0.928. Based on the rescoring process, the fit residuals of other items improved and some regressed slightly, but there was no longer any significant misfit.

Examples of two items (Question 1.3 and Question 3.5) whose category probability curves and ICCs improved with the rescoring are demonstrated in Figures 6 and 7.

Van Wyke and Andrich[19] explain that when ordered thresholds emerge in the Rasch analysis of responses to an item, these provide confirming evidence that the hierarchy of responses identified in the scoring rubric reflects the underlying order of the proficiency continuum. And disordered thresholds provide evidence that the scoring rubric for the item does not reflect the underlying proficiency continuum. Van Wyke and Andrich[19] suggest that disorder in the thresholds signals that the item has failed to function as intended, which presents an opportunity to rescore the items to try to reflect the hierarchy of responses. An observation of Item 1.3 in Figure 7 reveals disordered thresholds in the empirically derived initial category curves, suggesting that categories 1 and 3 are not working well. The problem is that the locations of the first and third thresholds are respectively greater than that of the second and fourth thresholds. These reversed thresholds are a result of the failure of the two categories, corresponding to scores of 1 and 3, to function as intended. At no point on the horizontal axis is a score of 1 most likely; neither is there an interval or point where a score of 3 is most likely. The thresholds suggest that achieving a score of 2 did not require more proficiency than achieving a mark of 1 and achieving a score of 4 did not require more proficiency than achieving a mark of 3. An examination of the marking memorandum in Figure 7 shows why this might be so. If the quadratic expression was factorised correctly (hence achieving the first mark), then obtaining one of the critical values (second mark) follows easily. Similarly, obtaining one correct interval (third mark) was not experienced as more difficult than getting both (fourth mark). Hence

Table 2: Initial summary statistics

	ITEMS [*n*=24]		**PERSONS [*n*=253]**	
	Location	**Fit residual**	**Location**	**Fit residual**
Mean	0.0000	-0.2018	0.4557	-0.2152
SD	1.0557	1.5987	0.8049	0.8741
			Person separation index 0.9007	
	Item–trait interaction Total item chi-square = 213.8966 Total d.f. = 72.000 Total chi-square probability = 0.000			

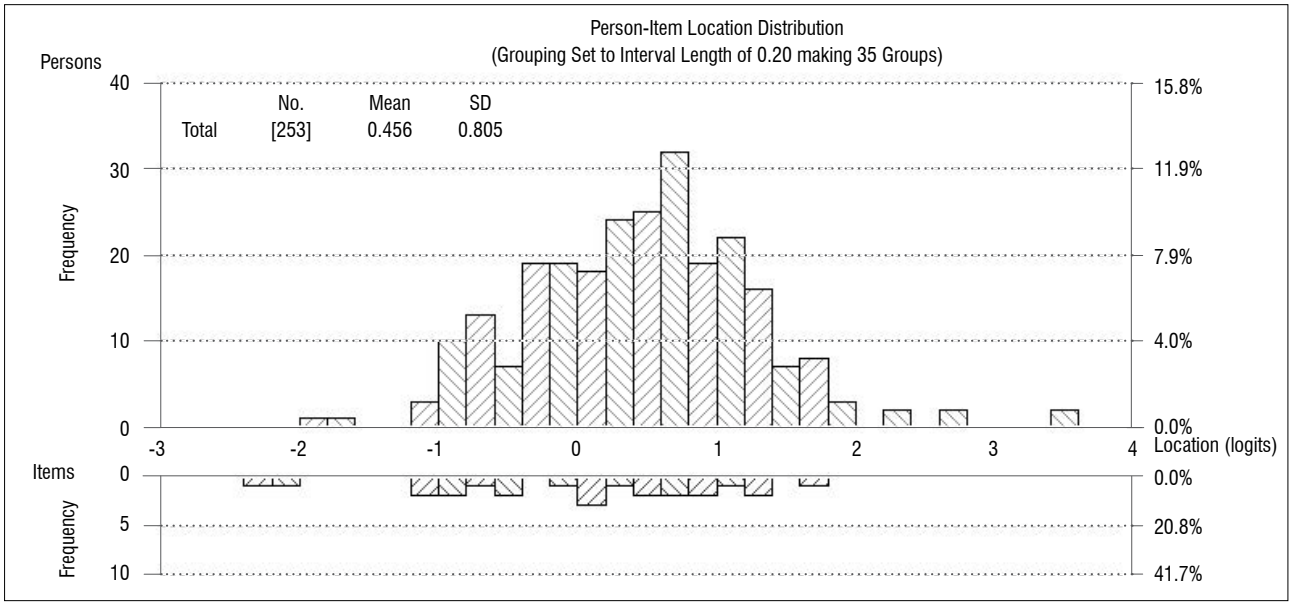


Figure 4: The initial person–item location distribution.

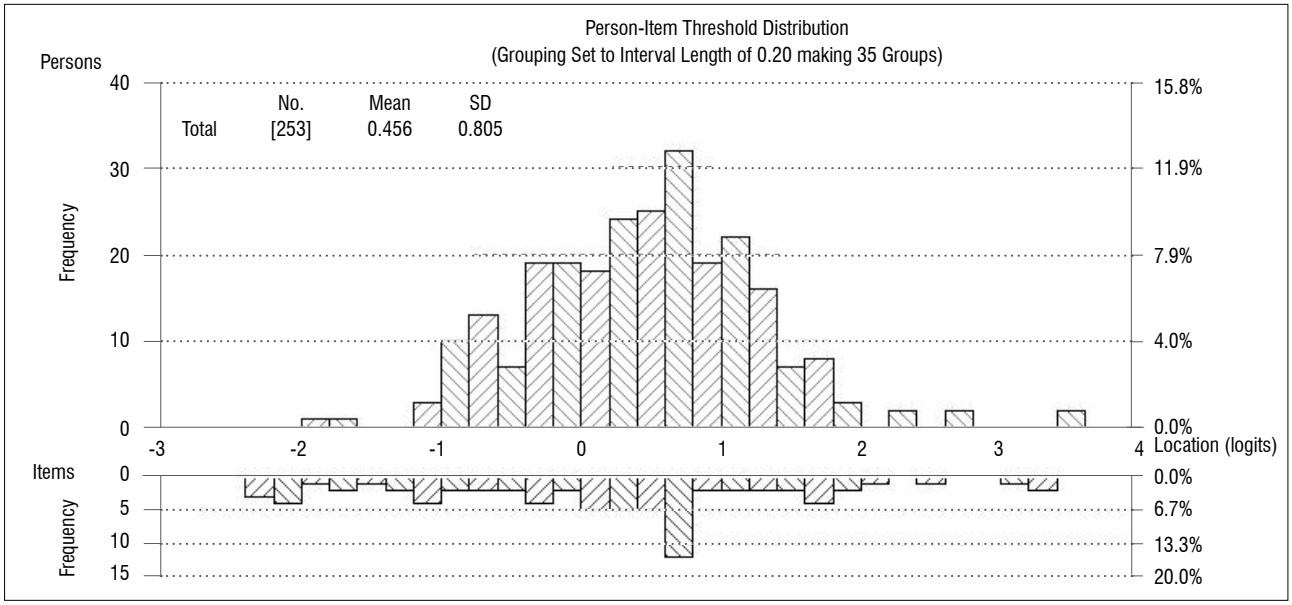


Figure 5: The initial person–item threshold distribution.

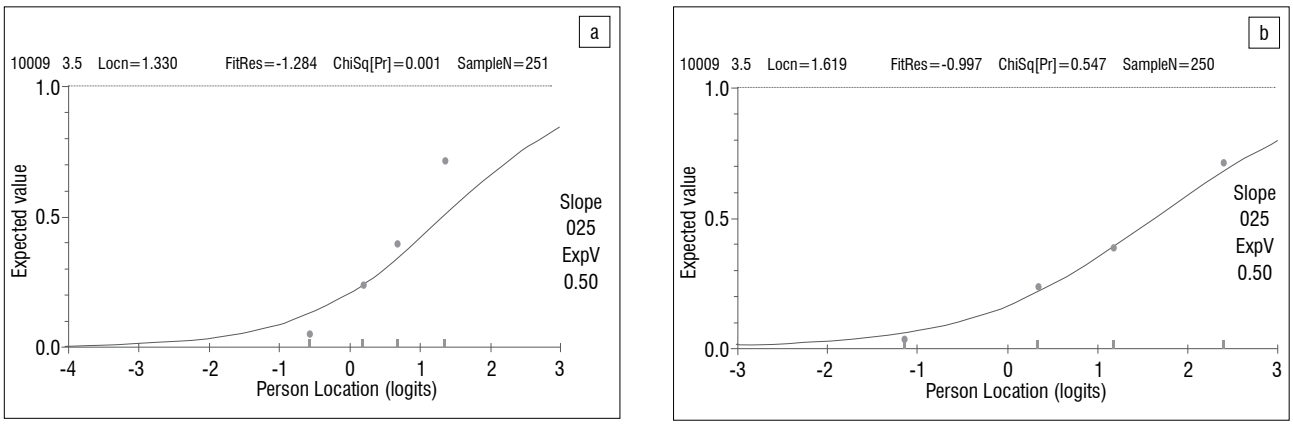


Figure 6: (a) Initial and (b) final item characteristic curve (ICC) for Item 3.5. The ICC in the original shows over discrimination. After a process of rescoring, the empirical distribution on the ICC shows much better fit, which is confirmed by the fit residual statistic which has moved from -1.284 to -0.997.

categories 1 and 2 were collapsed into 1 and categories 3 and 4 were rescored as 2. The category curves after the rescoring show that the categories are working much better. This item illustrates how rescoring can lead to a fairer outcome. Learners who produced the correct intervals were advantaged by scoring four points instead of two, while those who could not, were unduly penalised by 'losing' four possible points instead of two. The combination of these qualitative analyses of item content together with the empirical results, helps us identify possible anomalies and inconsistencies in the scoring rubrics which can alert us to possibilities that should be considered when devising scoring rubrics. A similar analysis, considering both the qualitative analysis of item content together with the empirical results, was conducted on each item.

Differential item functioning

Differential item functioning (DIF) is present when examinees from different groups have differing probabilities or likelihoods of success on an item, after they have been matched on the ability of interest.[20] That is, people from two groups, who have the same ability ranking, will perform differentially on the item with DIF. In order to preserve the unidimensionality trait of the construct under measurement, an important aspect of Rasch analysis is the investigation of the presence of DIF in the various items. For this sample, the first person factor that was considered was language. Sometimes the language used to describe the task is complicated and can pose a bigger challenge to second language speakers than first language speakers. Hence two levels of language were considered – English spoken as a first language and English spoken as a second language. Gender (female, male) was another factor that was investigated.

Before investigating for DIF in gender, the mean locations for each gender were determined. The mean location of the female group was -0.291 while that for the male group was 0.586. The probability value was 0.0036, showing that the difference was statistically significant. However, none of the specific items displayed DIF in terms of gender.

For the DIF for language, the mean location of the English second language group was not significantly different from that of the English first language group. However, one item that displayed significant DIF in terms of language was Item 7.3, shown in Figure 8.

Here the separate and sometimes parallel curves for the two groups suggest that there is uniform DIF present. As is evident in Figure 8, people at the same ability rankings have different probabilities of success for this item, based on the language person factor. For Item 23 the DIF [language] F-ratio is 22.26 with a probability value of 0.0000, showing a uniform DIF effect for language. For further technical details of detection and treatment of DIF, the reader is referred to the work by Andrich and colleagues[13,20].

Question 7.3 was part of the linear programming question and appears in Figure 9. A perusal of this question shows that the correct solution required the teachers to unpack the introductory information – the four statements signalling the constraints as well as the instruction. For a deeper understanding of the teachers' struggles, it may be helpful to consider the 'lexical density' of the instructions. Halliday[21] suggests that scientific (and mathematical) texts have a very high 'lexical density'. That is, they have a large number of lexical items (or content words) per clause. Informal spoken language has a lexical density of about two content words per clause, and written English has a lexical density of about four to six words per clause. The analysis of the instruction of Question 7.3 shows that the second clause has a lexical density of approximately 10 content words per clause. The third bulleted statement has a lexical density of 10. The other items in Question 7 (7.1; 7.2; 7.4) did not indicate DIF by language, indicating that English second language speakers who were on the same ability level as English first language speakers experienced those items as equally difficult. However, answering Question 7.3 correctly was harder for second-language English speakers than it was for first-language English speakers. The location for Question 7.3 for English second language teachers was 1.847 logits while the corresponding location of the item for

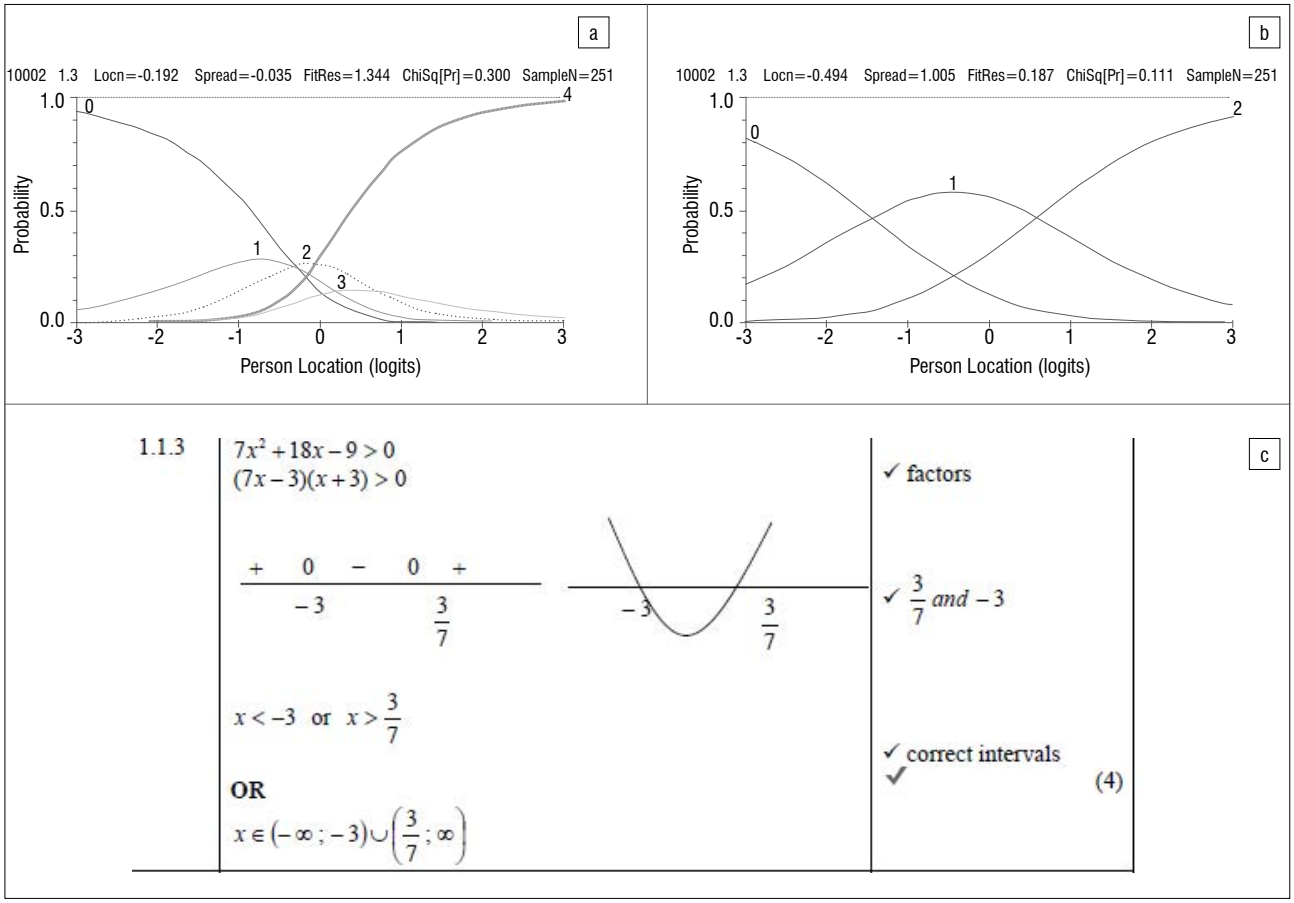


Figure 7: (a) Initial and (b) final category probability curves and (c) the marking memorandum for Item 1.3.

