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The economic value of nutrient cycling in the Swartkops and Sundays River estuaries

Nutrient cycling, a fundamental ecological process, directly impacts the health and functionality of marine environments and plays a pivotal role in maintaining water quality and supporting diverse marine life and human health. To date, there has been no ecosystem service valuation assessment for nutrient cycling in South Africa, mainly because of the scarcity of nutrient cycling capacity measurements. The lack of valuation assessments necessitates reliance on data-transfer valuation techniques that can produce misleading valuations. Given the similarity between estuary nutrient cycling processes and wastewater treatment work processes, as well as the relative abundance of published data on the latter's cost, the latter can be used as a proxy for the former. Cost and efficiency data for wastewater treatment works in Algoa Bay were sourced along with the published concentrations of dissolved inorganic nutrients in the Swartkops and Sundays River estuaries. The value of nutrient cycling in the Swartkops estuary has increased by about 1330% from USD466 076 in 1994 to USD6.7 million in 2022 but declined in the Sundays River estuary from USD1.6 million to about USD428 140 over the same period. In dollar terms, this value of nutrient cycling translates to USD18 681/ha for the Swartkops estuary when using the smallest area denominator and USD1747/ha for the Sundays River estuary (USD1 = ZAR18.4519). These estuaries offset the need for capital investment of this magnitude, reflecting their importance and the need for continued restoration and conservation.

Significance:

Few published valuations of the benefits of nutrient cycling in South African estuaries exist. An estimate is provided using the Swartkops and Sundays River estuaries as examples.

Introduction

Estuaries are dynamic environments characterised by fluctuating water levels, tidal flows and seasonal variations in temperature and salinity. They are located at the interface between freshwater and marine environments[1] and are highly productive, providing valuable goods and services[2]. However, population growth, urbanisation and industrial expansion near estuaries generate wastewater, often leading to contamination with raw sewage.[3] The introduction of untreated or inadequately treated wastewater into estuaries increases the levels of dissolved inorganic phosphates (DIP) and dissolved inorganic nitrogen (DIN).[4] Elevated concentrations of DIP and DIN, along with factors including elevated temperature and water column stratification, contribute to the growth of harmful algal blooms and worsen hypoxic conditions.[5,6] These blooms, often involving cyanobacteria, produce toxins that are harmful to humans.[7] High levels of these inorganic nutrients in estuaries can lead to oxygen depletion in coastal waters, causing marine life die-offs.[8,9]

To mitigate the risks to people and losses that industries could incur due to die-offs, society builds, operates and maintains wastewater treatment works (WWTWs) that reduce DIP and DIN concentrations before discharging wastewater into estuaries and coastal waters. In South Africa, annual municipal operation, expansion and maintenance costs for WWTWs can exceed ZAR1.2 billion[10,11] and still these facilities are often overwhelmed, resulting in inadequately treated effluents.

In estuaries, nutrient cycling removes constantly high, dangerous and unsustainable nutrient loads. Nutrient cycling refers to the transfer of organic and inorganic matter into an estuary and their conversion into the production of living biota. The cycling of nitrogen and phosphorus facilitates primary productivity, which forms the base of the food web. This process ensures that essential nutrients are available for various trophic levels, from phytoplankton to higher marine organisms. A balanced concentration of nutrients is required to sustain the estuary and will ensure the health of coastal ecosystems.[12]

Nutrient cycling is an important ecosystem service of estuaries that greatly benefits marine industries by reducing the environmental impacts of human wastewater. As society allocates money for WWTWs due to their important function in supporting the marine economy, a strong case can be made for estuarine conservation, as nutrient cycling has the same function. Some estuaries might contribute more to mitigating human waste than their municipal WWTW counterparts. However, the assessment of the value of estuarine nutrient cycling is rare, with no known valuations existing for the South African case.[13] Without knowing the extent to which a particular estuary treats wastewater as well as its efficacy relative to local WWTW in doing so, sub-optimal investment in estuary conservation or WWTW maintenance, construction and operation occurs.

We sought to address the knowledge gap of the economic value of nutrient cycling of estuaries by combining available data for two estuaries in Algoa Bay, South Africa, namely the Swartkops and Sundays River estuaries. Cost and efficiency data from WWTWs were used along with all available biological measurements of water quality in estuaries to present an estimate of the economic value of nutrient cycling in estuaries.

