Viability analysis for investing in ecological infrastructure to secure water supply: A case study of South Africa

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WATER
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“… our relentless conversion and degradation of remaining natural habitats is eroding overall human welfare for short-term private gain. In these circumstances, retaining as much as possible of what remains of wild nature through a judicious combination of sustainable use, conservation, and where necessary, compensation for resulting opportunity costs makes overwhelming economic as well as moral sense.”

- Balmford et al. (2002)

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PLAGIARISM DECLARATION

I know that plagiarism is wrong. Plagiarism is using another’s work and to pretend that it is one’s own. I have used the Harvard reference style as the convention for citation and referencing. Each significant contribution to, and quotation in, this project from the work, or works of other people, has been attributed, cited and referenced. This project is my own work. I have not allowed and will not allow anyone to copy my work with the intention of passing it off as his or her own work. I acknowledge that copying someone else’s work, or parts of it, is wrong, and declare that this is my own work.

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ABBREVIATIONS

BI	Built infrastructure
CGIAR	Consultative Group for International Agricultural Research
CMA	Catchment management agency
CoCT	City of Cape Town
CoGTA	Department of Cooperative Government and Traditional Affairs
CSI	Consortium for Spatial Information
DEA	Department of Environmental Affairs
DFFE	Department of Forests, Fisheries and the Environment
DWS	Department of Water and Sanitation
EI	Ecological infrastructure
GCTWF	Greater Cape Town Water Fund
IAP	Invasive alien plant
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IWS	Investments in watershed services
NbS	Nature-based solutions
NCAVES	Natural Capital Accounting and Valuation of Ecosystem Services
NIAPS	National Invasive Alien Plants Survey
NMBM	Nelson Mandela Bay Metro
NRM	Natural resource management
PES	Payments for ecosystem services
PV_c	Present value of costs
PV_w	Present value of water supplied
ROI	Return on investment
RSA	Republic of South Africa
RSS	Reconciliation strategy study
RWU	Regional water utility
SANCOLD	South African National Committee on Large Dams
SANLC	South African National Land-Cover
SDGs	Sustainable Development Goals
SWSAs	Strategic water source areas
UEIP	uMngeni Ecological Infrastructure Partnership
UN	United Nations
UNEA	United Nations Environment Assembly
UNEP	United Nations Environmental Programme
URV	Unit reference value
WC/WDM	Water conservation and water demand management
WfW	Working for Water
WMA	Water management area
WSA	Water service authority
WSP	Water service provider
WSS	Water supply system

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ABSTRACT

There is increasing understanding of the role that both ecological and built infrastructure can have in economic growth and development in terms of water supply. However, degradation of ecological infrastructure (EI) is resulting in the loss of valuable ecosystem services that benefit human well-being. Invasive alien plants (IAPs) are degrading catchment areas which negatively impacts delivery of hydrological ecosystem services. Clearing IAPs is considered a catchment conservation intervention that preserves these services. This study used South Africa as a case study to analyse the viability of investing in EI by way of IAP clearing compared to built infrastructure augmentation interventions to secure water supply in the long term. Unit reference values (URVs) were used to compare cost-effectiveness between ecological and built interventions for 11 of South Africa's regional water supply systems (WSSs). Built infrastructure URVs were available from government reports, while URVs for EI were calculated by modelling spread of IAPs, calculating the cost to clear them between 2022 and 2050 and the potential amount of water saved in their absence. The results provide quantitative evidence of the cost-effectiveness of investing in EI against built infrastructure options to secure water supply. The potential water to be gained by clearing IAPs from catchment areas of existing bulk water infrastructure was approximately 40% of what would be gained by implementing all built infrastructure interventions by 2050. It is recommended that IAP clearing be pushed ahead of built infrastructure interventions to delay costs associated with further built infrastructure development. Governing institutions, economists and natural resource managers are therefore encouraged to coordinate efforts towards designing EI investment frameworks as a sustainable, resilient approach to securing water supply.

Keywords: Ecological infrastructure; ecosystem services; sustainability; Natural Resource Management (NRM); water supply

INTRODUCTION

The Anthropocene has presented humanity with many challenges, the most pressing of which can be categorised into three major themes: adapting to climate change, protecting biodiversity, and ensuring human well-being (Seddon et al., 2020). Degradation of ecological infrastructure (EI) is a global issue that negatively affects all three of these major challenges by diminishing the capacity of naturally functioning ecosystems to provide valuable ecosystem services. EI is briefly defined as naturally functioning ecosystems that provide important services to humans (Audouin et al., 2021). Indeed, a global study found that the cost of land degradation due to land cover change and associated loss in essential ecosystem services is approximately US$300 billion annually, with Sub-Saharan Africa accounting for the largest share of this global cost (Nkonya et al. 2016). Intensive and extensive agricultural practices, invasive alien plants (IAPs), land transformation, fire suppression, hydrological alteration and urban sprawl are the main threats facing natural ecosystems and their biodiversity (IPBES, 2018; Turpie et al. 2017).

In an age of drastic environmental change and human population growth, opportunities for pursuing economic development in more sustainable ways are becoming better understood and more widely sought after. Investing in the resilience of natural systems through restoration and conservation are crucial aspects of achieving a more sustainable trajectory. This requires a holistic approach where economic growth, ecosystem health, as well as human well-being are considered. Investment in EI to secure hydrological ecosystem services presents an opportunity to reverse the effects of degradation, while restoring ecosystem functionality to produce essential ecosystem services, such as water provision.

There is increasing understanding of the role that both ecological and built infrastructure can have in economic growth and development in terms of water supply. Muller et al. (2015) argue that EI will not have the capacity to meet the demand of future water requirements such that built infrastructure will. This argument considers water supply investment as being directed exclusively to either EI or built infrastructure; however, water supply services are not solely derived from ecological or built infrastructure, but both. Therefore, investing in the protection and restoration of EI to complement existing built infrastructure has the potential to improve upstream water yields, while ensuring the longevity and most efficient use of existing built infrastructure. Essentially, investing in the restoration and maintenance of EI can simultaneously protect existing built infrastructure investments if water yields are indeed improved. A combination of investments in EI and built infrastructure should be considered crucial in securing resilient, reliable water supply.

There is currently a lack of quantitative information that shows the positive relationship between naturally functioning EI and built infrastructure to produce reliable water supply. The value of EI investments to secure water supply is nested within this information and would help to advance the pursuit of more sustainable, nature-based approaches to water supply globally. Therefore, this study had a specific focus on understanding the role that EI investments through IAP clearing could have in supplementing already existing bulk water supply infrastructure (i.e., built infrastructure).