English first language teachers was -0.488, showing that English second language teachers experienced this item as much more difficult than did English first language teachers. It was decided to delete the item because it was not a fair question.

Response dependency and multidimensionality

The assumption of unidimensionality in a Rasch model may also be violated through response dependency between items or by multidimensionality.[11] Response dependency manifests when items are linked in some way, so that a person's response on one item depends on the response to another item. In checking for response dependency, the item residuals matrix indicated no significant response dependency between items. In order to check for multidimensionality, a principal components analysis of the residuals showed no significant patterns in the residuals. For more details of a test that can be used to detect response dependency and multidimensionality the reader can consult Smith[22].

Final statistics

A final analysis was then done by including the rescoring process that was indicated. Recall that Question 7.3 was deleted because it displayed DIF. The individual item fit statistics then revealed that none of the items was displaying significant misfit, with the fit residual statistics ranging from -1.891 to 2.082. Furthermore, the DIF summary revealed no significant DIF effects for gender or language.

In conclusion we look at the overall fit statistics again. For the distribution of the items, the fit residual statistics show slight differences from the initial statistics. The mean of the fit residual for the items has become a larger negative number, moving a bit further from the ideal of 0. The standard deviation of the fit residual has moved closer to the ideal figure of 1. With respect to the person distribution, the mean of the fit residual has moved slightly from the ideal of 0 and the standard deviation has decreased, moving slightly further from the ideal of 1.

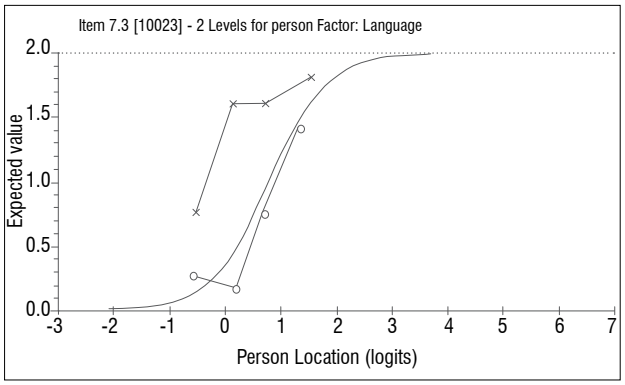


Figure 8: Item characteristic curve for Question 7.3, showing significant differential item functioning for language. English first language is represented by the crosses and English second language by the circles.

The standard deviation on the item locations is now 1.770, showing a wider spread than the original situation. The person location mean is now 0.7191, which reflects a higher proficiency than originally estimated. The standard deviation has increased, showing that there was much more variation in the person locations than originally estimated. The p-value of the chi-square statistic remained at $p=0.000$. The person separation index has remained above 0.9, showing that the test was able to differentiate between person proficiencies.

Person–item map

The Rasch ordering of the items, as compared to the cognitive levels of the items according to the Department of Basic Education assessment taxonomy,[15] is summarised in Table 4.

The ordering of the items shows that the empirical difficulty of items classified at the higher levels of the taxonomy was generally higher than those items classified at the lower levels of the taxonomy. The item difficulty was highest for Item 20 (Question 6.2), which was classified as Level 4, while that of Item 3, classified as Level 1 in the taxonomy, was the lowest. However, every item at a certain level may not necessarily be more difficult than all the items at a lower level. Sometimes certain items may, with practice, become easier to handle, or an alternative solution may provide a less complicated solution path than the expected one. This seems to have been the case for some items in this study in which not all the items in Level 4 were experienced as more difficult than items in Level 3. The item difficulty location for Item 24 (categorised as Level 4) was the same as that of Item 13 (classified as Level 2). It is also noted that the item difficulty of Items 13 and 4, which are on Level 2, were higher than some Level 3 items. Also, the item difficulty of Item 1 (Level 1) was higher than that of some items classified at Level 2. However, except for these four items, the empirical difficulty level of an item at a higher level of the taxonomy was higher than that of an item at a lower level of the taxonomy.

Figure 10 reveals a somewhat disturbing picture of many items being beyond the proficiency level of the teachers. For example, there are two teachers whose proficiency levels were measured as being lower than the difficulty levels of all the items, suggesting that these teachers could not fully answer any of the items. For 66 of the teachers, the location of all the items categorised at Levels 3 and 4 were beyond the location of their ability levels. This finding means that there is a low probability of the teachers producing correct answers to Level 3 and Level 4 items. Items placed at Level 3 (complex procedures) are those for which the solution is not straightforward and requires connections across concepts. According to the Department of Basic Education[15], Level 3 items should constitute 30% of the examination paper, while the Level 4 (problem solving) items dealing with the non-routine should constitute 15% of the paper. A burning question then arises: how will these teachers support their learners to handle those types of questions which account for 45% of the mathematics Grade 12 examination paper?

Discussion and concluding remarks

A rubric for assessment is essentially contributing to a description of a scale for measurement of the construct that is being assessed, in this

Question 7

While preparing for the 2010 Soccer World Cup, a group of investors decided to build a guesthouse with single and double bedrooms to hire out to visitors. They came up with the following constraints for the guesthouse:

- There must be at least one single bedroom.
- They intend to build at least 10 bedrooms altogether, but not more than 15.
- Furthermore, the number of double bedrooms must be at least twice the number of single bedrooms.
- There should not be more than 12 double bedrooms.

Let the number of single bedrooms be x and the number of double bedrooms be y.

7.1–7.2 *omitted here*

7.3 According to these constraints, could the guesthouse have 5 single bedrooms and 8 double bedrooms? Motivate your answer.

Figure 9: Item 23 (Question 7.3), which exhibited differential item functioning for language.

Table 3: Initial and (final) summary statistics

	ITEMS [$n=24$]		PERSONS [$n=253$]	
	Location	**Fit residual**	**Location**	**Fit residual**
Mean	0.0000 (0.000)	-0.2018 (-0.2572)	0.4557 (0.7191)	-0.2152 (-0.2319)
SD	1.0557 (1.4511)	1.5987 (1.1543)	0.8049 (1.277)	0.8741 (0.7751)
			Person separation index 0.9007 (0.9049)	
	Item–trait interaction Total item chi-square = 213.8966 (165.603) Total d.f. = 72.00 (69.00) Total chi-square probability = 0.000 (0.00)			

Table 4: Descriptors of each level of the assessment taxonomy used by the Department of Basic Education[15]

Cognitive levels	Description of problems or skills to be demonstrated
Knowledge 20%	Straight recall Identification of correct formula on the information sheet (no changing of the subject) Use of mathematical facts Appropriate use of mathematical vocabulary
Routine procedures 35%	Estimation and appropriate rounding of numbers Recall of proofs of prescribed theorems and derivation of formulae Identification and direct use of correct formula on the information sheet (no changing of the subject) Perform well-known procedures Perform simple applications and calculations which might involve few steps Derivation from given information may be involved Identification and use (after changing the subject) of correct formula Able to answer questions that are generally similar to those encountered in class
Complex procedures 30%	Problems involve complex calculations and/or higher order reasoning There is often not an obvious route to the solution Problems need not be based on a real-world context Could involve making significant connections between different representations Require conceptual understanding
Problem solving 15%	Non-routine problems (which are not necessarily difficult) Higher order reasoning and processes are involved Might require the ability to break the problem down into its constituent parts

case proficiency in mathematics. This suggests that for a test to have a fairer outcome, it is important that the rubrics are aligned with tenets of measurement. That is, if the total score allocated is made up from a sum of items, it is important to ensure that the test fulfils the measurement axioms. Tennant and Conaghan[11] explain that Rasch analysis allows for a unified approach to many measurement issues: testing the internal construct of the scale for unidimensionality, required for a valid summed raw score; response dependency and multidimensionality; appropriate category ordering of polytomous items (whether or not the category ordering of polytomous items is working as expected); and DIF (whether bias exists for an item among subgroups in the sample).

In this study, the overall fit statistics, which are an indication of how well the data fits the model, were considered first. Thereafter, individual items were analysed using the fit residual statistics, category probability curves and the ICCs together with a qualitative content analysis. It was evident that, by changing the scoring rubrics of certain items, the items produced better fitting category probability curves, and better fit statistics in most cases. No significant response dependencies were detected between items or multidimensionality. The analysis also revealed the presence of DIF with respect to the person factor of language in one item, which was evidence of bias in that item. Hence the item was deleted. After this analysis, the post-hoc improvements allowed greater precision than the original instrument scoring and the scoring was more consistent with the intentions of the scoring.

This analysis revealed that the test followed principles of good test design because the data fitted the model so well. The person–item location distribution showed a reasonable spread of items and people, and the test was targeted well at the sample. The mean of the person locations at 0.4556 logits was close to zero, suggesting that the test was a bit easy for the sample. However, this was a Grade 12 examination *written by teachers* who prepare their learners to write this examination. As such, as a group, their performance should have been much higher. The results suggest that questions based on complex procedures and those involving problem solving were beyond the competencies of many of these teachers. This study was carried out with 253 teachers representing approximately 16% of the 1581 public high schools in KwaZulu-Natal[23], and hence cannot be considered as a representative sample. However, the poor results of the teachers underscores the urgency of interventions that can succeed in improving the mathematics content knowledge of teachers. Stakeholders such as national and provincial education departments, universities and subject advisors need to collectively determine the extent of the problem of poor knowledge and to then design a systematic intervention that targets those teachers who require help. Such an intervention can work only if it is planned at a micro-level and implemented in fine detail that takes into account district factors, school factors and teacher factors.

In conclusion, it has been illustrated that Rasch measurement theory can be used to contribute to improving the scoring of an assessment instrument, and it is hoped that other researchers may opt to use the

methodology in different assessment settings. The study also revealed low proficiency levels of practising FET teachers who are expected to teach learners who will be writing similar examinations as the one used in this study. A recommendation is that FET mathematics teachers urgently need to be provided with opportunities that could help improve their proficiency levels, so that the possibility of teachers teaching learners content that they themselves do not know, is eliminated.

Acknowledgements

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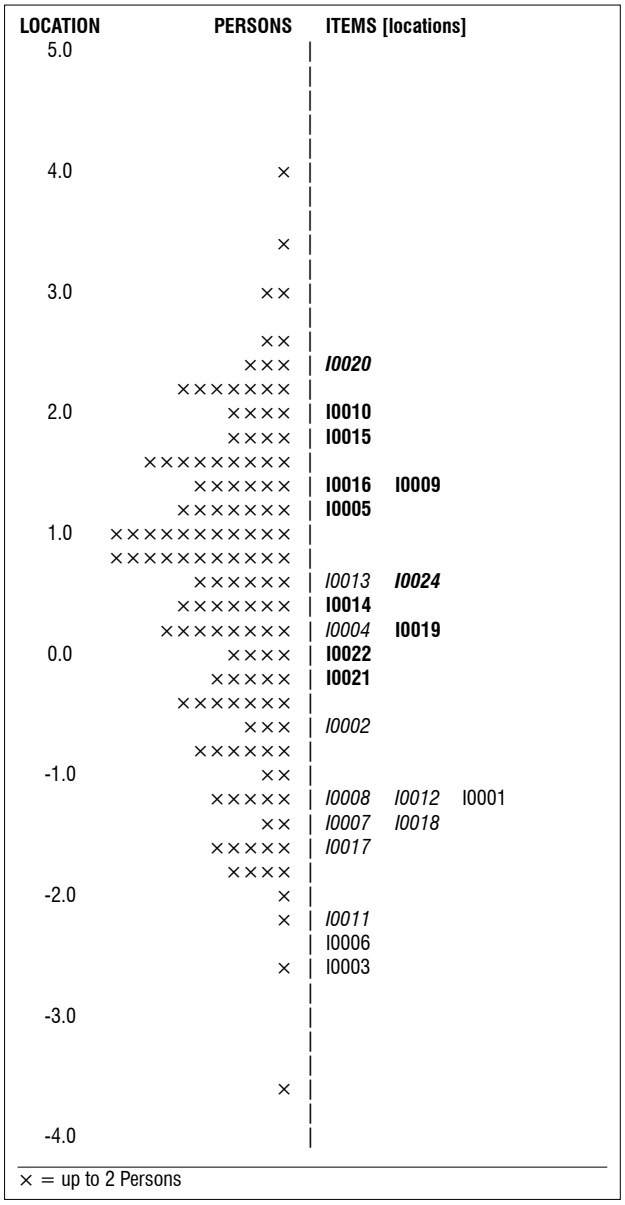

Figure 10: Person–item map approximating person proficiency and item difficulty on a common scale. Items classified at Level 1 are indicated in ordinary font, *Level 2* in italics; **Level 3** in bold and ***Level 4*** in bold italics.

References

1. Howie S. A national assessment in mathematics within an international comparative assessment. Perspect Educ. 2004;22(2):149–162.
2. Reddy V. Mathematics and science achievement at South African schools in TIMMSS 2003. Cape Town: Human Sciences Research Council; 2006.
3. Soudien C. The 'A' factor: Coming to terms with the question of legacy in South African education. Int J Educ Develop. 2007;27:182–193. http://dx.doi.org/10.1016/j.ijedudev.2006.07.006
4. Spaull N. A preliminary analysis of SACMEQ III South Africa [report]. Stellenbosch: Stellenbosch University; 2011.
5. Centre for Development and Enterprise (CDE). Value in the classroom: The quantity and quality of South Africa's teachers. CDE in Depth. 2011:11.
6. Mji A, Makgato M. Factors associated with high school learners' poor performance: A spotlight on mathematics and physical science. S Afr J Educ. 2006;26(2):253–266.
7. Hugo WJM, Wedekind V, Wilson D, et al. The state of education in KwaZulu-Natal: A report to the Provincial Treasury. Pietermaritzburg: KZN Provincial Treasury; 2010.
8. Bansilal S, Brijlall, D, Mkhwanazi TW. An exploration of the common content knowledge of high school mathematics teachers. Perspect Educ. 2014;32(1):34–50.
9. Rasch G. Probabilistic models for some intelligence and attainment tests (expanded edition with foreword and afterword by B.D. Wright). Chicago: University of Chicago Press; 1980.
10. Wright BD. A history of social science measurement. Educ Meas Issues Pract. 1997;Winter:33–45.
11. Tennant A, Conaghan PG. The Rasch measurement model in rheumatology: What is it and why use it? When should it be applied and what should one look for in a Rasch paper? Arthritis Rheum. 2007;57(8):1358–1362. http://dx.doi.org/10.1002/art.23108
12. Bond TG, Fox CM. Applying the Rasch model: Fundamental measurement in the human sciences. 2nd ed. Mahwah, NJ: Lawrence Erlbaum; 2007.
13. Andrich D. Introduction to Rasch measurement of modern test theory [course notes]. Perth: University of Western Australia; 2012.
14. Andrich D. A rating formulation for ordered response categories. Psychometrika. 1978;43:561–574. http://dx.doi.org/10.1007/BF02293814
15. Department of Basic Education (DBE). Curriculum and assessment policy statement (CAPS): Mathematics Grades 10–12. Pretoria: DBE; 2011.
16. Linacre JM. Understanding Rasch measurement: Optimizing rating scale category effectiveness. J Appl Meas. 2002;3(1):85-106.
17. Dunne T, Long C, Craig T, Venter E. Meeting the requirements of both classroom-based and systemic assessment of mathematics proficiency: The potential of Rasch measurement theory. Pythagoras. 2012;33(3), Art. #19, 16 pages.
18. Long C, Bansilal S, Debba R. An investigation of mathematical literacy assessment supported by an application of Rasch measurement. Pythagoras. 2014;35(1), Art. #235, 17 pages.
19. Van Wyke J, Andrich D. A typology of polytomously scored items disclosed by the Rasch model: Implications for constructing a continuum of achievement. Perth: Murdoch University; 2006.
20. Andrich DA, Hagquist K. Real and artificial differential item functioning. J Educ Behav Stat [serial on the Internet]. 2011 Sep 21 [cited 2014 Jun 15]. Available from: http://jebs.aera.net
21. Halliday MAK. Some grammatical problems in scientific English. In: Halliday MAK, Martin JR, editors. Writing science: Literacy and discursive power. London: Falmer; 1993. p. 69–85.
22. Smith E. Detecting and evaluating the impact of multidimensionality using item fit statistics and principal component analysis of residuals. J Appl Meas. 2002;3(2):205–231.
23. KwaZulu-Natal Department of Education. 2011 Snap survey report for ordinary schools. Pietermaritzburg: KwaZulu-Natal Department of Education; 2011.