Background

Ecosystem service valuations for estuaries

Economic valuation of ecosystem services helps prioritise conservation investments by identifying high-value ecosystems and justifying restoration costs through quantified benefits.[14] Estuaries are among the coastal ecosystems in socio-ecological systems with the highest economic value on a per hectare basis.[15] The global average value of coastal systems, including estuaries, was estimated to be USD36 026/ha in 2020 prices.[16] These high values can be attributed to ecosystem services such as nutrient cycling, recreation, food production and storm protection.[16-21] In South Africa, there is a dearth of published studies on the economic value of estuaries compared to elsewhere in the world.[20] Most of the studies that have been conducted have focused on water quality, water inflows and recreational or recreation-related services.

Du Preez and Hosking[22] valued the Klein and Kwelera estuaries using the travel cost method and found an increase in recreational value of freshwater inflow for both estuaries. Magobiane[23] revealed that recreational users highly valued improvements in water quality at the Swartkops River estuary. Sale et al.[24] documented the economic value of recreational services at the Kowie and Kromme estuaries for increased freshwater inputs. Lee et al.[25] used questionnaires on the Sundays River estuary to determine recreational users' willingness to pay for various ecosystem services. In a related study, Lee and Du Preez[26] explored the issue of boat congestion at the Sundays River estuary. Further emphasising the impact of congestion, more studies by Lee et al.[27,28] reported that users were prepared to pay more per year during peak hours to mitigate overcrowding effects. However, Turpie and Clark[29] provide the most comprehensive valuation of South African estuaries. They valued various ecosystem services such as subsistence, property, tourism, nursery and existence services, with the notable exception being nutrient cycling.

Globally, studies concerning the economic value of nutrient cycling have been conducted but mostly in developed countries (Table 1). The socio-ecological factors that influence estuaries differ between developed countries and developing countries like South Africa. Within the legal, institutional and social context of the United Kingdom, for example, the value of nutrient cycling is estimated to be USD579 632/ha[30], while within the Dutch context, it is estimated to be USD2661/ha[31]. While these two European studies were conducted in two geographically proximate countries, they revealed a substantial disparity of USD576 971/ha in the valuation of nitrogen and phosphorus removal services. This discrepancy underscores the nuanced nature of ecosystem service assessments and emphasises the need for meticulous consideration of regional variations and methodological intricacies.

Despite the vast contextual differences, these global assessments are, unfortunately, all we have concerning this important ecosystem service. Data transfer is the technique of importing values from elsewhere into a local context. The wide range of values derived from data transfer for ecosystem services presents significant challenges, particularly for crucial services such as nutrient cycling, where economic valuation studies are scarce. Limited data availability can lead to uncertainty and variability in the estimated value of ecosystem services, hindering decision-making processes. Without comprehensive studies, there is a risk of oversimplifying complex ecological processes or overlooking critical factors influencing nutrient cycling dynamics. Such findings highlight the inherent challenges in deriving accurate and comparable values for ecosystem services, even in seemingly similar contexts. Therefore, addressing the challenge of insufficient data in areas such as nutrient cycling is essential for improving the accuracy and reliability of ecosystem service assessments.

Table 1: Known estimates for nutrient cycling in estuaries

Country	Method	Value
United Kingdom[30]	Ecological network analysis using Ecopath with Ecosim software	USD579 632/ha
Netherlands[31]	Benefit transfer method (from water purification services and infrastructure) combined with scenario analysis	USD2661/ha
Difference		**USD576 971/ha**

Study area

The Swartkops and Sundays River estuaries

Both the Swartkops and Sundays River estuaries are permanently open, wave-dominated estuaries that are in the Eastern Cape Province of South Africa. The Swartkops River estuary lies at approximately 33°50′S, 25°36′E, where the Swartkops River meets Algoa Bay near Gqeberha (formerly Port Elizabeth). The Sundays River estuary is situated near the town of Colchester at approximately 33°42′53″S, 25°50′54″E. The Swartkops River estuary supports a rich mosaic of habitats, including salt marshes, intertidal mudflats and sandbanks. The Sundays River estuary is known for its scenic beauty and recreational value, particularly for boating and angling.