The overall aim of the study was to determine the cost effectiveness of investing in catchment restoration to secure water supply in the key water supply systems of South Africa over time by comparing estimated costs and benefits associated with IAP clearing to that of planned built infrastructure augmentation costs and benefits. The following objectives were set to achieve the overall aim:

1) Describe the current (2022) and future (2050) types and extent of IAP invasion in catchment areas of existing infrastructure owned and managed by Water Service Providers (WSPs) by simulating a spread model of the latest available South African IAP data, produced by Kotzé et al. (2010).
2) Determine the cost of clearing IAPs from relevant catchment areas based on their estimated extent and the amount of water that could be gained in their absence between 2022 and 2050.
3) Examine the planned sequence of water supply infrastructure developments and associated costs to meet projected demands between 2022 and 2050 across South Africa’s water supply systems.
4) Evaluate the cost-effectiveness of IAP clearing compared to built infrastructure developments for each water supply system.

Considering the overall aim, it was hypothesized that, within regional context, investing in EI in the form of IAP clearing could be a cost-efficient intervention for enhancing and securing future water supply when compared to other built infrastructure interventions and should be planned for ahead of these interventions when this is the case.

Although the benefits of catchment restoration are widely recognised, quantitative information and real-world examples regarding the cost-efficiency of catchment restoration for enhancing water supply is limited. South Africa was used as a case study to provide a national-scale indication of the viability of catchment restoration as a cost-effective EI investment mechanism to secure water supply in the long term.

LITERATURE REVIEW

CATCHMENT AREAS AS CRITICAL "ECOLOGICAL INFRASTRUCTURE"

Nature provides humans with a broad range of goods and services that are important for human well-being and for which we do not bear the cost (Costanza and Daly, 1992). However, as natural systems are degraded over time through increased human pressures, these benefits are lost (Sutton et al., 2016; IPBES, 2018). The valuation of ecosystem services has become increasingly recognised since the term's emergence in the early 1980s and has since been used to effectively communicate society's dependence on the benefits of naturally functioning ecosystems (Ehrlick and Ehrlick, 1981; Kumar and Kumar, 2008; Gómez-Baggethun et al., 2010). Valuation techniques had been used since the 1960s, however studies of this kind exploded in the 1990s as natural scientists began to recognise the appeal in presenting ecological issues in economic terms for decision-makers (Gómez-Baggethun et al., 2010). Understanding the value of ecosystem services started to reveal the costs associated with degradation of functioning ecosystems and has helped policy-makers prioritise actions that promote ecosystem service delivery and avoid the loss thereof (Akhtar-Schuster et al., 2011). However, despite the abundance of literature that aims to inform policy, formulation of policy that protects and conserves the systems that produce valuable ecosystem services is still lacking (Fisher et al., 2008; Laurans et al., 2013). Indeed, as an emerging tool, Ecosystem Services economic Valuation (ESV) is recognised as a formal subject for its potential to help with efficient decision-making in the political arena but is still criticised for its limitations (Laurans et al., 2013). Laurans et al. (2013) argue that much of the limitations of ESV are a result of a "literature blindspot" relating to the Use of Ecosystem Services Valuation (UESV). The absence of peer-reviewed literature on UESV that analyses its shortfalls, recommends improvements and documents examples of how ESV has been put to practice, is preventing ESV from having any real influence on policy formulation.

In addition to the lack of real-world examples of UESV, the issue of scale, context and applicability of existing literature also influences effective decision-making. To gain traction with policy-makers, the scale at which the valuation of ecosystem services occurs needs to be refined. Turpie et al. (2017) highlight that much of the work on ecosystem service valuation is based on studies from around the world and collated in global databases. While international values can be important for formulating conservation and biodiversity financing strategies, they often lack the reliability and policy relevance for local contexts (Turpie et al., 2017). There is therefore recognition of the need to refine the scale at which valuation of ecosystem services is assessed to better understand the distribution of their value and to optimize allocation of finance from a national context.

Another way of gaining the attention and interest of policy-makers is by referring to the complexity of ecosystem services by way of more familiar terms, for example 'infrastructure'. 'Ecological infrastructure' (EI) can be defined as naturally functioning ecosystems that provide important services to humans, such as water provision, disaster risk reduction, soil formation and climate regulation (Hughes et al., 2018; Audouin et al., 2021; Mbopha et al., 2021). The concept of EI has the same objectives as engineered infrastructure and can be considered the "nature-based equivalent" of engineered structures that provide the same services (Cumming et al., 2017). It is considered a subset of the more widely used 'natural capital' which is defined by the Natural Capital Forum (2017) as "the world's stocks of natural assets which include geology, soil, air, water and all living things". From an economic perspective, EI can be considered the source, raw material, or *asset* from which ecosystem services are derived (Cumming et al., 2014). To maintain this asset base, measures are needed to conserve and protect natural systems. Such measures are recognised at 'Nature-based solutions' (NbS).

NbS serve as an integrated approach to solving environmental and economic challenges holistically. There has been growing awareness of the potential for NbS to be included in national and global strategies to maximise the benefits received from nature and to achieve economic growth sustainably. However, the lack of investment in these initiatives is widely recognised as one of the main barriers to implementation and monitoring of NbS (Seddon et al., 2020). Building upon the concept of EI, 'investing in ecological infrastructure' (or "EI investments") is an emerging area of interest that falls under the NbS umbrella and serves as a relatively new approach to understanding and communicating the true purpose of restoring and maintaining natural ecosystems (Cumming et al., 2014). Just as built infrastructure requires an initial capital investment followed by on-going operation and maintenance investments to produce desired services, so does EI. Essentially, 'EI investments' refers to the long-term directing of money into schemes or initiatives that actively focus on the conservation or restoration of ecosystems that provide valuable services for human well-being. Vogl et al. (2017) highlights the need for a modification in widely accepted accounting standards to include natural capital (or EI) values. To achieve this, there should be a movement towards bettering frameworks that assess the costs, benefits, and cost-effectiveness of restoring natural systems that have been degraded over time, including (but not limited to) catchment areas (or 'watersheds') that are important for downstream water supply (Sutton et al., 2016). The lack of cost-benefit and cost-effectiveness analyses for the adoption of EI investment approaches in catchment areas and the role it plays in increasing the risk of such investments is also noted by Palmer et al. (2015). Without this information, investors are unlikely to participate due to the risk and uncertainty associated with this lack of evidence.

One of the main values of naturally functioning catchment areas lies in the hydrological services they provide. These systems are vital to human well-being and biodiversity as they regulate the quantity and quality of the water resource (Brauman et al., 2007; Hunter et al., 2010). Yet already limited resources are greatly threatened by catchment degradation (Le Maitre et al., 2020). Conservation and restoration of catchment areas is a common example of how EI investments can be harnessed to secure hydrological ecosystem services into the future and is attracting the interest of economists, conservationists and policymakers alike (Sun et al., 2020). However, in the pursuit of economic development, the conventional method for resource provision and management in the water supply sector has been through built infrastructure (Palmer et al., 2015). Many developing countries still address water security solely through engineered solutions, for example through dams, pumping schemes, and major inter-basin transfer schemes (Smakhtin et al., 2001). However, there is a growing body of literature that recognises the potential of investing in catchment restoration to restore and maintain the yield of existing built water supply infrastructure. In fact, evidence for its success in sustaining, supplementing, and even substituting investments for built water supply infrastructure is increasing (Cumming et al., 2014; UNEP, 2014; Palmer et al., 2015).