Eutrophication and cyanobacteria in South Africa's standing water bodies: A view from space

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Satellite remote sensing can make a significant contribution to monitoring water quality in South African standing water bodies. Eutrophication, defined as enrichment by nutrients, and toxin-producing cyanobacteria (blue-green algae) blooms pose a significant threat to the quality of South African surface water bodies. The status and trends of chlorophyll *a* (chl-*a*, a proxy for eutrophication), cyanobacterial blooms and cyanobacterial surface scum were determined for South Africa's 50 largest water bodies between 2002 and 2012, using a recently developed algorithm and 10 years of data from the Medium Resolution Imaging Spectrometer (MERIS) satellite. The majority (62%) of the 50 water bodies were highly nutrient enriched or hypertrophic, while 26 had cyanobacterial blooms which posed a high health risk from surface scums. This study is the first of its kind to provide quantitative water quality information for South Africa's water bodies from a time series of satellite remotely sensed data. We demonstrate the pivotal role that satellite remote sensing can play in greatly supplementing in-situ monitoring efforts such as the National Eutrophication Monitoring Programme. The finding that many water supply bodies are severely impacted by eutrophication and cyanobacterial blooms confirms that these remain issues of critical concern for water security and supply in South Africa.

Introduction

Eutrophication and cyanobacteria in South Africa

Water is a critical resource in South Africa and is of considerable importance for ensuring sustained economic growth and development. Water of sufficient quality and quantity is required to meet basic human needs and also the demands of agriculture, industry and conservational and ecosystem uses. The *National Water Act*[1] is the overarching framework setting forth how South Africa's water resources should be distributed, managed and protected. Under the Act, water quality guidelines are promulgated for potable (domestic), industrial, agricultural, recreational and other uses. These guidelines specify the minimum quality requirements to meet the intended use. Water quality can be specified in terms of chemical composition, biological composition (e.g. algae), microbiological composition and physical condition (e.g. clarity or temperature). Poor water quality constitutes a risk to human health and safety through waterborne diseases and reduced visibility, and has negative aesthetic and economic impacts that increase the cost of treatment.[2] Poor water quality is 'one of the major threats to South Africa's capacity to provide sufficient water...to meet its needs and ensure environmental sustainability'[3]. According to South Africa's water policy:

> *Ongoing monitoring and assessment* [is] *critical to our ability to manage and protect* [water] *resources on the basis of sound scientific and technical information and understanding. Adequate information is essential for effective resource management and protection.*[4]

Therefore there is substantial impetus for taking measures to assess, maintain and protect water quality, through using advanced tools such as remote sensing.

South Africa's limited freshwater surface waters are vulnerable to environmental degradation, in particular from eutrophication.[5] Eutrophication refers to the process of nutrient enrichment of water primarily from effluent and agricultural sources of nitrogen and phosphorus. The trophic status of water refers to the degree to which it is nutrient enriched. A water body may be classified as 'oligotrophic' (little nourished), 'mesotrophic' (medium nourished), 'eutrophic' (well nourished) or 'hypertrophic' (very well nourished). Eutrophic and hypertrophic waters suffer from a wide range of negative impacts including increased phytoplankton blooms, turbid water conditions, increased cyanobacteria (blue-green algae), taste and odour problems, oxygen depletion (anoxia), increased incidence of fish kills, loss of biodiversity and decreased aesthetic value. Cyanobacteria thrive in eutrophic water and pose a problem for water treatment through dense cell accumulation; some species pose a health risk as a result of the production of intracellular toxins that are fatal when ingested in large quantities by humans or other animals. Dense surface accumulations of cyanobacteria (called surface scums) have significant negative ecological consequences on the diversity and functioning of the plankton community and higher order organisms, and are a high-risk health threat for recreational and other water users.[6,7] Surface scums are also an important ecological indicator of over-enrichment and meteorological warming and senescence.[8]

It has been estimated that eutrophic conditions exist in one in five of 75 major impoundments[9] and in 18 of 25 major river catchments[10]. According to data collected by the National Eutrophication Monitoring Programme (NEMP) of the Department of Water Affairs between April and September 2013, approximately 28% of surface water samples are hypertrophic, 33% are eutrophic, 37% are mesotrophic and only 3% are oligotrophic.[11] Cyanobacteria, including *Microcystis* and *Anabaena* species, are present in all major impoundments at levels dependent on the trophic state.[12-14] Poisonings of domestic and wild animals by cyanobacterial toxins are geographically widespread and occur frequently.[15] These toxic blooms are 'a threat to the supply of safe drinking water to the whole population of South Africa'[14].

The severity of eutrophication and cyanobacterial blooms is an economic burden on South Africa because of: the costs associated with water treatment; negative effects on water-side property values; recreational and tourism losses as a result of users' negative perceptions of water quality; negative human health impacts from poor water quality including diarrhoea, cholera and waterborne diseases; animal fatalities; poor aquatic ecology negatively affecting ecosystem services; reduced biodiversity and proliferation of invasive species; and the cost of management and control of aquatic macrophytes (e.g. water hyacinth).[16] The economic cost of eutrophication is likely to extend to hundreds of millions of rands per year, being borne across all levels of society, but particularly affecting the livelihoods and health of the poor and vulnerable. This estimation is substantiated by studies in the USA and Great Britain in which it was found that the cost of eutrophication was greater than USD2.2 billion per year in 2009[17], and USD160 million per year in 2003[18], respectively.

Why satellite remote sensing?

South Africa's national monitoring systems are required to provide information on the quality and health of aquatic ecosystems and to assess compliance with quality objectives and progress of measures for rehabilitation.[1] The NEMP collects and analyses surface water samples from around 160 dams, lakes and rivers nationally on a nearly monthly basis. Point samples are analysed for chlorophyll-*a* concentration, phytoplankton type, chemical parameters nitrogen and phosphorus and the Secchi disk depth. The NEMP success story is under pressure from rising costs of sampling, the need to constantly sample more widespread locations, the uneven geographical distribution and capabilities of laboratories, the high rate of human capital overturn and limited budget allocations. There remain large information gaps regarding the trophic status and presence and severity of cyanobacterial blooms in South African water bodies which constitutes a risk to public health. The very large number of artificial impoundments (497 reservoirs with a capacity larger than one million cubic metres[16]) makes comprehensive monitoring using conventional methods an almost impossible task.

Satellite remote sensing can substantially contribute to alleviating some of the challenges faced by the NEMP through: supplementing in-situ surface monitoring; maximising the potential of the NEMP database and networks; monitoring geographically widespread locations; streamlining in-situ sampling operations leading to long-term cost savings; and providing retrospective and near-real-time information (Cele S 2014, oral communication, February 12). The integration of satellite remote sensing into the NEMP can enable resources to be more effectively utilised for the management, assessment and monitoring of eutrophication, and also reduce the risks associated with cyanobacterial blooms and surface scums through near-real-time response and warning systems.

Recent advances, new possibilities

Recent advances in space technology and ongoing research on water remote sensing in South Africa have made systematic monitoring of eutrophication and cyanobacterial blooms in small inland water bodies from space a reality.[19,20] The Medium Resolution Imaging Spectrometer (MERIS) satellite, which operated from 2002 until April 2012, had a spatial resolution of 260 m by 290 m, an acquisition frequency of 2 to 3 days, and 15 spectral bands ideally positioned for water-related applications. These specifications, not offered by current high spatial resolution satellites (e.g. Landsat or SPOT), coupled with the recent development of novel algorithms for detecting chlorophyll-*a* (chl-*a*) and cyanobacteria[20] have allowed MERIS data to be exploited for near-real-time monitoring (see http://www.afro-sea.org.za/php/damSearch.php for demonstration system). The most recent research reported on here includes a time series from 2002 to 2012 of eutrophication and cyanobacterial blooms in South Africa's 50 largest water bodies.[21] The coming launch of the Sentinel-3 mission in 2015 will ensure that MERIS-equivalent data is freely available from 2016 onwards until at least 2026. These data – along with those from other water-observing satellite missions to be launched in the near future, such as the high spatial resolution Sentinel-2 mission – will make satellite remote sensing an indispensable tool for monitoring small inland water bodies.

Aims and objectives

In this paper, we present additional results from a retrospective study[21] using 10 years of MERIS data to assess eutrophication and cyanobacterial blooms in 50 of South Africa's largest water bodies. We present case studies illustrating the usage of MERIS data for monitoring algal blooms, cyanobacterial blooms and surface scums. The robustness of the satellite estimates are demonstrated using a comparison between satellite estimates and data collected in situ through the NEMP. A summary is presented of the status and trends of eutrophication and the occurrence of cyanobacterial blooms and surface scum for the water bodies; and a scoring system is used to identify those water bodies in the most urgent need of management attention. Our intention is to illustrate the power of satellite remote sensing applied to small South African inland water bodies, and the potential application from both past and future satellite instruments.

Methods

Water-quality assessments from satellite remote sensing are restricted to *surface water* visible from space. Parameters that can be directly retrieved from remote sensing are limited to those that *effect a change in the colour of the water in the visible and near infra-red light spectrum*. Variables defined in the water-quality guidelines directly retrievable from remote sensing include phytoplankton measured by the concentration of chl-*a*, the dominant phytoplankton group, water clarity measured by Secchi disk or turbidity, total non-dissolved suspended solids and nuisance plants (macrophytes). These variables are essential for assessing water quality for various uses especially agriculture, recreation and ecological uses.

The 50 largest water bodies by surface area in South Africa were selected for the analysis. The data set excluded water bodies that were too narrow (<600 m) or had prolonged dry periods, and estuaries subject to tidal influence. The MERIS full-resolution data archive (approximately 20 Tb) over southern Africa was acquired. The data were available for the period between 2002 and April 2012 after which MERIS ceased collecting data. The details of the methods used to process the data and perform the time series analysis can be found in Matthews[21]. The chl-*a* and cyanobacterial products were computed using an algorithm (called the maximum peak height or MPH algorithm) recently developed for use in small South African inland and coastal waters.[20] The algorithm is the first of its kind to provide quantitative chl-*a* estimates for oligotrophic and hypertrophic waters and to discriminate between cyanobacteria and other phytoplankton blooms. Cases of potential cyanobacterial surface scum formation, which poses a high health risk, were identified by cyanobacteria with 753 nm reflectance peak positions or chl-*a* concentrations greater than 350 mg/m^3. This value is near the minimum at which the typical vegetation-like scum spectra might be observed[22]; however, scum may exist at even lower biomass. This definition does not include all high-risk cyanobacterial blooms which exist for chl-*a* concentrations greater than 50 mg/m^3.[7]

The precise time and location of in-situ NEMP chl-*a* data were not recorded. Therefore satellite data used for comparison with these data were extracted from the position corresponding with the most likely location of sampling using the mean value for ±10 pixels. Only same-day matchups were used. Water bodies that had very few matchups or poor correlations (likely because of spatial mismatch) were excluded.

The 50 water bodies were scored using a classification scheme. The score for chl-*a* was from 0 to 3, where 0 was for oligotrophic and 3 was for hypertrophic classes (see below for thresholds). Similar classes were determined for cyanobacteria coverage (0 to 1%, 1 to 10%, 10 to 30% and greater than 30%) and scum (0 to 1%, 1 to 5%, 5 to 10% and greater than 10%) and each class was scored between 0 and 3 from least to most impacted. The thresholds were determined after examining the data distributions. While the thresholds of the classes are somewhat arbitrary, they can help in identifying those water bodies which are most

impacted by eutrophication, cyanobacterial blooms and surface scum, although the management priority for each of these variables may not be equal. The overall score (between 0 and 9) for each water body was computed as the sum of the scores for the three variables.

Results

A view from space: Case studies

Ceratium hirundinella blooms in Albert Falls Dam

Hart and Wragg[23] first reported on the occurrence of *C. hirundinella* blooms at Albert Falls in 2006. The study included a detailed survey of the lake in October 2006 and January 2007 for which maps of the spatial distribution of chl-*a* were produced. The satellite imagery shows nearly identical values and spatial distribution of chl-*a* to the maps produced from interpolating in-situ samples (Figure 1). The clearer conditions that existed in January 2007 towards the main basin of the reservoir are vividly reproduced in the satellite observations, as are the high biomass *C. hirundinella* blooms towards the inflow in the southeast. The values estimated from the satellite compare closely with those measured in situ, with a maximum value towards the inflow near 200 mg/m^3 and satellite lake averages between 7.4 mg/m^3 and 19.5 mg/m^3 compared to in-situ lake averages for October and January of 11.7 mg/m^3 and 16.4 mg/m^3, respectively. There is a general correlation between a time series of satellite and in-situ observations for Albert Falls Dam (Figure 2). In particular, the *Ceratium* bloom events of spring/summer 2004 and winter 2006 are reproduced, as recorded in Hart and Wragg[23]. The satellite data suggest that *Ceratium* blooms occur periodically, coinciding with summer.

Winter cyanobacterial blooms in Midmar Dam

Winter cyanobacterial blooms that occurred in Midmar Dam in 2005 were first reported by Oberholster and Botha[24]. Winter maxima of cyanobacteria are not expected because cyanobacteria are known to generally favour water temperatures greater than 20 °C. However, recent satellite observations have shown that several South African water bodies have winter cyanobacterial blooms.[21] The explanation for winter cyanobacterial blooms could be related primarily to increased nutrient availability (nitrogen), tentatively attributed to large populations of waterfowl.[24] It is possible that the same explanation might be given for the observation of winter cyanobacterial blooms in perennial lakes in the semi-arid eastern summer rainfall region of South Africa, which serve as a refuge for waterfowl during the dry winter months.[25,26] The winter cyanobacterial blooms identified by Oberholster and Botha[24] were also identified from MERIS (Figure 3). The cyanobacteria flag was raised for certain pixels (coloured green) towards the shoreline (indicated by arrows). The location of the cyanobacterial detection corresponds closely with the observations of Oberholster and Botha[24]. This finding demonstrates the great sensitivity of the satellite data for detecting cyanobacterial blooms.

Microcystis surface scum in Hartbeespoort Dam

Hartbeespoort Dam is renowned worldwide for its extremely high biomass blooms of *Microcystis aeruginosa* cyanobacteria and the formation of surface scums which are often toxic (also called hyperscums[27]). The optical characteristics of *M. aeruginosa* blooms have recently been investigated in detail.[28] Oberholster and Botha[29] used

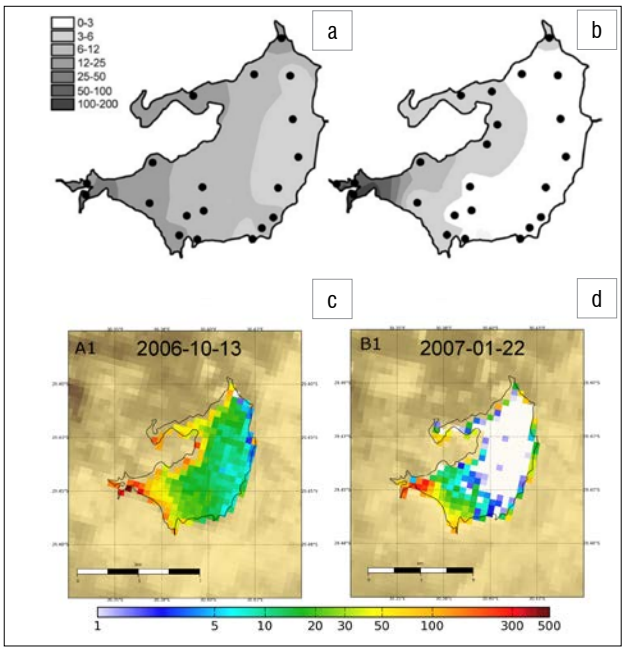

Figure 1: A comparison between the spatial distribution and magnitude of chl-*a* determined from in-situ and satellite measurements for *Ceratium hirundinella* blooms in Albert Falls Dam. The chl-*a* maps for (a) October 2006 and (b) January 2007 are taken from Hart and Wragg[23] with permission. MERIS scenes acquired simultaneous to in-situ measurements are shown for (c) 13 October 2006 and (d) 22 January 2007.