Table 2 and Figure 1 describe the Swartkops and Sundays River estuaries in terms of habitat types – an important consideration when measuring and valuing nutrient cycling. Each ecotype facilitates nutrient cycling to varying extents. To measure the capacity of an estuary for nutrient cycling from first principles requires extensive study and data collection from each ecotype, interactions between habitat types and the contribution of each ecotype to nutrient cycling. Within an ecotype, capacity for nutrient cycling will be further differentiated based on the resident flora and fauna, climate and ecosystem conditions. Consequently, comparing values for nutrient cycling in the Swartkops and Sundays River estuaries, with data transfer from different existing valuations, results in a wide range of estimates (ZAR27 million–ZAR375 million) (Supplementary table 1).

Table 2: Combined areas of Swartkops and Sundays River estuaries for different habitat types

Area	Total area (ha)	Swartkops River (ha)	Sundays River (ha)	Habitat types included
1	603	358	245	Open water
2	691	630	61	Salt marshes, reeds and sedges, submerged macrophytes
3	1294	988	306	Areas 1 and 2 combined
4	845	750	95	Salt marshes, reed and sedges, submerged macrophytes, sand- and mudbanks
5	1908	1245	663	Open water, salt marshes, reeds and sedges, sand- and mudbanks, terrestrial vegetation, flood plain and beach and dunes
6	2168	1460	708	Open water, salt marshes, reeds and sedges, sand- and mudbanks, terrestrial vegetation, flood plain and beach and dunes

Source: Based on the classification of Algoa Bay Project.[32]

While the reliance on data transfer is preferable to no valuation, it is always less desirable than valuation based on locally sourced data. However, there are severe limitations in terms of research capacity, funding and data availability that make a detailed measurement of nutrient cycling in the Swartkops and Sundays River estuaries unfeasible. In this study, therefore, we aimed to address the knowledge gap regarding the economic value of nutrient cycling in estuaries by combining various forms of available data.

Methods

Measure of nutrient cycling

The overview of the process and data sources are presented in Figure 2. Three data sets were used to estimate the value of nutrient cycling. A cost data set for WWTWs was sourced from the available literature. Data sets for the kg/year pollutant removed by the estuary and the kg/year pollutant removed by five WWTWs in Algoa Bay were constructed from available data in the literature.

To construct the database for the nutrients removed by the estuaries, we sourced studies that took place between 1994 and 2022 and reported average dissolved inorganic phosphorus (DIP) and DIN concentrations in the heads and mouths of the Swartkops and Sundays River estuaries. Average concentrations were selected over median concentrations only because average concentrations were reported more frequently than median concentrations. In total, we sourced 12 average DIP and DIN concentrations for the Swartkops estuary head and 5 for the Sundays River estuary head (Supplementary table 2). Over time, five observations for the average DIP and DIN concentrations were sourced for the Swartkops estuary mouth and three for the Sundays River estuary mouth (Supplementary table 3). The resulting data set is incomplete (i.e. data is missing for some years) and the data are reported in different units (e.g. µM, mg/L and kg/annum). The exact sampling locations at estuary heads and mouths also differ among the studies. The number of samples for which averages were calculated and the time of the year in which sampling was completed also differ.