INVASIVE ALIEN PLANTS AND THEIR EFFECTS ON WATER SECURITY

Water catchment areas are a source of provisional, supportive, and regulating ecosystem services, for example, the provision of water includes extraction for municipal, agricultural, industrial, commercial and thermoelectric power use, while supporting services provide water for plant growth and habitat for aquatic species (Brauman et al., 2007). However, catchment areas are also subject to varying degrees of degradation which diminishes their capacity to provide these services to downstream users (Brauman et al., 2007). Degradation of EI and the loss of ecosystem services are intimately related, where the ability and capacity of a system to provide essential services is diminished as degradation worsens (Favretto et al., 2016). This is explicitly evident in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Assessment Report on Land Degradation and Restoration, one of the most comprehensive global reviews on the connection between land degradation and ecosystem services to date (IPBES, 2018). It is estimated that up to 10% of annual global GDP is lost to the effects of land degradation, and when the value of economic benefits is taken into account, this translates to approximately USD 1.4 trillion each year (IPBES, 2018).

Surface water resource systems in South Africa are particularly threatened by land degradation in the form of IAP invasion, bush encroachment, and erosion (Lötter and Le Maitre, 2021). IAPs are particularly well-known as a driver of degradation worldwide and can have significant biological, financial, and economic impacts (van Wilgen et al., 2020). The effect of IAP infestations on streamflow reduction is well demonstrated in the literature (Prinsloo et al., 1999; Görgens and van Wilgen, 2004; Le Maitre et al., 2016). Therefore, from a financial standpoint, the presence of IAPs has two opportunity costs. The first is related to a loss in the value of production due to reduced water resources, while the second is related to the increased cost associated with new water supply augmentation schemes needed to compensate for water lost to IAPs (Le Maitre et al., 2020). From an economic standpoint, the impacts of IAP invasions are much broader as they negatively affect biodiversity and disrupt the optimal functioning of ecosystems that humans depend on for service provision (Le Maitre et al., 2020).

GOVERNMENT EFFORTS TO CONTROL IAPS

In 2017, it was estimated that the value derived from hydrological ecosystem services alone was worth approximately R275 billion for South Africans (Turpie et al., 2017). The South African government initiated the Natural Resources Management (NRM) programmes (also referred to as the "expanded public works programmes") to address land degradation through restoration while simultaneously addressing poverty alleviation for those employed on these programmes (Turpie et al., 2008). The largest and particularly well-known branch of the NRM programme is the 'Working for Water' (WfW) programme, which is focused on the clearance of IAPs in mountain catchment and riparian areas to restore the integrity and functioning of the natural ecosystem (Turpie et al., 2008). Running projects in all nine of South Africa's provinces, WfW is the largest natural resource-based poverty relief programme in the country with an annual budget of over R400 million (RSA, 2003; Turpie 2008). The bulk of funding for WfW is generated through poverty relief programmes such as the Expanded Public Works Programme and the Reconstruction and Development Programme, however the government has also made substantial contributions through tax revenue (Turpie et al., 2008). The South African government therefore recognises the economic and financial value of EI, and particularly the role it plays in ensuring water security (DWA, 2013).

Globally, catchment conservation as a means to secure hydrological services has also been achieved through payments for ecosystem services (PES) (Farley and Costanza, 2010; Cumming et al., 2014). This has been particularly successful in the Americas and Europe, but has largely failed in southern African countries (Ferraro, 2007). South Africa's experience with PES subscribes to the general southern African experience, with all attempts to initiate traditional projects being unsuccessful, despite the development of a national PES model led by SANBI (Turpie et al., 2008; SANBI, 2011; Cumming et al., 2014). Among other reasons, the failure of PES in South Africa has mainly been attributable to the public good nature of catchment systems and their services (Cumming et al., 2014). Consumers have been unwilling to pay higher tariffs for water services and has consequently resulted in a lack of capital to fund incentive schemes for landowners and -users to adopt best practice (Cumming et al., 2014; Mbopha et al., 2021). South Africa's failure to successfully implement the PES model has led to investigations into other approaches to funding catchment restoration that are currently ongoing (Mbopha et al., 2021; Letley and Turpie, 2022).

SOUTH AFRICA'S WATER SUPPLY SECTOR

Institutional governance is recognised as a major barrier to the successful implementation of EI investments for securing hydrological ecosystem services and can be referred to as 'institutional failure' (Vogl et al., 2017; Mbopha et al., 2021). It is critical to consider which level of institutional government would be most suitable for the effective management of incentive arrangements related to EI investments (Mbopha et al., 2021). From a hydrological EI investments context, a number of key actions must take place at the relevant level of institutional governance. Generally, the largest scales i.e., national and global, are responsible for influencing and designing water development policy and frameworks, directing resources into different types of EI investment strategies – particularly those with the highest return on investment (ROI), and allocating infrastructure funds to investments in EI specific to hydrological ecosystem services (Vogl et al., 2017). The regional and local levels are responsible for ensuring the effective implementation of EI investments to meet their respective water security goals (Vogl et al., 2017). This includes assessing different EI investment options, designing context-specific program, assessing ROI for the context-specific region, building and engaging in partnerships, and creating a plan to monitor the impacts of the program (Vogl et al., 2017). Context specificity refers to the ecological, economic and societal setting of the region in question.

South Africa's Constitution states that everyone has the right to access sufficient water. The legislative framework outlined in the Water Services Act 108 of 1997 aims to ensure this right by regulating institutions that provide water services. However, demand for water is expected to further increase with population growth, urbanisation, economic growth, and higher standards of living (Sun et al., 2008; Wang et al., 2017; Pan et al., 2018; Oiro et al., 2020). This has put governing water service institutions under significant pressure to deliver water requirements under often constraining conditions in relation to funding, water resources and bulk water supply infrastructure.

South Africa has a complex water management and supply system. Beck et al. (2016) highlighted the three major levels of institutional water governance in South Africa, which are simplified in **Figure 1**. Among other key institutions such as national NGOs, donor agencies, research institutions and international agencies and partnerships, South Africa's water sector can be viewed at the national, regional and local levels (Beck et al., 2016). The national level consists of governmental departments, which includes the Department of Water and Sanitation (DWS). The regional level consists of three main entities, including Catchment Management Agencies (CMAs); water boards, which are considered "organs of state"; and Water and Sanitation Forums (DWA, 2014; Beck et al., 2016). There was a proposal for the consolidation of water boards into fewer, stronger boards to be called 'Regional Water Utilities' (RWUs) (DWA, 2013). The purpose of the consolidation proposal was to "strengthen the development, financing, management, operation and maintenance of regional bulk water and wastewater infrastructure" (DWA, 2013). However, this proposition had not yet been established as of 2022 (Toxopeüs, 2019). Lastly, the local level of the water sector's institutional governance consists of municipalities, which are also referred to as Water Service Authorities (WSAs); Water Service Providers (WSPs), which can be public, private, or mixed entities, or municipal government; and Water User Associations (WUAs). The roles and responsibilities of each of these entities are described in

Table *1*.