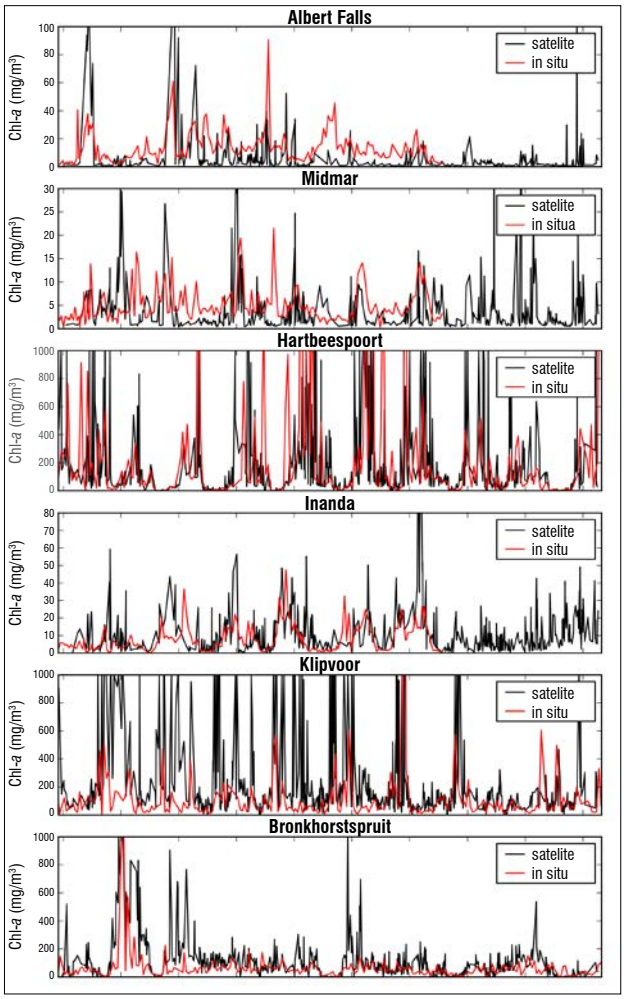

Figure 2: Comparison between time series of satellite-derived chl-*a* and that measured in situ by the National Eutrophication Monitoring Programme for six reservoirs. Note that the exact position of in-situ sampling was not recorded. GPS coordinates for MERIS pixel extractions (top to bottom): 30.38E 29.45S; 30.19E 29.50S; 27.86E 25.73S; 30.87E 29.69S; 27.81E 25.13S and 28.71E 25.89S.

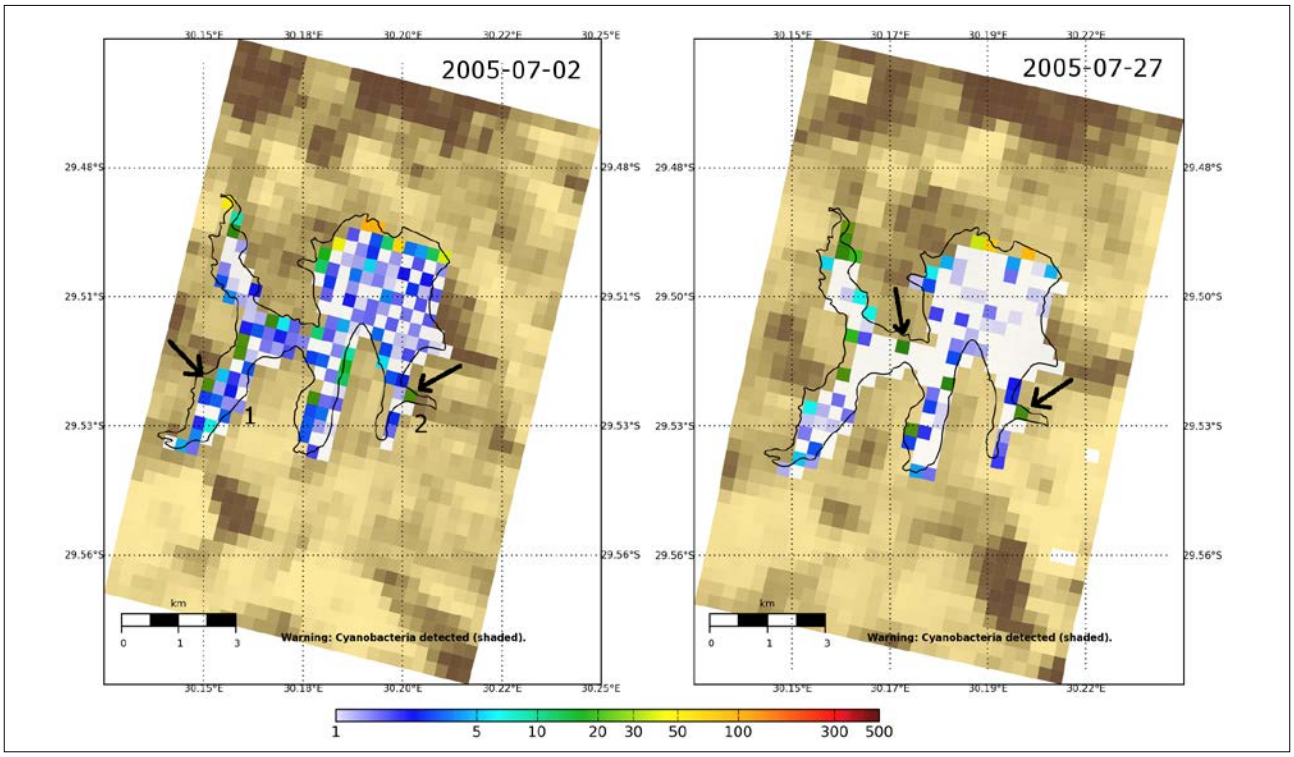

Figure 3: Chl-*a* maps for Midmar Dam showing two scenes acquired near or simultaneous to measurements made by Oberholster and Botha[24] illustrating winter cyanobacteria detection. The sample points in Oberholster and Botha[24] are indicated at 1 and 2; the maximum chl-*a* value measured was 92 mg/m^3. The arrows indicate pixels identified as cyanobacteria.

Landsat satellite imagery to observe these hyperscums and surface scum accumulations. These surface scums were also identified from MERIS[21]. MERIS data acquired 10 min or less apart from Landsat imagery is used to demonstrate the detection of scum (Figure 4). Surface scums appear as bright green slicks on the water surface in the true colour Landsat imagery,[29] and are coloured dark green for pixels in the MERIS scenes. The simultaneously acquired Landsat and MERIS scenes have very similar spatial patterns which verify the accuracy of scum detection from the lower spatial resolution MERIS data.

Comparison with National Eutrophication Monitoring Programme data

Sufficiently good matchup data were found for six water bodies. In general, there is a close similarity between the chl-*a* estimates from the satellite and those from the NEMP (Figure 2). The magnitudes and periodic occurrence of bloom events are closely reproduced for Hartbeespoort Dam, showing the clearer water periods which occurred in the winter months of 2004, 2005 and 2011. The magnitudes of chl-*a* determined from satellite data of Midmar Dam are generally slightly lower than those measured in situ. This difference could be a result of the location used to collect samples. The satellite estimates for Inanda Dam closely match the seasonal variability in in-situ measurements of chl-*a* which have very similar magnitudes. Klipvoor and Bronkhorstspruit Dams typically have blooms with much higher chl-*a* values which are also observed from the satellite. The values are quite similar, although there may be a slight tendency for the satellite data to overestimate chl-*a* for these dams. These examples demonstrate that satellite estimates typically match the magnitude and seasonal variability of the NEMP data, and can therefore be treated with confidence. For further matchup analysis see Matthews[21].

Ten years of MERIS observations

Status and trends

The results of the 10-year time series for 50 water bodies are summarised in Table 1 and Figure 5. Figure 5 shows the average values and trends for chl-*a*, cyanobacteria area coverage and surface scum between 2002 and 2012. Of the 50 water bodies, 36 were hypertrophic (chl-*a* greater than 30 mg/m^3), 3 were eutrophic (chl-*a* of 20–30 mg/m^3), 4 were mesotrophic (chl-*a* of 10–20 mg/m^3) and 7 were oligotrophic (chl-*a* less than 10 mg/m^3). Cyanobacterial blooms were identified in all 50 of the water bodies during the time period. Extensive cyanobacterial blooms (greater than 30%) were present in 5 water bodies, 18 had intermediate coverage (10–30%), 13 had little coverage (1–10%) and 14 had insignificant coverage (0–1%). Surface scum was recorded in 26 of the 50 water bodies in varying degrees. The coverage was less than 1% for 23 of these water bodies, indicating that surface scum was an infrequent or rare event. Occasional scum events (1–5% coverage) were found in Spitskop and Darlington Dams, while Hartbeespoort Dam had more than 10% coverage, signalling frequent scum events.

A group of highly turbid reservoirs – including Mthatha, Ncora, Erfenis, Krugersdrift, Ntshingwayo and Allemanskraal Dams – had the highest chl-*a* values. As mentioned by Matthews[21], these high values could be attributed to high turbidity which may cause unexpected operation of the MPH algorithm. These results should be considered preliminary until they can be further validated. Aside from these, the reservoirs most severely impacted by eutrophication were Grassridge, Klipvoor and Bloemhof. The three reservoirs least impacted were Sterkfontein, Pongolapoort and Midmar. The three water bodies most severely impacted by cyanobacterial blooms were Barberspan, Hartbeespoort and Koppies, with an average area coverage greater than 45%. Lake Chrissiesmeer, Spitskop and Vaal Dams were also heavily impacted with close to 30% average coverage. Cyanobacterial blooms and surface scum coverage reached their maximum extents at the end of the summer season in March and April. The high prevalence of cyanobacterial blooms in these water bodies is cause for immediate concern for potable, recreational and agricultural uses.

Analysis of the trends between 2005 and 2011 showed that water bodies had considerable variability in terms of the change in trophic status and cyanobacteria occurrence (Table 2, Figure 5). Trends were analysed for significance using a Student's *t*-test with a 95% confidence interval; only significant trends are reported. There were more negative trends (17) than positive trends (8) for chl-*a*. Those water bodies most vulnerable to increasing eutrophication were Darlington, Heyshope, Kalkfontein, Lubisi, Rustfontein, Vanderkloof and Xonxa.

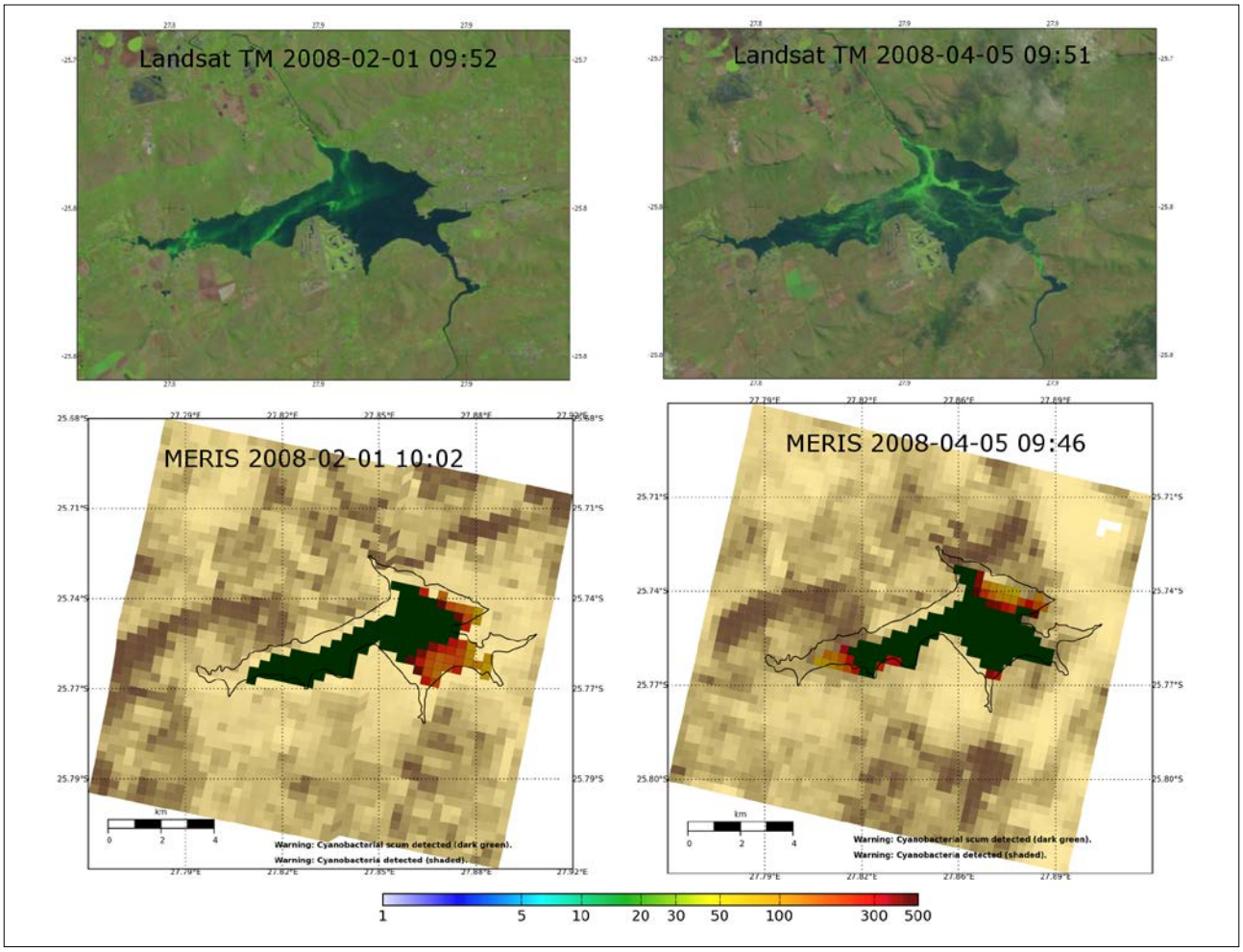

Figure 4: Surface scum maps of Hartbeespoort Dam from simultaneously acquired MERIS and Landsat imagery. Dark-green pixels correspond to surface scum in the MERIS imagery.