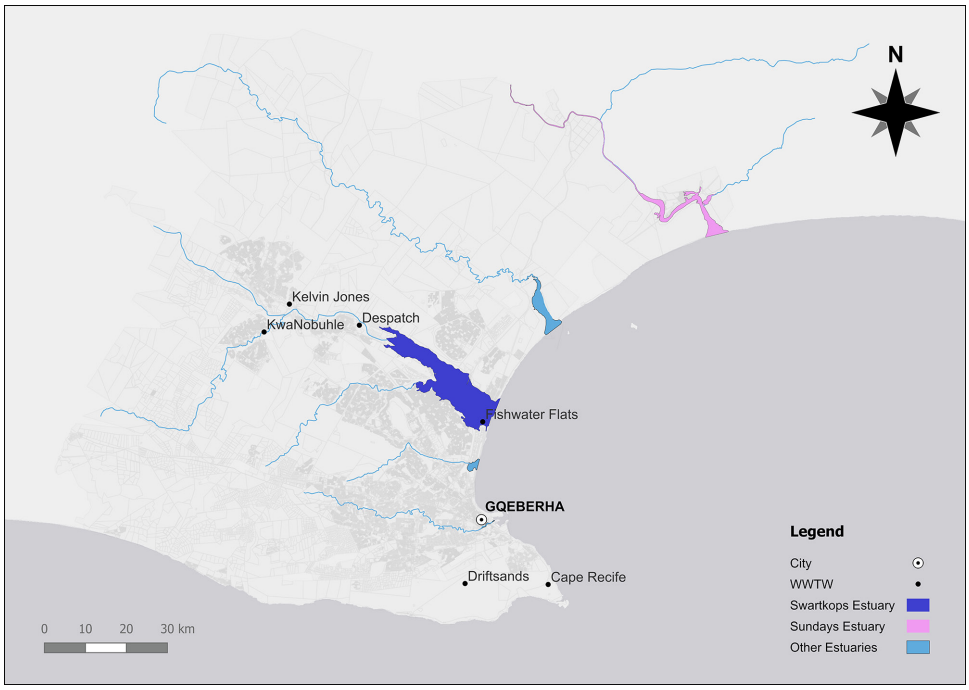
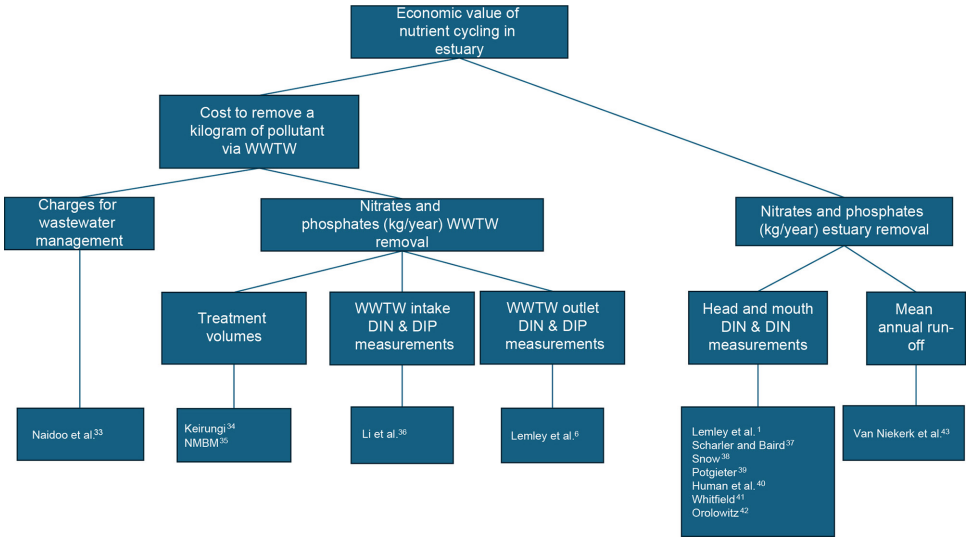


Figure 1: Map of the Swartkops and Sundays River estuaries showing the proximities relative to Gqeberha and surroundings.



WWTW, wastewater treatment works; DIN, dissolved inorganic nitrogen; DIP, dissolved inorganic phosphate

Figure 2: A diagram explaining the process of data collection and data sources.[1,6,33-42,43]

The database therefore consists of eight time series varying in the number of observations, namely: (1) DIP Swartkops head, (2) DIP Swartkops mouth, (3) DIN Swartkops head, (4) DIN Swartkops mouth, (5) DIP Sundays River head, (6) DIP Sundays River mouth, (7) DIN Sundays River head and (8) DIN Sundays River mouth. For each time series, annual nutrient loads in kilograms of DIN ($NO_3^- + NO_2^-$ and NH_4^+) and DIP were calculated with assumptions of average molar mass and mean annual run-off data (see Equation 1 with respect to DIP; a similar equation applies with respect to DIN). This calculation required converting all reported average concentrations into the same unit, namely μM – the commonly reported unit of average concentrations. Once converted, the difference between the concentration measured at the head and that measured at the mouth was calculated. To calculate the g/L of nutrient removed between the estuary head and its mouth for DIP and DIN per estuary, we applied the average molar mass (per nutrient type) and divided by 1000 (to convert to kg/L). We then multiplied this by the mean annual run-off (MAR) in litres to estimate the kilograms of the nutrient passing into the estuary and towards its interface with the ocean.