Population growth is a key driver of water use in South Africa and can influence the levels of water use in different sectors, such as the agricultural, industrial and domestic sectors (DEA, 2013). Water resource system planning requires detailed consideration and reliable coordination of institutions from all scales, however, in the scope of this study, water boards and the DWS are most relevant. The DWS produces reconciliation strategy studies (**Box 1**) which are used by water boards to determine future water requirements for a specific water supply system (WSS) (**Box 1**) and to guide planning for future water supply infrastructure (DEA, 2013).

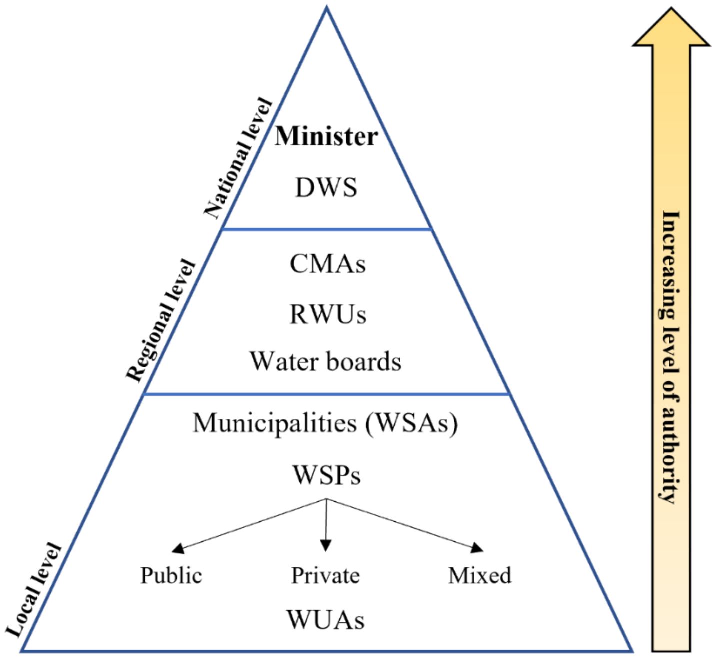

Figure 1. Graphical representation of some of the key institutions that govern South Africa's water supply sector at the national, regional and local scales. Based on: (DWS, 2014).

Box 1. Planning water supply in South Africa

Water supply systems (WSSs)

WSSs are regions delineated by the South African government related to institutional water supply services. Each region is dependent on existing and functioning water supply infrastructure that collects and/or delivers water from source areas (i.e., catchment areas). Government-owned entities called water boards (or water service providers (WSPs)) as well as the Department of Water and Sanitation (DWS) are responsible for the management of water services in these areas.

Reconciliation strategy studies

Reconciliation strategies involve a process of planning the water balance for a specific WSS, with the objective to ‘reconcile’ or balance available water sources with water requirements through various strategies in a given time frame, usually one or two decades (DEA, 2013). This can be achieved by increasing water supply through the construction of built infrastructure, restoring and rehabilitating catchment areas, and/or implementing water conservation and demand management (WC/WDM) strategies to reduce consumption. Each of South Africa’s major WSSs are associated with a context-specific reconciliation strategy study that outlines a portfolio of augmentation options and their relevant costs and energy requirements (DEA, 2013). The studies are conducted and published by DWS and serve as a strategic input for development planning in South Africa’s water sector.

Table 1. The roles and responsibilities of South Africa's governing water sector institutions at the national, regional and local levels. Adapted from: (DWS, 2014).

Institutional level	**Institution**	**Roles and responsibilities**
National	Department of Water and Sanitation (DWS)	Formulate policy in the water sector; regulate, monitor and provide support in ensuring suitable, equitable and safe water and sanitation services; and coordinate between lower-level institutions.
Regional	Catchment Management Agencies (CMAs)	Manage water resources at the regional or individual catchment level while involving local communities in their agenda. This is all planned and implemented within the scope of the National Resource Strategy Framework.
	Water boards (can also be referred to as 'water service providers' (WSPs))	Provision of water services in the form of bulk potable and bulk wastewater to other water services institutions (such as municipalities) within their areas of supply (also referred to as Water Management Areas (WMAs)).
	Regional Water Utilities (RWUs)	Build, operate, maintain, and support regional bulk infrastructure; and assist local and district municipalities, on an agency basis, to deliver services where they lack capacity to do so effectively.
Local	Municipalities (or Water Service Authorities (WSAs))	Ensure the provision of water services within their area of jurisdiction. These actions are regulated by the Department of Cooperative Government and Traditional Affairs (CoGTA).
	Water Service Providers (WSPs)	Provide water and/or sanitation services to end users within a specific geographical area through a contractual agreement with a WSA or other water services provider.
	Water User Associations (WUAs)	Co-operative associations made up of individual water users who wish to contribute to the undertaking of water-related activities for their mutual benefit.

METHODS

CONTEXT AND STUDY DESIGN OVERVIEW

South Africa is an arid country, with a mean annual rainfall of approximately 490 mm (Bailey and Pitman, 2015). There are 22 strategic water source areas (SWSAs) (**Figure 2**). SWSAs cover 10% of land that disproportionately supplies 50% of the country's water runoff (Lötter and Le Maitre, 2021). SWSAs roughly correlate with South Africa's water supply systems (WSSs) (**Box 1)**.