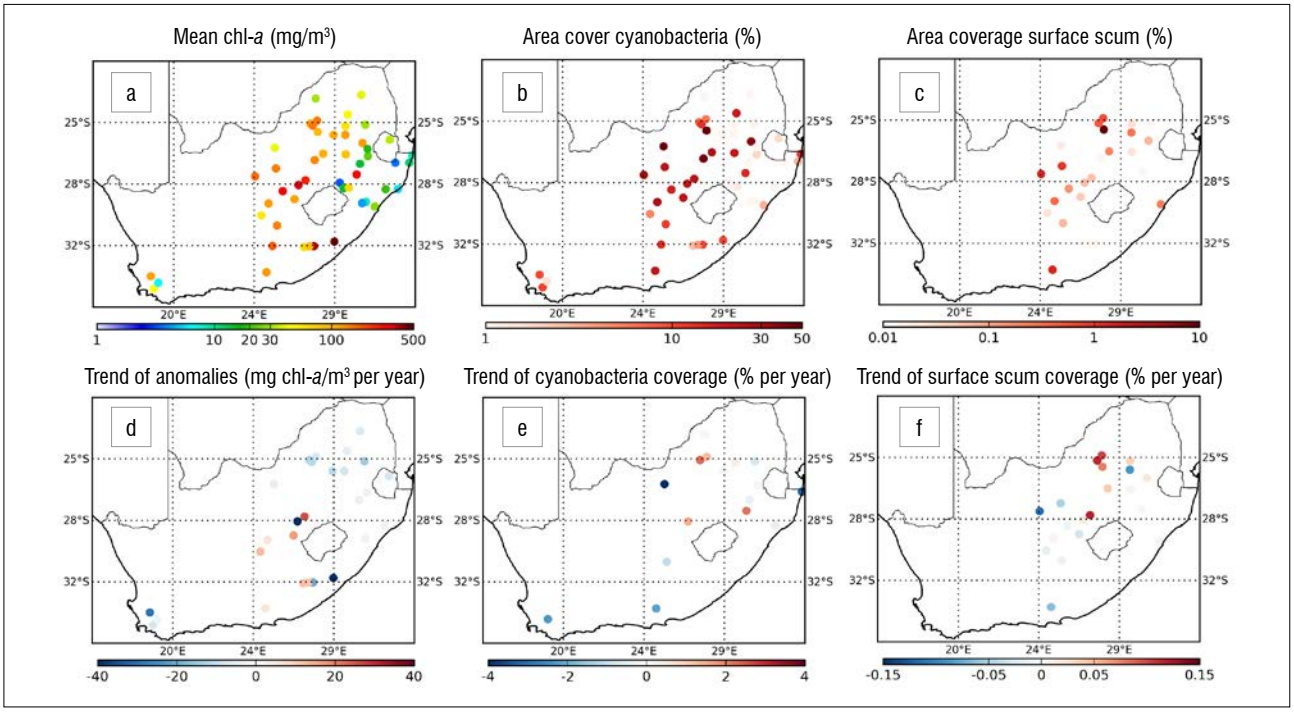

Figure 5: Maps of South Africa showing the mean and trends for (a, d) chl-*a*, (b, e) cyanobacteria coverage and (c, f) scum coverage determined from a time series of 10 years of MERIS data.

Table 1: Ten-year average values for chl-*a*, cyanobacteria area coverage (A_{cy}), surface scum area coverage (A_{sc}) and final classification score for 50 of the largest South African water bodies ordered by surface area. Italicised results require further verification.

Water body	Type	Chl-*a* (mg/m³)	A_{cy} (%)	A_{sc} (%)	Score
Gariep	Reservoir	137.2	11.6	0.1	5
Vaal	Reservoir	99.6	27.1	0.2	5
Bloemhof	Reservoir	142.8	22.1	0.8	5
Pongolapoort	Reservoir	3.8	0.3	0.0	0
Vanderkloof	Reservoir	55.3	5.1	0.0	4
Sterkfontein	Reservoir	3.3	0.0	–	0
Lake Sibhayi	Coastal lake	10.8	2.9	–	2
Darlington	Reservoir	120.5	19.8	1.3	6
Theewaterskloof	Reservoir	43.1	10.4	–	5
Heyshope	Reservoir	23.7	1.8	–	3
Kalkfontein	Reservoir	117.3	26.8	0.3	5
Grootdraai	Reservoir	81.8	18.9	0.0	5
Spitskop	Reservoir	163.4	31.7	1.3	7
Erfenis	*Reservoir*	*351.4*	*21.4*	*0.1*	*5*
Kuhlange	Coastal lake	8.3	13.1	–	2
Allemanskraal	*Reservoir*	*248.0*	*22.7*	*0.1*	*5*
Woodstock	Reservoir	14.3	0.5	–	1
Loskop	Reservoir	58.1	0.4	0.0	3
Albert Falls	Reservoir	8.4	0.0	–	0
Brandvlei	Reservoir	6.4	1.6	–	1
Ntshingwayo	*Reservoir*	*314.2*	*15.3*	*0.0*	*5*
Tzaneen	Reservoir	39.9	0.0	–	3
Hartbeespoort	Reservoir	92.6	48.6	10.2	9
Krugersdrift	*Reservoir*	*317.9*	*17.1*	*0.1*	*5*
Mthatha	*Reservoir*	*478.3*	*9.8*	–	*4*
Voëlvlei	Reservoir	114.7	10.0	–	5
Midmar	Reservoir	4.4	0.0	–	0
Xonxa	Reservoir	65.6	2.5	0.0	4
Spioenkop	Reservoir	67.5	1.3	–	4
Ncora	*Reservoir*	*380.5*	*10.5*	–	*5*
Barberspan	Endorheic pan	42.0	52.8	0.0	6
Klipvoor	Reservoir	145.7	6.0	0.5	4
Grassridge	Reservoir	176.7	14.7	–	5
Koppies	Reservoir	133.0	46.9	0.0	6
Zaaihoek	Reservoir	14.3	0.8	–	1
Lubisi	Reservoir	82.8	4.0	0.0	4
Lake Chrissiesmeer	Endorheic pan	116.8	37.1	0.1	6
Flag Boshielo	Reservoir	42.6	18.6	–	5
Goedertrou	Reservoir	20.1	0.5	–	2
Rustfontein	Reservoir	115.6	21.4	0.0	5
Fairview	Reservoir	33.3	1.7	–	4
Vaalkop	Reservoir	108.5	7.0	–	4
Kwena	Reservoir	30.2	1.1	0.0	4
Roodekoppies	Reservoir	147.0	13.1	0.5	5
Witbank	Reservoir	117.5	0.7	0.3	3
Lake Msingazi	Coastal lake	5.6	0.0	–	0
Bronkhorstspruit	Reservoir	105.9	0.4	–	3
Jericho	Reservoir	18.7	0.1	–	1
Mokolo	Reservoir	31.4	0.0	–	3
Inanda	Reservoir	27.3	3.1	0.2	3

In contrast, those water bodies which had the greatest improvement were Bronkhorstspruit, Kwena, Ncora, Roodekoppies, Vaalkop and Voëlvlei. These trends must be treated with some caution as the time period is short (2005 to 2011, because of years with incomplete data) and the data are therefore vulnerable to outliers and anomalous events. There were significant increases in cyanobacteria for Klipvoor and Vaalkop Dams. By comparison, decreased cyanobacterial blooms were recorded in Barberspan, Brandvlei, Darlington and Kuhlange (Kosi Lake). There was a small but significant increase in the occurrence of surface scums in Lake Chrissiesmeer, Loskop, Vaal and Roodekoppies Dams. The occurrence of only one significant decrease for scums signals that these events likely became more common over the time period.

Classification

In terms of the synthesis, the most impacted reservoir was Hartbeespoort Dam which scored a nine (Table 1, Figure 6). According to the data, the reservoir is hypertrophic and heavily impacted by frequent and extensive cyanobacterial blooms and scum events. These findings are corroborated by many studies which indicate the reservoir is one of the most productive in the world and is severely impacted by the toxin-producing *M. aeruginosa*. Spitskop scored the next highest with seven, and is also affected by severe eutrophication, cyanobacterial blooms and scum events. Darlington, Barberspan, Koppies and Lake Chrissiesmeer scored six and are all heavily impacted by eutrophication and cyanobacterial blooms (although not necessarily scums). Alarmingly, these include South Africa's two largest natural endorheic pans (Barberspan and Chrissiesmeer) which are crucial for biodiversity and avian conservation.

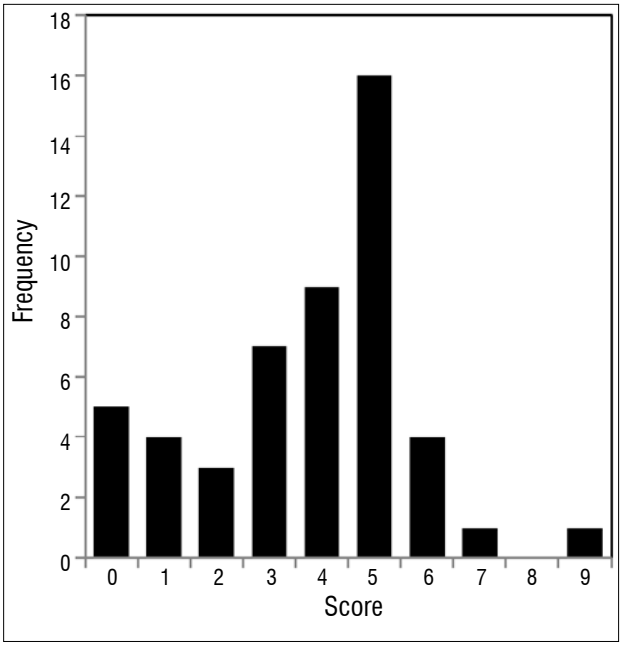

Figure 6: Histogram of frequency of scores according to the classification scheme in which zero is least impacted and nine is most impacted (see text for significance of score).

Table 2: Trends significant at 95% confidence interval between 2005 and 2011. Empty entries were not significant. Preliminary results from highly turbid water bodies excluded.

Water body	Chl-*a* (mg/m^3 per year)	A_{cy} (% per year)	A_{sc} (% per year)
Albert Falls	-1.7		
Barberspan	-3.6	-6.3	
Brandvlei	-1.3	-2.3	
Bronkhorstspruit	-10.5	-0.1	
Lake Chrissiesmeer			0.02
Darlington	5.3	-2.1	
Fairview	-6.9		
Flag Boshielo	-3.5		
Gariep		-1	
Goedertrou	-1.3	-0.3	
Heyshope	2.1		
Jericho		0.02	
Kalkfontein	5.1		
Klipvoor	-6.7	1.2	
Kuhlange	-1.9	-3.2	
Kwena	-14.2	-0.8	
Lake Msingazi	0.4		
Loskop		0.3	0.03
Lubisi	11.2		
Roodekoppies	-10.7		0.11
Rustfontein	16.7		
Theewaterskloof	-7.0		
Tzaneen	-5.8		
Vaal			0.04
Vaalkop	-12.4	2.3	
Vanderkloof	12.7		-0.01
Voëlvlei	-28.8		
Witbank	-7.2		
Xonxa	12.0		
Zaaihoek	-2.6	-0.3	

The highest number of water bodies had scores of four or five with common to occasional cyanobacterial blooms. These water bodies should also receive priority from management. There were 12 water bodies with scores of two or less, which indicates oligotrophic or mesotrophic water bodies with infrequent/insignificant cyanobacterial blooms. Although these water bodies are in a favourable state, measures should be taken to maintain their condition.

Conclusion

Satellite remote sensing has been used to assess the condition of 50 of South Africa's largest water bodies with regard to trophic status (chl-*a*) and the occurrence of cyanobacterial blooms and surface scums. We have shown that the majority of these water bodies are heavily impacted by eutrophication and cyanobacterial blooms. As much as 62% of the water bodies were hypertrophic, cyanobacterial blooms were recorded in all the water bodies, and cyanobacteria surface scum posing a high health risk occurred in 26 (or 54%) of the 50 water bodies. Surface scum events became more common between 2005 and 2011 in four water bodies. Therefore eutrophication and cyanobacterial blooms remain issues of critical concern for water security in South Africa and require urgent and sustained management attention.

In this study, we have demonstrated both the power and efficiency of satellite remote sensing used on a sub-continental (national) scale. We have shown how satellite remote sensing estimates compare closely with in-situ data from the NEMP, and can be used to supplement monitoring programmes to fill information gaps and provide new insights into the occurrence and seasonality of cyanobacterial blooms and surface scum. We recommend that satellite remote sensing be integrated into the NEMP to take advantage of historical data and those data that will become available from future satellite missions, in particular from the Sentinel-3 mission.

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Authors' contributions

This work is based on a PhD thesis by M.W.M. who performed the analysis and wrote the manuscript. S.B. supervised and reviewed the work.

References

1. Republic of South Africa. The National Water Act (36 of 1998). Pretoria; 1998.
2. Department of Water Affairs and Forestry (DWAF). South African water quality guidelines, Volume 2: Recreational use. 2nd ed. Pretoria: DWAF; 1996.
3. Department of Water Affairs and Forestry (DWAF). National water resources strategy. Pretoria: DWAF; 2004. p. 22.
4. Department of Water Affairs and Forestry (DWAF). White paper on a national water policy for South Africa. Pretoria: DWAF; 1997. p. 6.8.
5. Van Ginkel CE. Eutrophication: Present reality and future challenges for South Africa. Water SA. 2011;37(5):693–701. http://dx.doi.org/10.4314/wsa.v37i5.6
6. Oberholster PJ, Botha A-M, Ashton PJ. The influence of a toxic cyanobacterial bloom and water hydrology on algal populations and macroinvertebrate abundance in the upper littoral zone of Lake Krugersdrift, South Africa. Ecotoxicology. 2009;18(1):34–46. http://dx.doi.org/10.1007/s10646-008-0254-5
7. Chorus I, Falconer IR, Salas HJ, Bartram J. Health risks caused by freshwater cyanobacteria in recreational waters. J Toxicol Environ Health. 2000;Part B(3):323–347.
8. Paerl HW, Huisman J. Climate change: A catalyst for global expansion of harmful cyanobacterial blooms. Environ Microbiol Rep. 2009;1(1):27–37. http://dx.doi.org/10.1111/j.1758-2229.2008.00004.x
9. Department of Water Affairs and Forestry (DWAF). Trophic status report: Trophic status of impoundments. Pretoria: DWAF; 2003.
10. De Villiers S, Thiart C. The nutrient status of South African rivers: Concentrations, trends and fluxes from the 1970s to 2005. S Afr J Sci. 2007;103(7–8):343–349.
11. Department of Water Affairs. National Eutrophication Monitoring Programme phosphorus and chlorophyll summaries. Pretoria: DWA; 2013. Available from: http://www.dwaf.gov.za/iwqs/eutrophication/NEMP/report/NEMPyears.htm
12. Scott WE. Occurrence and significance of toxic cyanobacteria in southern Africa. Water Sci Technol. 1991;23(1–3):175–180.
13. Van Ginkel CE, Silberbauer MJ, Vermaak E. The seasonal and spatial distribution of cyanobacteria in South African surface waters. Verhandlungen Int Vereinigung für Theor und Angew Limnol. 2000;27:871–878.
14. Van Ginkel CE. A national survey of the incidence of cyanobacterial blooms and toxin production in major impoundments. Report No.: N/0000/00/DEQ/0503. Pretoria: Department of Water Affairs and Forestry; 2004.
15. Oberholster PJ, Botha A-M, Myburgh JG. Linking climate change and progressive eutrophication to incidents of clustered animal mortalities in different geographical regions of South Africa. J Biotechnol. 2009;8(21):5825–5832.
16. Oberholster PJ, Ashton PJ. State of the nation report: An overview of the current status of water quality and eutrophication in South African rivers and reservoirs. Pretoria: CSIR; 2008. p. 1–14.
17. Dodds WK, Bouska WW, Eitzmann JL, Pilger TJ, Pitts KL, Riley AJ, et al. Eutrophication of US freshwaters: Analysis of potential economic damages. Environ Sci Technol. 2009;43(1):12–19. http://dx.doi.org/10.1021/es801217q
18. Pretty JN, Mason CF, Nedwell DB, Hine RE, Leaf S, Dils R. Environmental costs of freshwater eutrophication in England and Wales. Environ Sci Technol. 2003;37(2):201–208. http://dx.doi.org/10.1021/es020793k
19. Matthews MW, Bernard S, Winter K. Remote sensing of cyanobacteria-dominant algal blooms and water quality parameters in Zeekoevlei, a small hypertrophic lake, using MERIS. Remote Sens Environ. 2010;114(9):2070–2087. http://dx.doi.org/10.1016/j.rse.2010.04.013
20. Matthews MW, Bernard S, Robertson L. An algorithm for detecting trophic status (chlorophyll-a), cyanobacterial-dominance, surface scums and floating vegetation in inland and coastal waters. Remote Sens Environ. 2012;124:637–652. http://dx.doi.org/10.1016/j.rse.2012.05.032
21. Matthews MW. Eutrophication and cyanobacteria blooms in South African inland waters: 10 years of MERIS observations. Remote Sens Environ. 2014;155:161–177. http://dx.doi.org/10.1016/j.rse.2014.08.010
22. Kutser T. Quantitative detection of chlorophyll in cyanobacterial blooms by satellite remote sensing. Limnol Oceanogr. 2004;49(6):2179–2189. http://dx.doi.org/10.4319/lo.2004.49.6.2179
23. Hart RC, Wragg PD. Recent blooms of the dinoflagellate *Ceratium* in Albert Falls Dam (KZN): History, causes, spatial features and impacts on a reservoir ecosystem and its zooplankton. Water SA. 2009;35(4):455–468.
24. Oberholster PJ, Botha AM. Use of PCR based technologies for risk assessment of a winter cyanobacterial bloom in Lake Midmar, South Africa. Afr J Biotechnol. 2007;6(15):1794–1805.
25. Petrie SA, Rogers KH. Satellite tracking of white-faced whistling ducks in a semiarid region of South Africa. J Wildl Manage. 1997;61(4):1208–1213. http://dx.doi.org/10.2307/3802118
26. Herremans M. Waterbird diversity, densities, communities and seasonality in the Kalahari Basin, Botswana. J Arid Environ. 1999;43(3):319–350. http://dx.doi.org/10.1006/jare.1999.0546
27. Zohary T. Hyperscums of the cyanobacterium *Microcystis aeruginosa* in a hypertrophic lake (Hartbeespoort Dam, South Africa). J Plankton Res. 1985;7(3):399–409. http://dx.doi.org/10.1093/plankt/7.3.399
28. Matthews MW, Bernard S. Using a two-layered sphere model to investigate the impact of gas vacuoles on the inherent optical properties of *Microcystis aeruginosa*. Biogeosciences. 2013;10(12):8139–8157. http://dx.doi.org/10.5194/bg-10-8139-2013
29. Oberholster PJ, Botha AM. Use of remote sensing and molecular markers to detect toxic cyanobacterial hyperscum crust: A case study on Lake Hartbeespoort, South Africa. Afr J Biotechnol. 2010;9(51):8791–8799.