$$\text{kg DIP removed} = \frac{\left(\text{DIP}\,\frac{\mu M}{L}\ \text{Head} - \text{DIP}\,\frac{\mu M}{L}\ \text{Mouth}\right)}{10^6} * \frac{\text{Molar Mass P}}{1000} * \text{MAR(L)}. \quad \text{Equation 1}$$

Each of the eight series was plotted, and the best-fit curves were estimated through the available data points (Supplementary figure 1). These curves were used to simulate the calculated flow of nutrient concentrations over the past 18 years based on the reported averages.

Economic valuation of nutrient cycling

Algoa Bay has several WWTWs and information is available on their operating and capital costs, their treatment capacities and the concentrations of DIP and DIN found at their inlets and outlets.[6,33-36] Data on the concentrations of DIP and DIN in wastewater entering a particular WWTW, the amount of wastewater treated and the concentrations of DIP and DIN in treated wastewater at outlets are also available. These concentrations and treated amounts vary over time based on the efficiency of the WWTW as well as the socio-economic development trajectories of its location (the number ofmany housing units connected to the sewerage system vs those unconnected, number of people per housing unit, number of housing units per square kilometre, number of industries, etc.).

In Supplementary table 4, the average kg/mL nutrients removed, as reported by Lemley et al.[6], fell from 37 kg/mL pre-2013 to 26 kg/mL post-2013 for data observed between 2009 and 2017. A linear curve was fitted to the pre-2013 and post-2013 average values. The operating and capital costs[33] (reported in ZAR/kL) are converted to ZAR/mL and divided by the average nutrient removed. This gives a time series of the cost of removing a kilogram of DIP and DIN using WWTWs in Algoa Bay. By subtracting the concentration of the wastewater leaving the WWTW from that of the wastewater entering, and multiplying this concentration by molar mass and total annual water treated figure, we can calculate the phosphate or nitrate removal value; it is a similar calculation to Equation 1, but using the total water treated instead of mean annual run-off. As the cost to treat a kilolitre of water, the volume of water treated in a typical WWTW and the amount of nutrients removed are known, it is possible to calculate the unit cost for removing a kilogram of pollutant (see Equation 2 with respect to DIP, but the same applies for DIN):

$$\frac{\text{ZAR}}{\text{kg DIP removed}} = \frac{\text{ZAR}}{\text{L treated}} \Big/ \left(\frac{\text{kg DIP in}}{\text{L treated}} - \frac{\text{kg DIP out}}{\text{L treated}}\right). \quad \text{Equation 2}$$

By applying this cost to remove a kilogram of pollutant via a WWTW to the kilogram of pollutant removed by the estuary, we calculated a value for the work done by the nutrient cycling ecosystem service of the Swartkops and Sundays River estuaries. This value provides an estimate of the cost to society for the amount of work the estuary performs in terms of nutrient cycling, using the operational costs of WWTWs.

Table 3: The economic value (ZAR million) of nutrient cycling by the Swartkops and Sundays River estuaries

Year	Swartkops River estuary	Sundays River estuary	Total
1994	8.6	29.9	38.5
2001	3.5	29.2	32.6
2002	3.9	26.1	30.1
2003	4.8	23.4	28.2
2013	36.1	8.8	44.9
2018	74.2	7.2	81.4
2019	84.7	7.2	91.9
2020	96.1	7.3	103.4
2021	109.5	7.6	117.2
2022	123.4	7.9	131.4

Results

Table 3 summarises the estimated total value of nutrient cycling. If manufactured capital had to be used to remove the nutrients from the estuary, it would have cost society approximately ZAR38.4 million (USD2.08 million using an exchange rate of USD1 = ZAR18.4519) in 1994 and increased to ZAR131.4 million (USD7.12 million) in 2022 (Table 3). The volume of wastewater treated by the WWTWs has increased over time, but the estimated kg/mL pollutant removed has declined, while available data indicate estuaries are removing more pollutants over time. The relative efficiencies of WWTWs in Algoa Bay, compared to the efficiency of the Swartkops and Sundays River estuaries, in reducing DIP and DIN concentrations are therefore moving in opposite directions (Table 4): the efficiencies of the WWTWs have declined by 47% from 43.9 kg to 23.4 kg of nutrient removal per millilitre, and that of the estuaries has increased by 650%, albeit from a very low base of 0.2 kg to 1.5 kg of nutrient removal per millilitre.