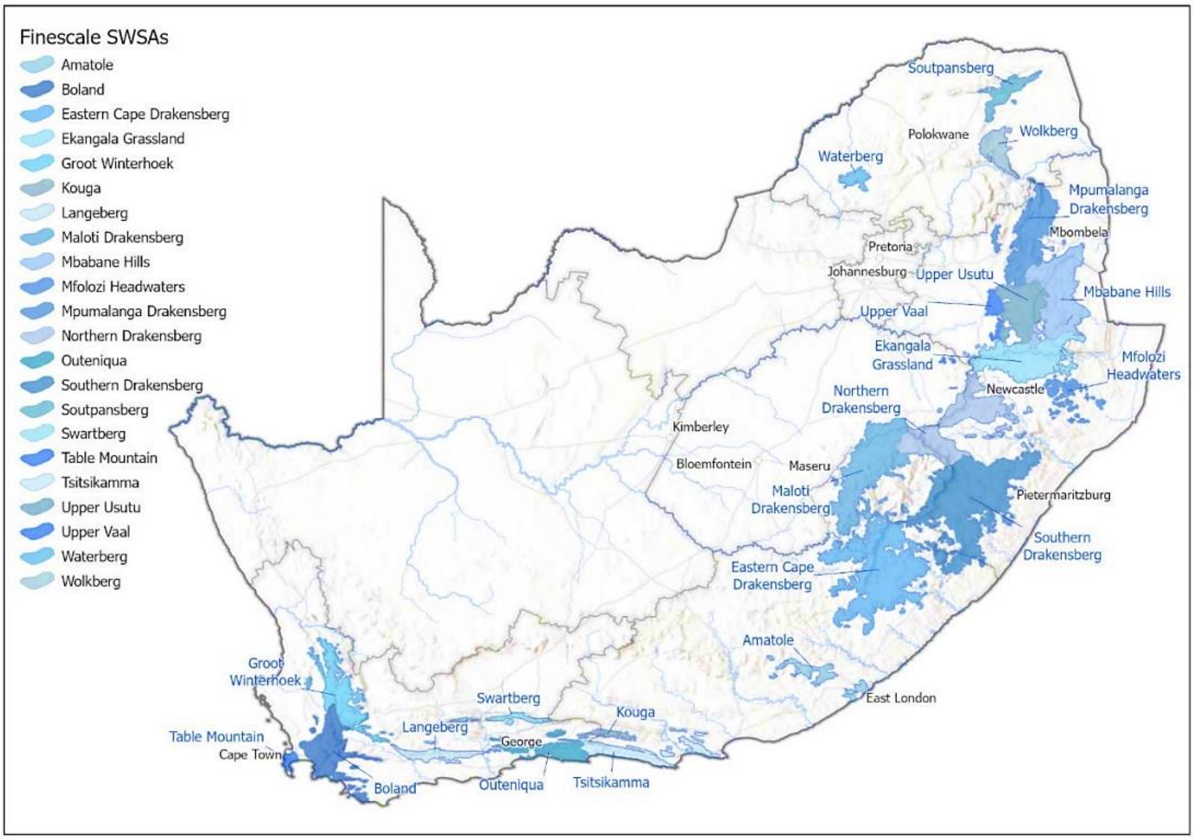

Figure 2. The Fine-scale Strategic Water Source Areas (SWSAs) for surface water in South Africa. Source: Lötter and Le Maitre (2021).

To assess the viability of investing in EI as a means to secure hydrological ecosystem services into the future, the costs and benefits of associated interventions were compared to the alternative built infrastructure interventions, which vary from smaller-scale dam augmentation schemes to large-scale multi-phase schemes[1]. The primary approach to securing hydrological ecosystem services is addressing catchment degradation. Presence of invasive alien plants (IAPs), erosion, siltation, and bush encroachment are all common indicators of catchment degradation (Al Sayah et al., 2021; Turpie et al., 2021). The key type of land degradation assessed in this study was IAP invasion. Therefore, the costs

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[1] Multi-phased schemes are large-scale water infrastructure development projects for a certain region, where water supply interventions are grouped in phases and initiated in a staggered manner.

of clearing IAPs in catchment areas of major surface water infrastructure was weighed against the benefit of additional water supply through these interventions. Similarly, the costs of engineered interventions were weighed against the benefit of their additional water supply.

The extent of IAP clearing was focused on water catchment areas of existing large dams owned by WSP's at the regional level of South Africa's institutional water supply system, i.e., water boards. Water boards are responsible for the management of South Africa's bulk surface water and are therefore considered key stakeholders in the water supply sector. There are currently nine official water boards in the country, however, the City of Cape Town and Nelson Mandela Bay Metro were also included as water boards as they manage their local infrastructure and supply as independent WSPs. Therefore, a total of 11 WSPs were considered. WSSs were considered the most relevant level of analysis as South Africa's Department of Water and Sanitation (DWS) analyses water demand, requirements and the relevant interventions needed to meet demands at this level. These analyses are referred to as 'reconciliation strategy studies' which contain the most detail for planned built infrastructure interventions at the relevant scale. The WSSs considered in this study and associated details are listed in **Table 2**.

Table 2. List of the South African water supply systems (WSSs) considered in this study and their relevant water management areas (WMAs)/catchment areas, reconciliation strategy studies (RSS), and the responsible water service providers (WSPs) for each area.

WSS	WMA/catchment	RSS	Responsible WSP(s)
Algoa Water Supply System	Kouga River System, Sundays River System	Algoa	Nelson Mandela Bay Metro
Amatole Water Supply System	Buffalo, Nahoon and Upper Kubusi rivers	Amatole	Amatola Water
Crocodile West Water Supply System	Crocodile River Catchment	Crocodile (West)	Magalies Water, Rand Water
Integrated Mgeni Water Supply System	Thukela, uMngeni, Mvoti, Mooi, and Umkomaas river catchments	KZN Coastal Metropolitan	Umgeni Water
Integrated Vaal River System	Upper, Middle and Lower Vaal River	Vaal	Rand Water, Sedibeng Water
Limpopo WMA North	Mogalakwena Catchment	Limpopo	Lepelle Northern Water, Magalies Water
Luvuvhu-Letaba Water Supply System	Luvuvhu-Letaba WMA	Luvuvhu-Letaba	Lepelle Northern Water
Olifants Water Supply System	Olifants River Catchment	Olifants	Lepelle Northern Water
Orange River System	Upper and Lower Orange River WMAs	Orange River	Bloem Water, Sedibeng Water
Richard's Bay Water Supply System	Mhlatuze River Catchment	Richard's Bay	Mhlatuze Water
Western Cape Water Supply System	Riviersonderend – Berg River System	Western Cape	City of Cape Town, Overberg Water

DELINEATING DAM CATCHMENT AREAS

The areas where IAP clearing would take place were limited to catchment areas that currently feed bulk water supply dams, i.e., South Africa's 'large dams'. Evaluating the costs and related water gains of IAP clearing at this scale was considered the most relevant and comparable to those of built infrastructure interventions.

To achieve this, a sub-dataset of South Africa's large dams was created using the South African National Committee on Large Dams (SANCOLD) 'South African Register of Large Dams' dataset (SANCOLD, 2018) to include only large dams either owned and managed by the relevant WSPs or owned by DWS but managed by the relevant WSPs. To be considered a 'large dam' the following criteria had to be met: 1) dams with a wall height of ≥15 m from the lowest point of the foundation; and 2) dams with a wall height between 5 m and 15 m and a capacity of >3 million m^3 (SANCOLD, 2018). The coordinates of each dam in the subset were retrieved from Google Earth.

All spatial analysis was conducted using the ArcGIS software (ArcMap version 10.4.1). A STRM derived 30 m DEM retrieved from Consultative Group for International Agricultural Research's (CGIAR) Consortium for Spatial Information (CSI) (CGIAR CSI, 2022) was used to create a flow accumulation raster[2] for South Africa. The flow accumulation raster was then used as a reference for pour point placement. The raster was categorised into two classes, including 'feeder cells' and 'flow cells'. Feeder cells are those that flow into other cells along a downslope and were set to have a flow accumulation value between 0 and 4000 so that all cells with an accumulated weight within that range represented the downslope area. Conversely, flow cells essentially represented the intersection line of two or more downslopes, or the bottom of a valley where water would flow. These cells were defined by a flow accumulation value of more than 4000. Pour points, which are considered the point where water would flow into a dam, were then placed within flow cells where branching rivers/streams