Quantifying the catchment salt balance: An important component of salinity assessments

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Soil and stream salinisation is a major environmental problem because it reduces the productivity of landscapes and degrades water quality. The Berg River (South Africa) has been exhibiting a trend of increasing salinity levels, which has primarily been attributed to the manifestation of dryland salinity. Dryland salinity occurs as a result of changes in land use (indigenous vegetation to agriculture and/or pasture), which cause a change in the water and salt balance of the landscape, consequently mobilising stored salts. The quantification of salinity fluxes at the catchment scale is an initial step and integral part of developing dryland salinity mitigation measures. The objective of this study was to quantify the salinity fluxes in the Sandspruit catchment, a tributary catchment of the Berg River. This included the quantification of salt storage, salt input (rainfall) and salt output (in run-off). The results of the catchment salt balance computations indicate that the Sandspruit catchment is exporting salts, i.e. salt output exceeds salt input, which may have serious implications for downstream water users. Interpolated regolith salt storage generally exhibited increasing storage with decreasing ground elevation. A salinity hotspot was identified in the lower reaches of the catchment. It is envisaged that the data presented in this study may be used to classify the land according to the levels of salinity present; inform land management decisions; and provide a guide and framework for the prioritisation of areas for intervention and the choice and implementation of salinity management options. The data which were generated may also be used to calibrate hydrosalinity models.

Introduction

Soil and stream salinisation is a major environmental problem and occurs in many parts of the world. It reduces the fertility of landscapes, impacting agricultural activities, and degrades water quality, resulting in water that is unfit for domestic, recreational, agricultural and/or industrial use. These effects result in significant economic losses and water supply issues. The salinisation of soils and water resources may be either a natural phenomenon (primary salinity) or a result of anthropogenic activities (secondary salinity).[1] Primary salinity is associated with the release of salts through the weathering of naturally saline rocks and/or deposition by climatic controls (aeolian or rainfall deposition). Climatic controls are largely a function of proximity to the coast.[2] Human-induced or secondary salinisation may either be a function of the direct addition of saline water to the landscape and/or water resources, e.g. through industrial effluent and/or saline irrigation water, or it may be a result of a change in the water balance (quantity and dynamics) of a catchment causing the mobilisation of stored salts (dryland/non-irrigated salinity).[3-5] Dryland/non-irrigated salinity commonly occurs as a result of changes in land use (indigenous vegetation to agriculture and/or pasture) and management which cause a change in the water and salt balance of the landscape, consequently mobilising stored salts.[1]

Salinity has long been identified as one of the main water quality problems in South Africa.[6] Many rivers exhibit high salinities, which is either a result of the naturally saline geology in which the rivers flow[7] or a result of anthropogenic activities. The Berg River, which is located in the Western Cape, is an example of a river which has been exhibiting a trend of increasing salinity levels. The Berg River is a pivotal source of fresh water to Cape Town, the agricultural sector, the industrialised town of Saldanha and the in-stream ecology. Streamflow quality data collected by the Department of Water Affairs[8] indicates that the Berg River exhibits a salinity gradient, i.e. it increases from the upstream sections of the catchment towards the mid-stream and downstream sections. The upstream sections exhibit an average electrical conductivity (EC) of 11 mS/m, while the downstream sections (20 km from the estuary) exhibit an average EC of 102 mS/m and a maximum of 730 mS/m.[8]

Consequently, research projects were initiated to comprehend the cause and dynamics of the salinisation in the catchment. It was reported that, in addition to the occurrence of naturally saline geology, the increase in salinity observed in the Berg River may also be attributed to dryland salinisation.[9-11] According to De Clercq et al.[11], changes in land use over the last century or more, from extensive pastoral use to intensive cropping, have triggered the same process of salt mobilisation and decantation that is so widespread in Australia.[2,5,12,13] The Sandspruit catchment, a tributary of the Berg River, has particularly been impacted by dryland salinity.[11] According to Flügel[9] the total salt output from the Sandspruit catchment in 1986 was 8052 t, of which a third may be accounted for by atmospheric deposition. The change in land use has changed the water balance in the catchment, resulting in the mobilisation of stored salts.[14]

The quantification of salinity fluxes at the catchment scale is an initial step and integral part of developing dryland salinity mitigation measures. The catchment salt balance (or salt output/input ratio) is a key indicator for a catchment that is undergoing salinisation,[15] that is, it provides an indication of whether the catchment is in a state of salt depletion or accumulation and/or the rates of accumulation or depletion. Additionally, it also provides information pertaining to the salinity trend in the catchment. The salt balance is also an efficient measure through which to encapsulate all of the salinity processes occurring in a catchment.[16] The computation of salinity fluxes will also generate data which will facilitate the calibration and validation of salinity management models. Ultimately, however, the salt balance provides an indication of the severity of the salinity problem in an area. The objective of this study was to quantify the salinity fluxes in the 152-km^2 Sandspruit catchment, including the quantification

of salt storage (in the regolith and underlying shale), salt input (rainfall) and salt output (in run-off). Salt storage was quantified on a spatially distributed basis with the aim of identifying salinity hotspots.

Study area

This research was conducted in a significantly saline tributary catchment (a result of dryland salinity) of the Berg River: the Sandspruit catchment (Figure 1). The Sandspruit catchment is located in quaternary catchment G10J in the Western Cape Province of South Africa, approximately 80 km northeast of Cape Town (Figure 1). The Sandspruit catchment is regarded as a medium-sized catchment (152 km^2) and is a seasonal stream which generally only flows between the months of June and November.

The climatic conditions evident in the area may be classified as semi-arid, characterised by long, dry summers and cool, wet winters. The annual rainfall in the area is generally 300–400 mm, and is dominated by long-duration and low-intensity frontal rainfall between the months of April and October. All precipitation occurs in the form of rainfall. Winter extreme minimum temperatures vary from 2 °C to 4 °C and summer extreme maximum temperatures vary from 38 °C to 40 °C. Mean annual potential evaporation for the area is approximately 1615 mm, with marked seasonal differences between evaporation losses in summer (250 mm per month) and winter (50 mm per month).[11]

Geology in the Sandspruit catchment shows minimal variation, being dominated by Table Mountain Group sandstone in the high elevation areas (south) and Malmesbury shale in the mid- to low-elevation parts (north). An alluvium cover is also evident, which increases in thickness towards the lower elevation areas of the catchment.

Land use in the Sandspruit catchment is dominated by cultivated lands and pastures (approximately 145 km^2). The catchment falls within the 'bread basket' of South Africa and thus agriculture is dominated by wheat cultivation. However the growing of lupins and canola is not uncommon. Farmers in the area generally follow a 3-year planting rotation, i.e. cultivation only occurs every third year. Lands are left fallow between planting rotations and used for grazing. Soil erosion is minimised through the use of constructed anti-erosion contours, which are evident throughout the catchment.

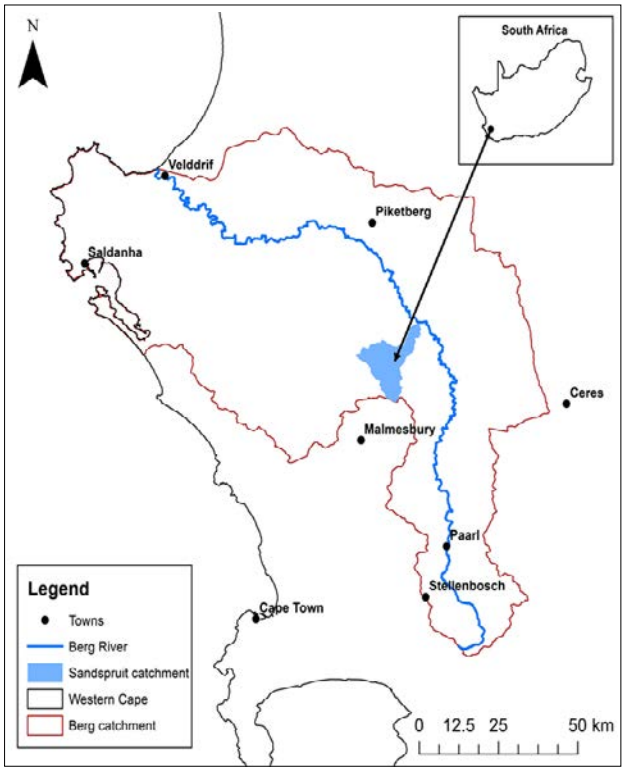

Figure 1: The locality of the study area in the Western Cape (South Africa).

For a detailed description of the physiography of the Sandspruit catchment, the reader is referred to Bugan et al.[17]

Methodology

The Sandspruit catchment is located in the mid to lower reaches of the Berg catchment, an area which stores large quantities of soluble inorganic salts in the regolith. The change in land use, from indigenous vegetation to agriculture, has altered the water balance (changes in evapotranspiration and infiltration/recharge dynamics) causing the mobilisation of these salts and the subsequent salinisation of soils, groundwater and streams. Salt output is interpreted to be well in excess of salt input and considered to be mainly mobilised by interflow, as interflow from the soil horizon is the dominant contributor to streamflow (94.68% of streamflow).[17] As evapotranspiration exceeds precipitation throughout most of the year, leaching of salts is likely to be limited and soluble salts accumulate in the soil horizon. During rainfall events, the resultant run-off and infiltration periodically flush these salts throughout the landscape and into rivers.

The annual salinity fluxes of the Sandspruit catchment were quantified for the period 2007–2010, thus studying four rainfall seasons. The following components of the catchment salt balance were considered.

Salt input

The main source of salt input to the Sandspruit catchment occurs via rainfall. As dryland farming is mainly practised, the potential for salt input to occur via irrigation with saline water is minimal. Salt input may also occur via dry aeolian deposition, as a result of the proximity to the coast; however, because of the low volumes associated with this mechanism and the complexity of quantifying it, it was not considered in this investigation. Salt input to a catchment from rainfall may be quantified using Equation 1[18]:

$$TSI = R * CA * SFC, \qquad \text{Equation 1}$$

where TSI is the total salt input (kg/catchment), R is the rainfall (mm), CA is the catchment area (km^2) and SFC is the salt fall concentration (mg/L).

Results from previous investigations[18-20] suggest that a rainfall salinity gradient generally occurs with distance from the coastline, i.e. rainfall salinity decreases with distance from the coastline. Thus, salinity is expected to decrease from west to east across the Sandspruit catchment. Keywood et al.[20] reported TSI figures for western regions of Australia of 1.0 kg/ha and 0.8 kg/ha per annum at 615 km and 780 km inland, respectively. The salinity of rainfall was not monitored during this study, which is a limitation. However, data in this regard are available from previous investigations. Flügel[9] estimated that the Sandspruit catchment receives approximately 440 mm/year (mean), with a salt concentration of 14–125 mg/L (averaging 37 mg/L). The data exhibit a large range, which may be representative of a rainfall salinity gradient across the catchment, i.e. with distance from the coastline. Sodium and chloride transported by wind from the Atlantic Ocean were the dominant ions. Recent rainfall salinity data are unavailable, but it is assumed that the data presented by Flügel[9] are still valid and representative of the catchment average rainfall salinity.

The TSI for the 2007–2010 rainfall seasons was quantified using catchment average rainfall values calculated by Bugan et al.[17], and the average rainfall salt concentration derived by Flügel[9]. The limited data of rainfall chemistry (temporally and spatially) is a limitation to this study.

Soil salinity

During April–June 2009, 26 boreholes were drilled throughout the Sandspruit catchment (Figure 2). Drilling sites were spatially distributed so as to be representative of geological and topographical variation within the catchment. The rotary percussion method was used to drill the boreholes and collect samples. The depth of drilling was determined by the depth to groundwater and the depth to consolidated hard rock

(Malmesbury shale). In some cases, boreholes were drilled deeper so as to investigate whether further water strikes would be intersected within the shale. Borehole site characteristics are summarised in Supplementary table 1 of the online supplementary material.

The salinity of soil is generally measured by drawing salts from the soil into solution and measuring the salinity of the solution. During borehole drilling, sediment samples were collected at intervals of 0.5–1 m. The samples were sealed in sampling bags and used to measure soil water content. Sub-samples were subsequently used to prepare 1:5 solid:solution extracts and the resulting solution was used to measure $EC_{1:5}$ (mS/m).[21] Sampling and testing soil is an accurate method of measuring salt levels and can also determine whether factors other than salinity are affecting an area. The $EC_{1:5}$ was then converted to the EC_e (EC of the soil extract) using a multiplication factor.[22] The multiplication factor is based on the soil texture.[14] The salinity of the topsoil (0–0.5 m) was then assessed according to the salinity classes proposed by Richards[23] and Van Hoorn and Van Alphen[24] (Table 1).

Salt storage

The sediment samples collected during borehole drilling were also used to quantify the salt storage in the regolith across the catchment. The regolith zone, in this instance, is defined by the soil zone and the unsaturated/vadose zone. Infiltration and temporary winter saturated horizons are interpreted to mobilise salts stored within this zone towards lower valley locations and the Sandspruit River. Groundwater, encountered at the interface of the regolith and the Malmesbury shale, is also interpreted to be a significant salt mobilising agent.

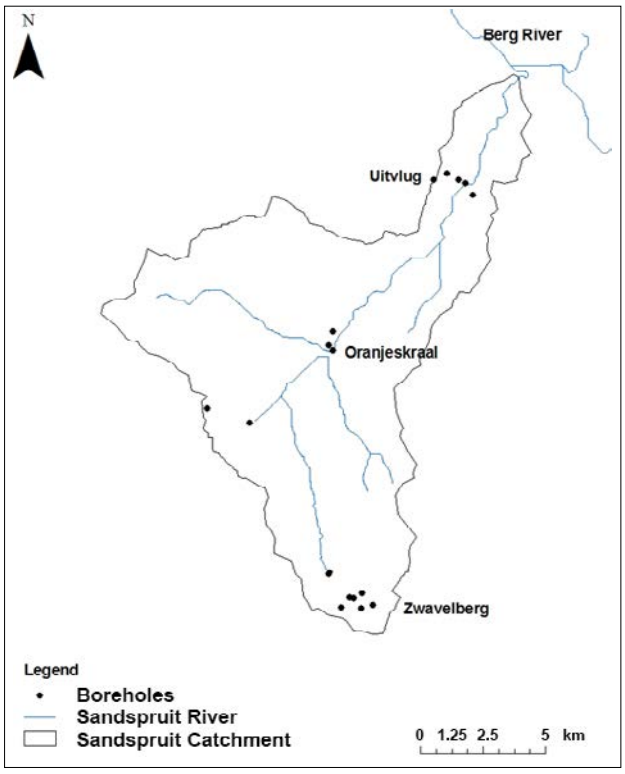

Figure 2: The location of the boreholes in the Sandspruit catchment.