Discussion

Data constraints and limitations

Under ideal circumstances, the valuation of nutrient cycling in estuaries would require multi-year median concentrations of DIP and DIN derived from many annual samplings at locations in the estuary head and mouth that would be regarded as ecologically equal (estuaries change and move over time). Furthermore, regular wastewater concentrations of DIP and DIN entering and leaving WWTW at outlets, along with fluctuating WWTW throughput volumes, would be required. In addition, the change in the cost of removing nutrients from wastewater (ZAR/kg removed) would also be necessary. These changes in nutrient levels might be due to changes in population, industrial activity and management vectors. Due to resource and capacity constraints, these estimates, properly sourced and archived in an easy-to-access central and open database, are not available. We thus must revert to alternative methods. These methods are either the use of data transfer, importing values from other studies, or the use of limited data pertaining to DIP and DIN concentrations as is. While data transfer is relatively quick and cheap, it tends to provide very weak estimates due to contextual differences, as will be highlighted below. Here, we therefore propose an alternative method by using data sources from WWTWs as a proxy to conduct the valuation of nutrient cycling within an estuary. It has its limitations due to incomplete data records but is considered contextually more relevant and appropriate than data transfer.

Data transfer inadequacy

The findings of this analysis provide some evidence that the economic value of nutrient cycling in estuaries is highly variable across different systems due to a complex interplay of ecological, geographical and socio-economic factors, and that this variability prevents convergence to

Table 4: Comparing the efficacy of the wastewater treatment works (WWTW) and the estuaries in removing pollutants over time

	WWTWs		Estuaries	
	Treated water (mL/year)	Removal estimate (kg/mL)	Combined mean annual run-off (mL/year)[43]	Removal estimate for both estuaries (kg/mL)
1994	10 950	43.9	339 200	0.2
2001	25 550	38.8	339 200	0.1
2002	29 200	38.1	339 200	0.1
2003	32 850	37.3	339 200	0.1
2013	58 400	30.0	339 200	0.6
2018	60 225	26.3	339 200	1.0
2019	59 495	25.6	339 200	1.1
2020	58 217	24.9	339 200	1.2
2021	57 670	24.1	339 200	1.3
2022	56 575	23.4	339 200	1.5

a narrow range of values. Ecosystem services are not typically normally distributed.[44] This highlights the fallacy of using data transfer techniques in producing valuations for other estuaries or for aggregation to a national average, as well as the dangers of communicating ecosystem service values in terms of ranges, means and standard deviations.

The economic value of nutrient cycling

As noted in Table 2, the spatial extent of an estuary can be defined in various ways depending on which of its features are included and which are not. Using the smallest denominator, that of open water only, a hectare of the Swartkops River estuary provided society an annual benefit of ZAR344 692/ha (USD18 681/ha) in 2022. The equivalent value for the Sundays River estuary is ZAR32 245/ha (USD1747/ha).

The two international studies listed in Table 1 provide a range from USD2661/ha to USD579 632/ha. This, however, is misleading as these estuaries are defined with different habitat characteristics. When adjusting these to reflect the open-water value only, the range changes to between USD4624/ha and USD9377/ha (Supplementary table 1). The estimate for the Sundays River is only 37% of the lowest estimate within this range, while the estimate for the Swartkops River estuary is about double the highest value.

The value of nutrient cycling in the Swartkops River estuary has increased considerably from ZAR8.6 million (USD466 076) to ZAR123.4 million (USD6.7 million; using an exchange rate of USD1 = ZAR18.4519). This is due to increases in DIP and DIN concentrations in the Swartkops River estuary, which are most probably due to the expansion of industry and informal settlements in Gqeberha. This, considered together with evidence of the declining efficiency of WWTWs in Algoa Bay, implies the system is facing increasing anthropogenic stress.