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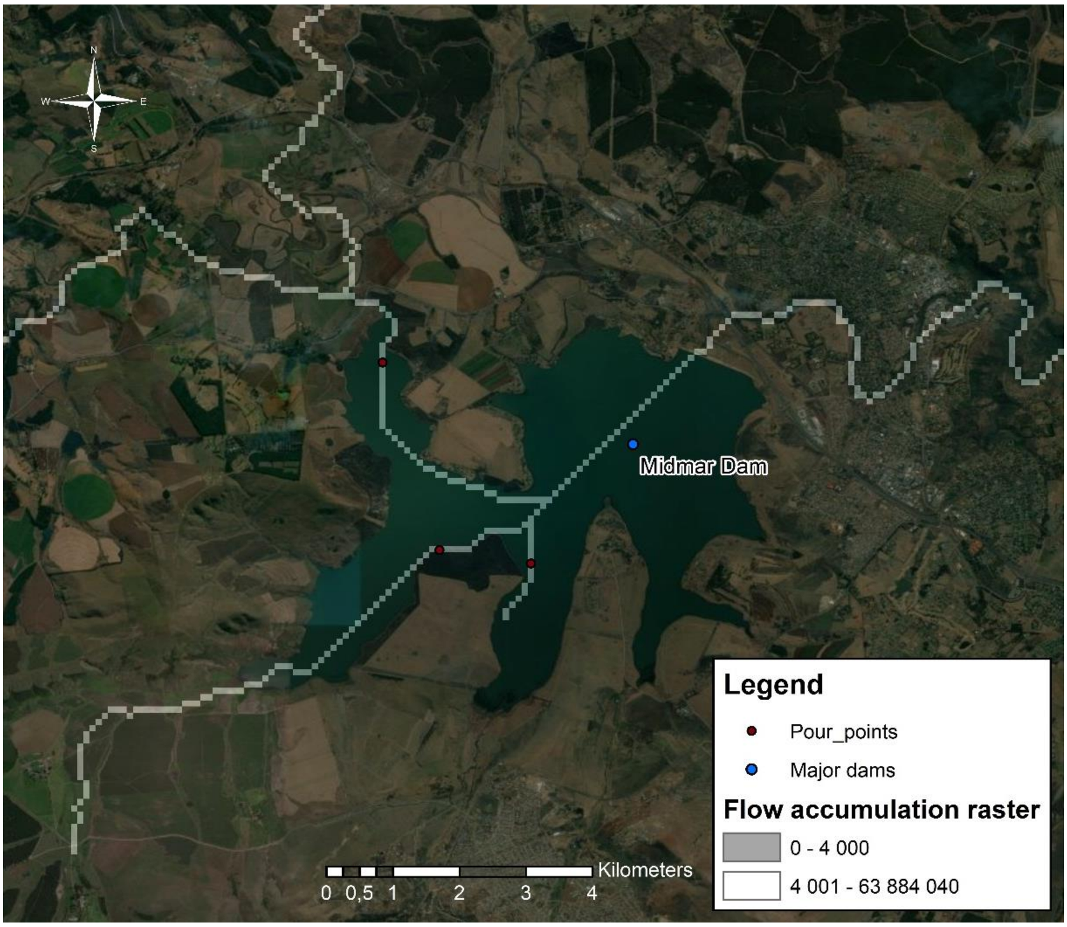
[2] A flow accumulation raster is tool that calculates the accumulated weight of cells that flow into each downslope cell.

converged into a single inlet for each dam (see example in **Figure 3**). The 'Watershed' tool was then used to delineate catchment areas for each pour point, i.e., sub-catchment areas, which were later consolidated into single catchment areas per dam.



To accommodate more efficient and accurate analysis, particularly for modelling IAP spread, South African quaternary catchment data (DWS, 2011) were spatially joined to the dam catchment data, providing a new dataset (hereafter referred to as the "dam-quat" dataset) that provided information on quaternary catchments relevant to each dam. To achieve this, it was assumed that 1) dam catchment areas aligned with the boundaries of one or many quaternary catchment areas, and 2) if a dam catchment area was too small to be assigned a quaternary catchment by the GIS tool, the quaternary catchment that contained the dam catchment area was manually selected and included in the dam-quat dataset. This process resulted in each dam catchment area being represented by one or more quaternary catchment areas.

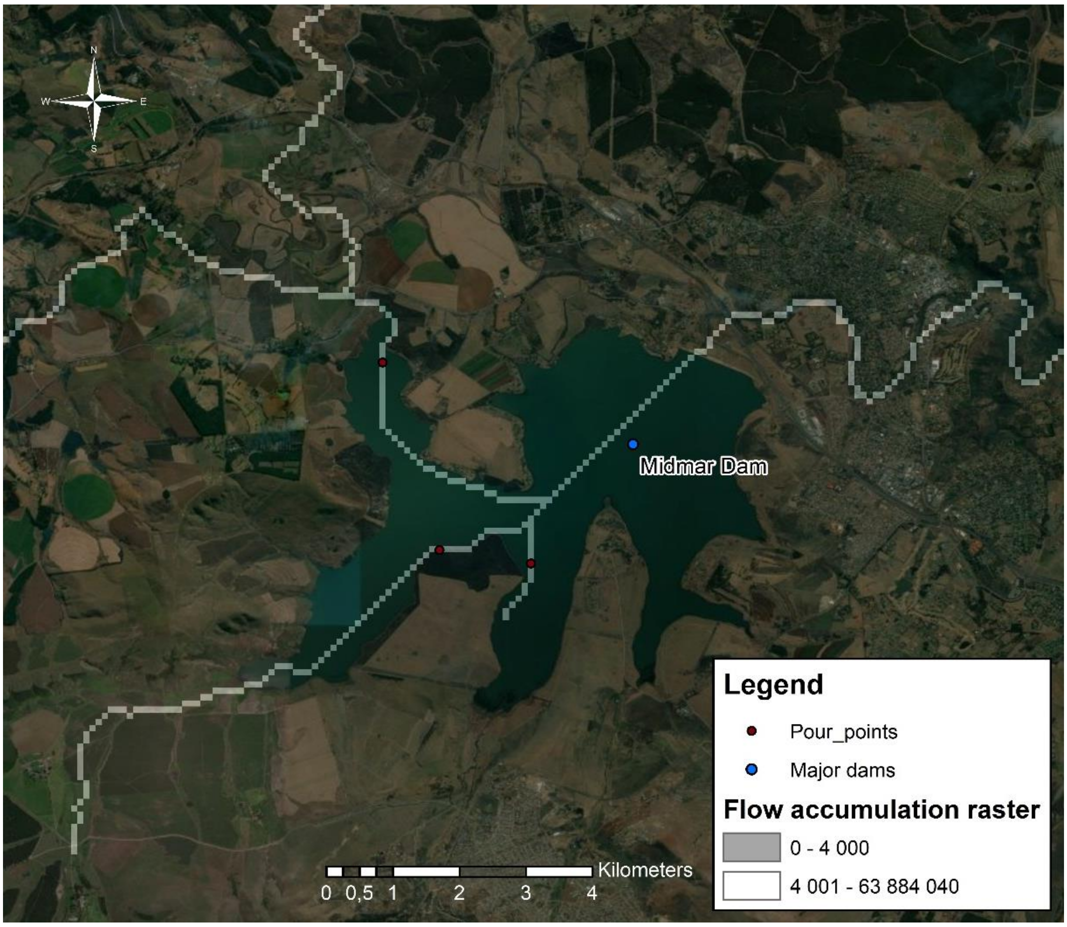


Figure 3. Example image showing the placement of pour points for the Midmar Dam owned and managed by Umgeni Water and situated in the Integrated Mgeni Water Supply System. 'Flow cells' are displayed in transparent white and 'feeder cells' in transparent black.