Groundwater flow and salt storage within the saturated zone, defined by the regional Malmesbury Group aquifer, was not considered in this study. The contribution from this aquifer to the Sandspruit River is considered to be minimal[17] and thus will also have minimal effect on the catchment salt output via streamflow.

The regolith samples were used to prepare 1:5 solid:solution extracts. The EC results of the 1:5 solid:solution extracts are, however, not a true representation of field conditions because of the diluting effect of the added water in the preparation of the 1:5 solid:solution extracts. This diluting effect was accounted for using the following process:

- As the mass of water is five times the mass of soil, the soil sample is said to have a water content of 500% in gravimetric terms. The gravimetric water content is thus 5 g water per 1 g soil.
- The gravimetric water content may then be converted into volumetric water content using the soil bulk density. As disturbed samples were collected, it was not possible to measure porosity, density and hydraulic properties. However, the bulk density of the regolith was measured on drilling cores collected in a catchment adjacent to the Sandspruit exhibiting similar physical conditions.[25] The cores exhibited similar geological layering (sequence) to that observed in the Sandspruit catchment. The bulk density of these cores ranged between 1.25 g/cm^3 and 1.52 g/cm^3.
- A dilution factor may then be obtained for each sample by dividing the volumetric water content of the solid:solution extracts by the actual volumetric water content, calculated as a product of the field measured gravimetric water content and the bulk density values estimated by Samuels[25]. EC measured on 1:5 solid:solution extracts were then multiplied by this dilution factor to obtain true EC values.
- The total dissolved salts (TDS) was then inferred from the EC using results from regression analysis ($R^2 = 0.90$) performed by Bugan[26], i.e. TDS (mg/L) = 534.91 * EC (dS/m) – 12.655.

The TDS concentrations of the sediment solution were used to calculate the salt storage in t/ha. These data represented model inputs for the simulation of inorganic salt fluxes as well as allowed the identification of areas of maximum salt storage in the catchment. Salt storage (t/ha) from TDS (mg/L water) may be quantified using Equations 2–4.

Calculate the soil mass (kg/ha)[27] as:

$$M = T*BD*10^s \quad \text{Equation 2}$$

where M is the soil mass (kg/ha), T is the thickness of the horizon (cm) and BD is the bulk density (g/cm^3).

Calculate the soil salt concentration (mg salt/kg soil) as:

$$C_s = C_w \text{ x } GWC, \quad \text{Equation 3}$$

Table 1: Electrical conductivity (EC_e) values of soil salinity classes[21,22]

Class	Salinity class	EC_e (mS/m)
Non-saline	0	<200
Slightly saline	1	200–400
Moderately saline	2	400–800
Very saline	3	800–1600
Highly saline	4	>1600

where C_s is the soil salt concentration (mg salt/kg soil), C_w is the water salt concentration (mg/L water) and GWC is the gravimetric water content (kg/kg).

Calculate the salt mass (kg/ha) as:

$$SC = C_s * M / 10^6 \quad \text{Equation 4}$$

where SC is the salt mass (kg salt/ha), C_s is the soil salt concentration (mg salt/kg soil) and M is the soil mass (kg soil/ha).

Spatial variability in salt storage

Knowledge of the spatial distribution of salt storage in the catchment is essential for salinity management, particulary for the implementation of distributed salt balance models. As salt storage is usually quantified on an area basis and expressed as t/ha, interpolation methods are used to distribute these data across a catchment. Flügel[9] suggested that salt distribution in the Sandspruit catchment is a function of the topographic location. Cox et al.[28] are also of the opinion that spatial variability in salt storage is predominantly a function of elevation. The topographic wetness index, which combines local upslope contributing area and slope, is also commonly used to quantify topographical controls on hydrological processes.[29] Point data of regolith salt storage was correlated with ground elevation and the topographic wetness index to investigate whether this relationship could be used to interpolate the data. According to Bennetts et al.[30], elevated groundwater salinity is expected to correlate well with elevated soil salinity. Thus, as a further measure, groundwater EC, which is well defined across the catchment, was also correlated with regolith salt storage. In addition to groundwater EC data collected at boreholes drilled during this study, historical groundwater EC data gathered from the National Groundwater Database of the Department of Water Affairs (now the Department of Water and Sanitation) were also utilised for the interpolation. The National Groundwater Database contains data for 93 boreholes located in quaternary catchment G10J from 1990 to the present. The inverse distance weighted interpolation method was utilised as the procedure is versatile, easy to program and understand, and is fairly accurate under a wide range of conditions.[31]

In addition to the coefficient of determination, the correlations were also evaluated using Spearman's rank correlation coefficient (Rs).[29] Rs is a measure of the statistical dependence between two variables. If there are no repeated data values, a perfect Rs of $+1$ or -1 occurs when each of the variables is a perfect monotone function of the other. The sign of Rs indicates the direction of association between *X* (the independent variable) and *Y* (the dependent variable). If *Y* tends to increase when *X* increases, the Rs is positive, and if *Y* tends to decrease when *X* increases, the Rs is negative.

Salt output

The total salt output from a catchment may be quantified using streamflow quantity and salinity data sets, i.e. the salt load is equal to the product of the streamflow (m^3/s) and the corresponding stream water salinity (TDS, mg/L). The salinity of the Sandspruit River was monitored with an electronic EC sensor, hourly, from June 2007 to October 2010. Data for the period 06/06/2009–30/07/2009 are missing as a result of sensor malfunction. The sensor was located at the Sandspruit gauging weir (G1H043), for which streamflow quantity (m^3/s) data are available for the period from May 1980 to the present. This station is maintained by the Department of Water Affairs and Sanitation. Periods for which data were missing were filled using a correlation ($R^2 = 0.7$) with streamflow, i.e. salt output (t/day) = 169.49 * streamflow (m^3/s) + 26.743. The streamflow (m^3/s) and logged EC data (mS/m) for the period of observation are shown in Figure 3.

The salt output from the Sandspruit catchment was quantified using Equation 5[32]:

$$SL = TDS * Q * 1000, \quad \text{Equation 5}$$

where SL is the salt load (kg/s), TDS is the total dissolved solids (mg/L) and Q is the discharge (m^3/s). The TDS was inferred from EC using the conversion TDS (mg/L) = EC (mS/m) * 6.5,[33] which is commonly used in South Africa.

Catchment salt balance

The salt mass balance is an indicator of the stage of hydrological change after changes in land use and salinity development. Prior to the clearing of indigenous vegetation, the output/input ratio may be considered to be at equilibrium,[34] which does not imply that it is equal but that it is stable. Clearing of the indigenous vegetation may result in output exceeding input, or increased output. The rate of migration back to a state of equilibrium is dependent on the leaching rate and the magnitude of the salt stores.[35] In catchments with a mean annual rainfall of less than 500 mm, the time required to restore the salt equilibrium is expected to be of the order of hundreds to tens of thousands of years, depending on rainfall, hydrogeological conditions, salt storage, catchment size and the amount of vegetation clearance.[35]

The salt mass balance approach has been used with some success to predict the effect of upstream catchment land use on salinity. Generally, a favourable salt balance (mass out ≥ mass in) is considered necessary for sustainable agriculture.[36] The salt balance may be represented by[37]:

$$M_{in} - M_{out} = (^{dM}/_{dt}), \quad \text{Equation 6}$$

where M_{in} and M_{out} are the mass per unit time of salt input and output, respectively, and $^{dM}/_{dt}$ is the rate of change in mass in the system. This equation implies that equilibrium, in terms of salt, is achieved when there is no change in the mass of salt in the system, i.e. $^{dM}/_{dt}$ is zero. The salt balance of a system that has a net accumulation or insufficient leaching rates of salt can be considered to be at risk of the salinisation of land and water resources.[38]

Two additional terms are also used to describe the salt balance: the salt balance index (SBI) and salt export ratio (SER).[34,37,38] These similar terms are defined by the salt output from a given hydrological volume and time period, divided by the salt input. The system is in equilibrium when the SBI or SER equals 1. The system is in a state of salt accumulation when the SBI or SER is less than 1, and in a state of salt depletion when the SBI or SER is greater than 1.[36]

Results

Salt input

The TSI to the Sandspruit catchment during the period of observation is shown in Table 2. Rainfall was assumed to exhibit a TDS concentration of 37 mg/L. Average catchment rainfall was obtained from Bugan et al.[17] The salt input was therefore a function of rainfall amount as variable rainfall chemistry data were not available. The TSI ranged between 2261 t and 3684 t per catchment. The TSI is expected to vary across the catchment, particularly with distance from the coastline.

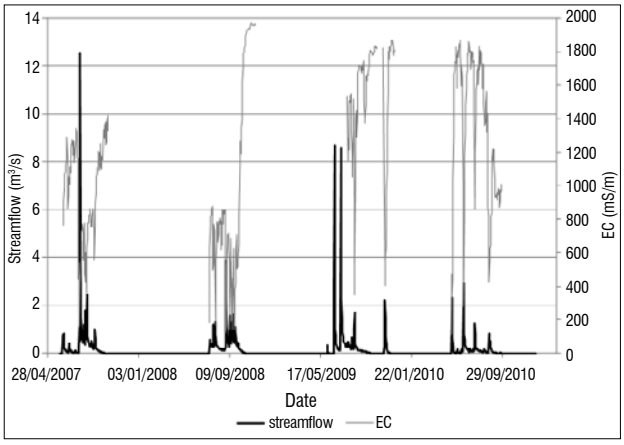

Figure 3: Streamflow volume and electrical conductivity (EC) measured during June 2007 to October 2010.

Soil salinity

The salinity of the topsoil (0–0.5 m) samples collected during borehole drilling (Figure 2) is presented in Table 3. The $EC_{1:5}$ was converted to EC_e using a multiplication factor,[22] which is based on soil textural analysis. The results indicate that the majority of the topsoil samples may be classified as non-saline.[24] However, two samples, from the downstream parts of the catchment (Uitvlug, Figure 2), may be classified as very saline.[24] This finding may be indicative of the influence of topography on soil salinisation processes.

Salt storage

The regolith salt storage measured at each borehole is presented in Table 4. The regolith is defined as the layer of loose, heterogeneous material which overlies hard rock (soil zone and vadose zone).[39] The salt storage ranged between 15 t/ha and 922 t/ha. If expressed as the storage within a fixed depth, i.e. 10 m, the salt storage ranged from 9 t/ha to 636 t/ha. The regolith salt storage dominantly depends on the depth of the profile as well as elevation, i.e. the regolith salt storage generally increased with decreasing ground elevation. Profiles located at Uitvlug (downstream in the catchment) exhibited elevated salt concentrations, indicating that a salinity 'hotspot' may be located there. It should, however, be noted that the quantification technique employed here incorporates a degree of uncertainty, which is mainly associated with the bulk density values. The estimates used in this quantification are from a small sample set collected at a different site and at different depths.

Spatial variability in salt storage

Data of regolith storage obtained from point measurements were correlated with ground elevation (mAMSL), the catchment topographic wetness index and groundwater EC to identify relationships with which to interpolate the data. The coefficients of determination of the correlation analysis are presented in Table 5.

Salt storage did not correlate well with elevation. This result is interpreted to be a consequence of the fact that the borehole locations did not sufficiently account for elevation variations in the catchment, i.e. the borehole transects (Figure 2) were essentially drilled across three elevation zones/bands. Also, as the topographic wetness index incorporates elevation, the inadequate representation of elevation variation affected this correlation. Regolith salt storage correlated well with groundwater EC (mS/m), exhibiting an R^2 of 0.75.

The correlation between groundwater EC (mS/m) and regolith salt storage (t/ha) may be described by Equation 7:

$$\text{Salt storage (t/ha)} = 0.3269\ (\text{groundwater EC mS/m}) + 1.429 \quad \text{Equation 7}$$

This correlation was used to interpolate salt storage across the catchment (Figure 4). Interpolated regolith salt storage ranged between 3 t/ha and 674 t/ha. The reduction in the salt storage range from that reported in Table 4 is a result of the interpolation process. The data also indicate that storage increases with decreasing ground elevation, i.e. in a northeasterly direction. Salt storage is expected to be lower in the hilltops, as a result of salt leaching (groundwater recharge/infiltration), and higher in the valleys, as a result of salt accumulation. The spatially averaged regolith salt storage in the Sandspruit catchment is 110 t/ha. Because of the interpolation procedure and the historical nature of the groundwater EC data, these results incorporate uncertainty. They should thus not be considered as absolute values, but rather as estimates of salt storage.

Salt output

The total annual export of salt from the catchment was calculated using the catchment discharge and streamflow salinity data sets (Equation 5). The results are presented in Table 2. During the period of observation, the salt output from the Sandspruit catchment ranged between 12 671 t/year and 21 409 t/year. The average monthly salt output ranged between 2433 t and 3378 t. The maximum monthly salt output was generally observed during July to September, which corresponds to the period of highest discharge. The minimum monthly salt output was observed during October to December, which corresponds to the period of lowest discharge. The increased discharge and salt output observed in 2009 cannot be attributed to increased rainfall as it was below that observed during 2007 and 2008 (Table 2). The spatial distribution of the wheat/fallow fields and rainfall characteristics (intensity and temporal distribution) are interpreted to exert a greater influence on discharge and salt output than the annual rainfall total.

Catchment salt balance

The catchment salt balance, i.e. salt output/input (O/I) ratio, is presented in Table 2. The rate of change in mass of the system ($^{dM}/_{dt}$) and the SBI/SER indicate that the Sandspruit catchment is in a state of salt depletion, i.e. salt output exceeds salt input. No previous data pertaining to the salt balance are available for the study area and thus long-term dynamics cannot be evaluated.

Conclusions

The quantification of salinity fluxes at the catchment scale is an initial step and integral part of developing salinity mitigation measures. The objective of this study was to quantify the salinity fluxes in the 152-km^2 Sandspruit catchment.

The TSI to the catchment from rainfall ranged between 2261 t and 3684 t per catchment. The salt input was calculated as a function of the rainfall amount as variable rainfall chemistry data were not available. The lack of rainfall chemistry data is a limitation of this study. The acquisition of additional rainfall chemistry data may significantly influence these estimates. Rainfall salinity has been proven to be a function of the distance from the coastline,[16,18-20] i.e. the salinity decreases with distance from the coastline. Thus, the rainfall salinity may be higher in the western parts of the catchment than the eastern parts. The optimal method with which to determine the salt input via rainfall would be to utilise coverage of interpolated rainfall and a network of rainfall salinity monitoring stations. The impact of the lack of rainfall chemistry data on the catchment salt balance may, however, only be quantified through the provision of additional data. The lack of similar data in South Africa prevents a quantitative interpretation of the data, that is, whether these values are low or high. Jolly et al.[18] reported that the salt input to the

Table 2: Components of the catchment salt balance

Year	Rainfall (mm/year)	TSI (t/catchment)	TSI (t/ha)	Discharge (mm)	Total salt output (t/year)	Average monthly salt output (t)	Maximum monthly salt output (t)	Minimum monthly salt output (t)	dM/dt (t/year)	SBI/SER
2007	655	3684	0.24	32	16 890	3378	7160	130	-13 206	4.6
2008	519	2919	0.19	27	12 671	2534	4839	29	-9752	4.3
2009	444	2497	0.16	37	21 409	3058	6912	15	-18 912	8.6
2010	402	2261	0.15	15	14 599	2433	5179	29	-12 872	8.5

TSI, total salt input; SBI, salt balance index; SER, salt export ratio

Table 3: Topsoil salinity

Sampling site	$EC_{1:5}$ (mS/m)	Multiplication factor	EC_e (mS/m)	Salinity class
Zwavelberg				
ZB001	8	10	82	0/non-saline
ZB002	6	10	62	0/non-saline
ZB004	5	9	45	0/non-saline
ZB005	3	9	30	0/non-saline
ZB006A	3	10	28	0/non-saline
ZB007	7	17	121	0/non-saline
ZB007A	15	17	252	1/slightly saline
Oranjeskraal				
OK001	7	10	68	0/non-saline
OK002	3	10	25	0/non-saline
OK003	7	10	74	0/non-saline
Uitvlug				
UV001	11	10	112	0/non-saline
UV002	170	9	1530	3/very saline
UV003	97	10	970	3/very saline
UV004	27	10	270	1/slightly saline
UV005	5	10	52	0/non-saline

Table 4: Salt storage (t/ha) in the Sandspruit catchment

Borehole number	Soil zone salt storage (t/ha)	Soil profile depth (m)	Regolith salt storage (t/ha)	Regolith profile depth (m)	Salt storage (t/ha) to 10-m depth
Zwavelberg					
ZB001	8	3	28	11	25
ZB002	14	4	23	9	–
ZB003	8	2	52	11	48
ZB004	4	4	15	19	9
ZB005	4	4	16	13	11
ZB006	38	12	40	16	36
ZB006A	5	3	21	11	20
ZB007	4	2	75	15	56
ZB007A	8	2	97	12	91
Oranjeskraal					
OK001	4	2	18	8	–
OK002	4	3	79	29	15
OK003	10	4	39	29	18
Uitvlug					
UV001	8	3	349	69	35
UV002	168	3	922	15	636
UV003	55	2	519	22	173
UV004	211	16	341	30	144
UV005	45	18	97	53	25

Murrumbidgee catchment (155 km²) in Australia ranged between 395 t and 785 t per year. However, the catchment experienced significantly higher rainfall amounts (566 mm to 1060 mm per year) and the distance from the coastline is unknown.