Conversely, the value has declined in the Sundays River estuary from ZAR29.9 million (USD1.6 million) to about ZAR7.9 million (USD428 140). There are three possible, not mutually exclusive, explanations for the reduction in nitrate nutrient loads in the Sundays River estuary since 1994. The first is that agricultural legislation has becom stricter and its enforcement has caused fewer agricultural pollutants to find their way into the river. The second is that the Orange-Fish-Sundays Rivers water scheme is affecting the amount of water flowing in the river, which may dilutethe pollutants and thus the value. The final explanation is that the growth in conservation activities, particularly the continual expansion of Addo Elephant National Park as well as the declaration in 2018 of a Marine Protected Area[45], has affected the extent to which pollutants enter these river systems and, subsequently, the marine environment.

Implications

The change in valuation over time is significant. This change reflects changes in WWTW efficiency, economic development and population growth, and also includes conservation efforts, the adoption of environmentally friendly agricultural practices and regulation upstream, as well as water transfer schemes.[46] Irrespective of these changes, the available data indicate the sizable contribution of the estuaries pertaining to nutrient cycling services. In 2022, estuaries in Algoa Bay – with little cost to society – removed nutrient loads at an estimated value of ZAR131.4 million. The cost to remove this additional pollutant using WWTWs would need to be larger to compensate for the loss of plant efficiency and capacity shortages. It should be noted that, although there has been no recent public tender, upgrades and expansions to existing facilities in the Eastern Cape would have cost between ZAR200 million and ZAR800 million (depending on scope) in 2010.[47]

By allowing these estuaries to decline, society could gradually lose this free annual benefit and place at risk the economic value that a healthy marine environment contributes to the local economy. In 2024, Nelson Mandela Bay's tourism sector generated approximately ZAR4.2 billion, while logistics and port-related activities contributed an estimated ZAR6.8 billion to the metro's economy.[48] Protecting the value added by marine ecosystems necessitates substantial efforts towards estuarine conservation to ensure future ongoing nutrient cycling occurs.

Conclusion

Ecosystems render services that have economic value, such as nutrient cycling, and that are often underappreciated because their economic contributions are not made explicit due to significant complexities. Making these values explicit is important to mobilise resources towards the protection, conservation and restoration of ecosystems to enhance the capabilities thereof to perform their functions. Robust nutrient cycling valuations can support the development of evidence-based policies aimed at reducing nutrient pollution and enhancing ecosystem services. Policymakers can use these valuations to justify the implementation of regulations and initiatives that protect and restore estuarine environments.

According to the data transfer method, the range of nutrient cycling is very large, ranging between ZAR27 million (USD1.4million) and ZAR375 million (USD20.32 million), depending on the source, the valuation method and the area over which the unit values are applied. This broad range, while useful, introduces too much uncertainty and has little value from a planning perspective. Even within a data-poor and resource-constrained context, it is possible to use the data available to estimate the budget required for WWTWs to remove the same amount of nutrients. This estimate, albeit not perfect, is considered more reliable as it uses locally sourced data. Also, as the

cost and efficiency data for WWTW are more readily available and nutrient concentrations at estuary heads and mouths are more easily measured, additional estimates in other estuaries are feasible. Within this case, the value of the nutrient cycling services of the Swartkops and Sundays River estuaries is estimated to have increased from approximately ZAR38.5 million (USD2.09 million) in 1994 to ZAR131.4 million (USD7.12 million) in 2022.

These estuaries offset the need for capital investment of these magnitudes, reflecting their importance and the need for continued restoration and conservation.

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Data availability

The data supporting the results of this study are available upon request to the corresponding author.

Declarations

We have no competing interests to declare. We have no AI or LLM use to declare. Ethical clearance was obtained from Nelson Mandela University (H20-BES-DEV-003).

Authors' contributions

R.P.: Investigation, methodology, formal analysis, writing – original draft, writing – review and editing. M.A.O.: Conceptualisation, visualisation, formal analysis, writing – original draft. J.N.B.: Conceptualisation, validation, supervision, writing – review and editing. B.S.: Project administration, funding acquisition, writing – review and editing. All authors read and approved the final manuscript.

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