EXTENT OF IAP COVERAGE IN CATCHMENT AREAS

To estimate IAP clearing costs, it was necessary to estimate the extent of current and projected IAP coverage in the relevant catchment areas. The extent of IAP coverage was based on the National Invasive Alien Plant Survey (NIAPS) dataset which was attained through low level aerial surveys and statistical interpolation (Kotzé et al., 2010). This dataset is currently the most recent and comprehensive spatial dataset available for IAP coverage across South Africa and provided information on the average density of IAPs at a 250 m^2 spatial resolution as in 2010. Although the NIAPS data includes information for a number of IAP species, this study focused on gums (*Eucalyptus spp*.), pines (*Pinus spp*.) and wattles (*Acacia spp*.) due to their impacts and prominence in South African water resource systems.

Since the NIAPS dataset was published in 2010, IAP coverage firstly needed to be updated to current (2022) and modelled to future (2050) estimates of infestation to enable the calculation of potential clearing costs at both time steps. To achieve this, a simple logistic population growth model (**Equation 1**) was applied to the 2010 data. The equation applies the effect of an environment's finite resource availability which limits the growth of a population (Seidl and Tisdell, 1999). This is otherwise known as the 'carrying capacity' (Seidl and Tisdell, 1999). The equation is defined by the product of the growth of an existing population and the carrying capacity, where k is the growth rate, P is the population size, t is the relevant time step, and K is the carrying capacity, which in this case was considered to be area available for infestation, or 'invadable' land.

$$\frac{dp}{dt} = kP_{t-1}(1 - \frac{P_t}{K}) \qquad \textbf{Eq. 1}$$

To determine a measure of the potentially 'invadable' land, i.e., the carrying capacity, the South African National Land-Cover dataset (SANLC) 2020 (DFFE, 2021) was used to determine the number of 'invadable hectares' per quaternary catchment area. The SANLC 2020 dataset is the latest available version of South Africa's national landcover consisting of 73 landcover classes with an overall map accuracy of 85.47% (DFFE, 2021). It was assumed that invadable area included all land that was not classed as "built-up", "cultivated", "mines and quarries", or "waterbodies".

The spread of IAPs is largely determined by the rate at which the species under consideration can reproduce. The literature presents a wide range of spread rates for gums, pines and wattles, ranging from 2.6% per annum for wattle (Rebelo et al., 2013) to 15.6% per annum for pine (van Wilgen and Le Maitre, 2013). Therefore, a more general spread rate of 7.5% per annum was applied to all three types of IAP species to account for the broad range of spread rates seen in the literature. This spread rate was also used by Turpie et al., (2021) for the same collection of high water-using species. **Equation 1** was applied to the NIAPS 2010 data to calculate condensed ha estimates for gums, pines and wattles in each quaternary catchment area from 2022 to 2050.

COST-EFFECTIVENESS ANALYSIS

Overview

To derive the costs of interventions for catchment restoration and rehabilitation, information was gathered from literature that addressed the spread of IAPs (Le Maitre et al., 2016; Turpie et al., 2018; Turpie et al., 2021) and methods of calculating estimates of the cost to clear IAPs per hectare. Similarly, all information pertaining to built infrastructure interventions was retrieved from reports published by DWS, who provide access to reconciliation strategy studies for bulk water supply augmentation options for each water supply system in South Africa. These reports included the relevant cost and yield information

Unit reference values (URVs) can be used as a direct measure of the benefits derived from water resource interventions and are commonly used to assess the feasibility of projects in the water supply sector (van Niekerk and du Plessis, 2013). This is done by calculating the cost per cubic meter of water over the lifetime of the project (van Niekerk and du Plessis, 2013). Hence, URVs were used as a measure to compare the financial costs and benefits (additional water gain) derived from EI and built infrastructure interventions in this study. The economic lifespan of a particular water development scheme is usually between 30 to 45 years (van Niekerk et al., 2013). Most of South Africa's existing WSS reconciliation strategy studies are evaluated up to 2050. Therefore, given the timing of the study, all analyses assumed that interventions would begin in 2022 and were evaluated up to 2050. This assumed a 28-year project lifespan for IAP clearing and management if the water supply benefits of these EI interventions are to be seen by the same year as other built infrastructure interventions.

Assessment of planned infrastructure development

Each of the study focus regions are depicted in **Figure 4.** To determine the planned sequence of infrastructure development to meet future demand per WSS, each of the relevant reconciliation strategies (explained in **Box 1** and listed in **Table 2**) were analysed. Only the interventions planned to take place between the base year of 2022 and the end year of 2050 were considered.