Topsoil samples gathered during borehole drilling may generally be regarded as non-saline, with an EC_e < 200 mS/m. However, two samples gathered at Uitvlug, which is located in the downstream parts of the catchment (Figure 2), exhibited elevated EC_e (800–1600 mS/m) and may thus be classified as very saline. The increased soil salinity in the downstream parts of the catchment provides evidence for the influence of topographic controls on salinisation processes. Increased rainfall, and subsequent infiltration/groundwater recharge in the upper reaches of the catchment, dissolve and mobilise salts towards the lower elevation parts of the catchment. This situation manifests in the appearance of saline scalds – patches in the wheat fields – which become increasingly evident particularly in the lower lying areas of the catchment. These saline scalds are areas in which the wheat is unable to germinate. This investigation provides an initial assessment of the topsoil salinity, which requires further validation through extensive mapping of the soil and soil salinity.

Sediment samples collected during borehole drilling were used to quantify the salt storage in the regolith zone. The salt storage in the regolith ranged between 15 t/ha and 922 t/ha and a salinity 'hotspot' was identified in the lower reaches of the catchment. The point data of regolith salt storage were correlated with ground elevation (mAMSL), the catchment topographic wetness index and groundwater EC to identify relationships with which to interpolate these data. Regolith salt storage correlated well with groundwater EC (mS/m), exhibiting an R^2 of 0.75. Interpolated regolith salt storage ranged between 3 t/ha and 674 t/ha, exhibiting generally increasing storage with decreasing ground elevation. The average regolith salt storage in the Sandspruit catchment is 110 t/ha. It may also be useful to investigate the potential for mapping/interpolating regolith salt storage through correlations with soil type, slope, lithology or soil depth. Data of a similar nature are not available for South Africa and thus comparisons cannot be made. Even though these results may not be taken as absolute values, the identification of areas of high salt storage holds important implications for water resources management and land use planning. It enables resource managers to make informed decisions in terms of vegetation distribution or planting strategies and the locations for the implementation of salinity management measures.

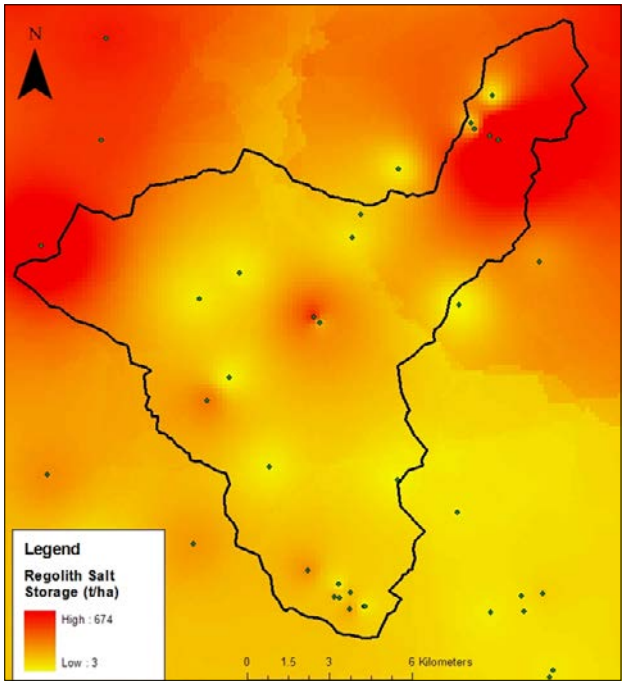

Figure 4: Interpolated regolith salt storage (t/ha) in the Sandspruit catchment.

Table 5: Correlation of regolith salt storage (t/ha) with catchment variables

Variable	Groundwater electrical conductivity (mS/m)†	Ground elevation (mAMSL)	Topographic wetness index
R^2	0.75	0.41	0.07
Rs	0.72	-0.76	-0.21

†*Groundwater samples collected in September 2010.*

During the period of observation, the salt output from the Sandspruit catchment ranged between 12 671 t and 21 409 t per year. The salt output was much larger than that reported by Jolly et al.[18] for the Murrumbidgee catchment (155 km²) in Australia, which was a mean of 2626 t/year. The salt storage in the Murrumbidgee catchment is, however, unknown. The stream salinity typically decreases during high flow events, as a result of the increased dilution capacity; however, large streamflow events can still deliver considerable salt loads. The export of salts from the Sandspruit catchment has implications for downstream water users of the Berg River.

The results of the catchment salt balance computations indicate that the Sandspruit catchment is exporting salts. This is a function of the development of agricultural lands and the resultant changes in the hydrosalinity dynamics in the catchment. Under natural conditions, in semi-arid to arid areas in which evaporation/evapotranspiration greatly exceeds rainfall, landscapes generally accumulate salts.[40] Changes to the catchment hydrology as a result of agricultural or other developments can cause significant changes to the salinity dynamics of a catchment, typically in the form of increased salt exports. The Sandspruit catchment exhibits SBI/SER, which ranges between 4.3 and 8.6. Catchments which mobilise salts are likely to exhibit ratios in excess of 1, and sometimes even as high as 15–30.[34,35]

It is clear that the Sandspruit catchment is exporting significant quantities of salt to the Berg River (most likely driven by changes in land use). A continuation of this trend over the larger Berg catchment is expected to sustain the trend of increasing salinity levels in the Berg River. Because of the scarcity of water in the Western Cape, which may be further exacerbated by the impending impacts of climate change, it is essential that water resource management initiatives be implemented. It is envisaged that this information may be used to classify the land according to the levels of salinity present, inform land management decisions, provide a guide and framework for the prioritisation of areas for intervention, and provide a guide for the choice and implementation of salinity management options. The data gathered during this investigation may also be used as reference data for scenario simulations which aim to evaluate potential changes to the salt balance caused by, for example, water abstractions and inter-basin transfer.

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Authors' contributions

This work forms part of R.B.'s PhD dissertation; R.B. was thus responsible for formulating the research concept, conducting field work and laboratory analysis, performing calculations and drafting the manuscript. N.J. acted as co-supervisor during the PhD study, assisted with field work and made conceptual contributions to the work, and reviewed the manuscript. W.d.C. acted as supervisor during the PhD study, made conceptual contributions to the work, and reviewed the manuscript.

References

1. Pannell DJ, Ewing MA. Managing secondary dryland salinity: Options and challenges. In: Proceedings of the 4th International Crop Science Congress: New directions for a diverse planet; 2004 Sep 26–Oct 01; Brisbane, Australia. Gosford: The Regional Institute Ltd; 2004. p. 1–12.
2. Clarke CJ, George RJ, Bell RW, Hatton TJ. Dryland salinity in south-western Australia: Its origins, remedies and future research directions. Aust J Soil Res. 2002;40:93–113. http://dx.doi.org/10.1071/SR01028
3. Greiner R. Catchment management for dryland salinity control: Model analysis for the Liverpool Plains in New South Wales. Lyneham: CSIRO Publishing; 1998.
4. Walker G, Gilfedder M, Williams J. Effectiveness of current farming systems in the control of dryland salinity. Adelaide: CSIRO Publishing; 1999.
5. Acworth RI, Jankowski J. Salt source for dryland salinity – Evidence from an upland catchment on the Southern Tablelands of New South Wales. Aust J Soil Res. 2001;39:12–25. http://dx.doi.org/10.1071/SR99120
6. Department of Water Affairs and Forestry (DWAF). Management of the water resources of the Republic of South Africa. Pretoria: DWAF; 1986.
7. Lerotholi S. The role of salinity as an abiotic driver of ecological condition in a rural agricultural catchment [MSc dissertation]. Grahamstown: Rhodes University; 2005.
8. Department of Water Affairs (DWA). Resource quality information services [homepage on the Internet]. c2011 [cited 2014 May 13]. Available from: http://www.dwaf.gov.za/iwqs/default.aspx
9. Flügel W. River salinity due to dryland agriculture in the Western Cape Province, Republic of South Africa. Environ Int. 1995;21:679–686. http://dx.doi.org/10.1016/0160-4120(95)00073-T
10. Fey MV, De Clercq WP. Dryland salinity impacts on Western Cape rivers. Report No 1342/1/04. Pretoria: Water Research Commission; 2004.
11. De Clercq WP, Jovanovic NZ, Fey MV. Land use impacts on salinity in Berg River water. Report No K5/1503. Pretoria: Water Research Commission; 2010.
12. Peck AJ, Hatton T. Salinity and the discharge of salts from catchments in Australia. J Hydrol. 2003;272:191–202. http://dx.doi.org/10.1016/S0022-1694(02)00264-0
13. Crosbie RS, Hughes JD, Friend J, Baldwin BJ. Monitoring the hydrological impact of land use change in a small agricultural catchment affected by dryland salinity in central NSW, Australia. Agr Water Manage. 2007;88:43–53. http://dx.doi.org/10.1016/j.agwat.2006.08.009
14. Bugan RDH. Modelling and regulating hydrosalinity dynamics in the Sandspruit River Catchment (Western Cape) [PhD thesis]. Stellenbosch: Stellenbosch University; 2014.
15. Williamson DR. Land degradation processes and water quality effects, water logging and salinity. In: Williams J, Hook RA, Gascoigne HL, editors. Farming action-catchment reaction, the effect of dry-land farming on the natural environment. Collingwood, VIC: CSIRO Publishing; 1998. p. 162–190.
16. Biggs AJW, Silburn DM, Power RE. Catchment salt balances in the Queensland Murray-Darling Basin. J Hydrol. 2013;500:104–113. http://dx.doi.org/10.1016/j.jhydrol.2013.07.027
17. Bugan RDH, Jovanovic NZ, De Clercq WP. The water balance of a seasonal stream in the semi-arid Western Cape (South Africa). Water SA. 2012;38(2):201–212. http://dx.doi.org/10.4314/wsa.v38i2.5
18. Jolly ID, Dowling TI, Zhang L, Williamson DR, Walker GR. Water and salt balances of the catchments of the Murray-Darling Basin. Technical Report 37/97. Dickson ACT: CSIRO Land and Water; 1997.
19. Biggs AJW. Rainfall salt loads in Southern Queensland, Australia. In: Proceedings of the 13th International Soil Conservation Organisation Conference: ISCO 2004; 2004 July 4–8; Brisbane, Australia. Warragul, VIC: Australian Society of Soil Science Incorporated; 2004. p. 1–4.
20. Keywood MD, Chivas AR, Fifield LK, Cresswell RG, Ayers GP. The accession of chloride to the western half of the Australian continent. Aust J Soil Res. 1997;35:1177–1189. http://dx.doi.org/10.1071/S97001
21. Allison LE, Bernstein L, Bower CA, Brown JW, Fireman M, Hatcher JT, et al. Diagnosis and improvement of saline and alkali soils. Agricultural Handbook No. 60. Washington DC: United States Department of Agriculture; 1954.
22. Slavich PG, Petterson GH. Estimating the electrical conductivity of saturated paste extracts from 1:5 soil, water suspensions and texture. Soil Res. 1993;31(1):73–81. http://dx.doi.org/10.1071/SR9930073
23. Richards LA. Diagnosis and improvement of saline and alkali soils. Agricultural Handbook No. 60. Washington: United States Department of Agriculture; 1954.
24. Van Hoorn JW, Van Alphen HA. Salinity control. In: Ritzema HP, editor. Drainage principles and application. 16th ed. Wageningen: International Institute for Land Reclamation and Improvement; 1994.
25. Samuels D. Hydraulic properties of the vadose zone at two typical sites in the Western Cape for the assessment of groundwater vulnerability to pollution [MSc dissertation]. Bellville: University of the Western Cape; 2007.
26. Bugan RDH. Hydrosalinity fluxes in a small scale catchment of the Berg River (Western Cape) [MSc dissertation]. Bellville: University of the Western Cape; 2008.
27. White RE. Principles and practice of soil science: The soil as a natural resource. 4th ed. Victoria: Blackwell Publishing; 2006.
28. Cox J, Davies P, Spouncer L. Water and soil degradation in the Keynes Catchment, South Australia. Technical Report 40/99. Dickson ACT: CSIRO Land and Water; 1999.
29. Sorensen R, Zinko U, Seibert J. On the calculation of the topographic wetness index: Evaluation of different methods based on field observations. Hydrol Earth Syst Sci. 2005;2:1807–1834. http://dx.doi.org/10.5194/hessd-2-1807-2005
30. Bennetts DA, Webb JA, Stone DJM, Hill DM. Understanding the salinisation processes for groundwater in an area of south-eastern Australia, using hydrochemical and isotopic evidence. J Hydrol. 2006;323:178–192. http://dx.doi.org/10.1016/j.jhydrol.2005.08.023
31. Lam NS. Spatial interpolation methods review. Am Carto. 1983;10:129–149. http://dx.doi.org/10.1559/152304083783914958
32. Verhoff FH, Yaksich SM, Melfi DA. An analysis of total phosphorous transport in river systems. Hydrobiologia. 1982;91:241–252. http://dx.doi.org/10.1007/BF02391941
33. Department of Water Affairs and Forestry (DWAF). South African water quality guidelines. Volume 4: Agricultural use: Irrigation. 2nd ed. Pretoria: DWAF; 1996.
34. Peck AJ, Hurle DH. Chloride balance of some farmed and forested catchments in southwestern Australia. Water Resour Res. 1973;9:648–657. http://dx.doi.org/10.1029/WR009i003p00648
35. Jolly ID, Williamson DR, Gilfedder M, Walker GR, Morton R, Robinson G, et al. Historical stream salinity trends and catchment salt balances in the Murray-Darling Basin, Australia. Mar Freshwater Res. 2001;52:53–63. http://dx.doi.org/10.1071/MF00018
36. Thayalakumaran T, Bethune MG, Mcmahon TA. Achieving a salt balance – Should it be a management objective? Agr Water Manage. 2007;92(1–2):1–12. http://dx.doi.org/10.1016/j.agwat.2007.05.004
37. Wilcox LV. Salt balance and leaching requirement in irrigated lands. Report No 1290. Washington DC: Agricultural Research Service, US Department of Agriculture; 1963.
38. Gilfedder M, Walker G, Williams J. Effectiveness of current farming systems in the control of dryland salinity. Clayton, VIC: CSIRO Publishing; 1999.
39. Taylor G, Eggleton RA. Regolith, geology and geomorphology. Chichester: Wiley and Sons; 2001.
40. Charman PEV, Murphy BW. Soils – Their properties and management. Soil Conservation Commission of New South Wales. Sydney: Sydney University Press; 1991.

A massive bright green surface cyanobacterial bloom extending more than 20 km out over Lake Taihu, China, as seen by the Medium Resolution Imaging Spectrometer satellite instrument on 14 August 2007 (image: Mark Matthews, Daniel Odermatt; data courtesy of the European Space Agency). Matthews and Bernard discuss the use of satellite remote sensing to detect eutrophication and cyanobacteria in South Africa's water bodies in an article on page 77.

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