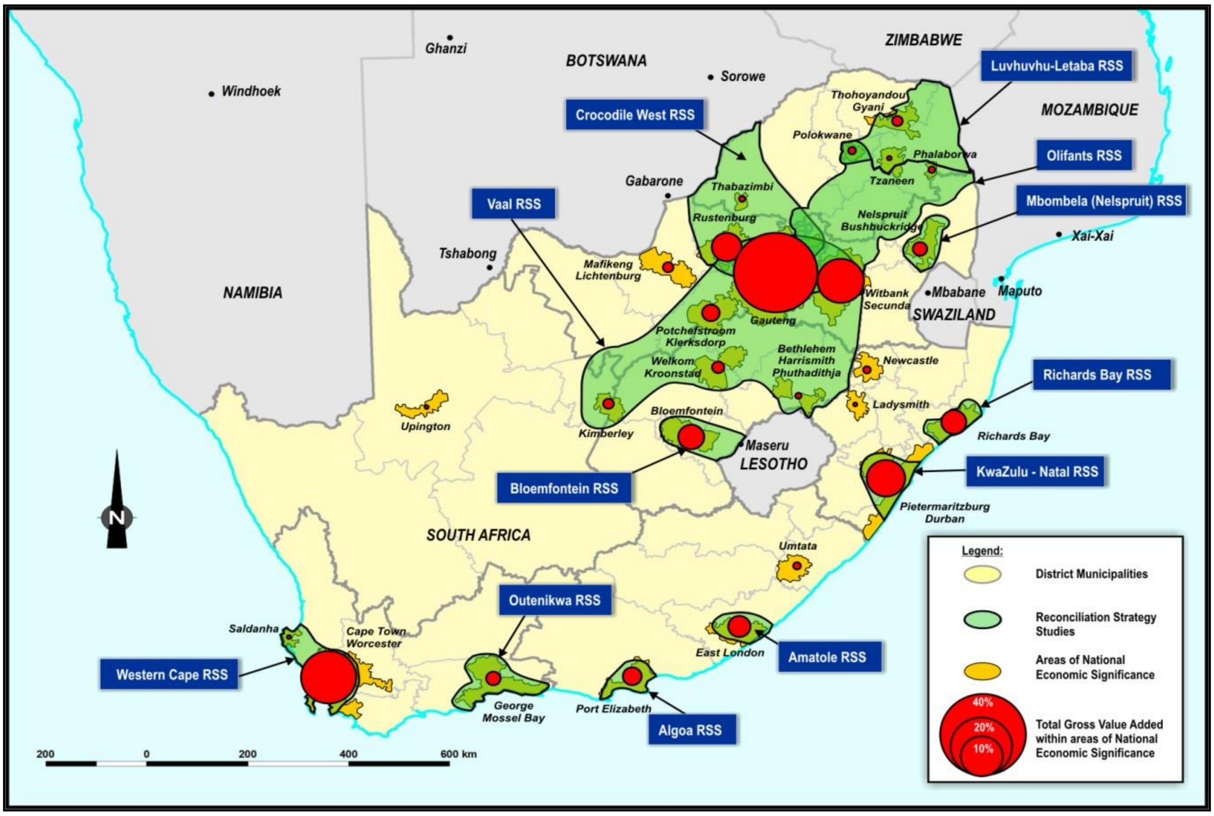


Figure 4. The regions and scales of the twelve reconciliation strategy studies conducted and published by South Africa's Department of Water and Sanitation. Source: DWS (2022).

To determine the benefit associated with built infrastructure interventions, yield gains and URVs for each water supply option were extracted directly from the relevant WSS reconciliation strategy reports. Where cost and URV information was not available for a given intervention, a representative URV based on the average of similar interventions planned for in other WSSs was calculated and assigned to it. Taking inflation into account, the URVs of each intervention were reported in 2022 Rands.

Costs of clearing IAPs

Cost estimates for clearing IAPs in South Africa were based on person-day estimates provided by the Working for Water (WfW) programme. Person-day estimates are derived from data collected over the lifespan of the WfW programme and are based on the costs to clear different groups and age classes of IAPs in riparian and landscape settings using different treatment methods (Turpie et al., 2021). Further, Turpie et al. (2019) developed a set of regression models that estimated the number of person days required to clear one hectare of gum, pine and wattle trees under certain conditions. The regression models used to calculate person-day estimates for each of these species are shown in **Table 3**. In the same study, the cost to clear one condensed hectare of IAPs through the WfW programme was estimated to be R450 in 2018, which covered management, equipment and training (Turpie et al., 2019). Taking inflation into account, the cost to clear IAPs in 2022 was estimated to be R499/ha. Based on the person-day estimates and the cost to clear one condensed hectare of infested land, the cost of initial and follow up clearing events for gums, pines and wattles was calculated for each quaternary catchment. If a quaternary catchment area had an IAP density of less than 5%, it was assumed that investment in clearing would be inefficient (Turpie et al., 2021). Therefore, a 5% density threshold was applied to the base year (2022) whereby all quaternary catchments that had an IAP infestation of less than 5% were excluded from the cost model. It was assumed that the first two follow up clearing events would take place in three-year intervals after the initial clear in 2022 (i.e., in 2025 and 2028) and every six years thereafter (i.e., in 2034, 2040 and 2046) until 2050. A discount rate of 8% was used to determine the present value of costs and the present value of the quantity of water over the time period considered (based on van Niekerk and du Plessis, 2013). All cost calculations were conducted at the quaternary catchment level and later consolidated to the WSS level.

Table 3. Regression models used to calculate the number of person-days required to clear one hectare of gum, pine, and wattle species, where I_{ha} is the invadable hectares in the relevant quaternary, and x is the average percentage density per pixel (Source: Turpie et al., 2019).

Species	**Initial clearing**	**Follow ups**
Gums (*Eucalyptus spp.*)	$I_{ha}(2.4254e^{0.028x})$	$I_{ha}(1.7074e^{0.1(0.028x)})$
Pines (*Pinus spp.*)	$I_{ha}\ (2.0647e^{0.027x})$	$I_{ha}(1.6161e^{0.1(0.027x)})$
Wattles (*Acacia spp.*)	$I_{ha}\ (2.0057e^{0.028x})$	$I_{ha}(0.2006e^{0.1(0.028x)})$

Calculating URVs for IAP clearing

The URV for securing water supply through clearing IAPs is derived by dividing the total present value of costs (PV_c) by the present value of water supplied (PV_w), as shown in **Equation 2** (van Niekerk and du Plessis, 2013). The total PV_c to clear IAPs from a given area is the sum of initial and follow up PV_c costs. The initial PV_c ($PV_{c(i)}$) is the product of the number of person-days required to clear IAPs in the first year and the cost to clear one condensed hectare of infested land, while the PV_c of one follow up event ($PV_{c(f)}$) is the product of the number of person-days required to clear IAPs in a follow up event and the cost to clear one condensed hectare of infested land. The total PV_c is the sum of $PV_{c(i)}$ and $PV_{c(f)}$ for all three IAP groups (**Equation 3**).

$$URV\left(\frac{R}{m^3}\right) = \frac{PV_c}{PV_w} \qquad \textbf{Eq. 2}$$

$$Total\ PV_c = \left(\text{Gum } PV_{c(i)} + \text{Gum } PV_{c(f)}\right) + \left(\text{Pine } PV_{c(i)} + \text{Pine } PV_{c(f)}\right) + (\text{Wattle } PV_{c(i)} + \text{Wattle } PV_{c(f)}) \qquad \textbf{Eq. 3}$$

The PV_w is based on the quantity of water gained if IAPs are removed from catchment areas. To determine the quantity of water that would be gained through IAP removal by 2050, estimates of streamflow reduction as a result of IAPs was used. Le Maitre et al. (2016) provide information on estimated flow reduction and condensed hectares of IAPs for the primary catchment level for South Africa, but not for quaternary catchments. Therefore, a factor to represent the amount of water used by IAPs per unit area was calculated for all primary catchments and then applied to each relevant quaternary catchment (see **APPENDIX B**). An estimate of the quantity of water that could be gained if IAPs were cleared was then calculated for the period between 2022 and 2050 using **Equation 4**, where W_t is the quantity of water at year t, and r is the discount rate (see van Niekerk and du Plessis, 2013 for justification of the above equations and an explanation for the use of discounting in the water supply context).

$$PV_w = \sum\left(\frac{W_t}{(1+r)^t}\right) \qquad \textbf{Eq. 4}$$

RESULTS

CATCHMENT AREAS

The sub-dataset of dams consisted of 64 large dams that were owned and/or managed by one of the 11 South African WSPs (**APPENDIX A**). The catchment areas were made up of a total of 64 quaternary catchment areas with a combined catchment area of approximately 230 500 km^2 (**Figure 5**). The Integrated Vaal River System contributed the greatest of this area (46.9%), and the Western Cape Water Supply System the least (0.7%).

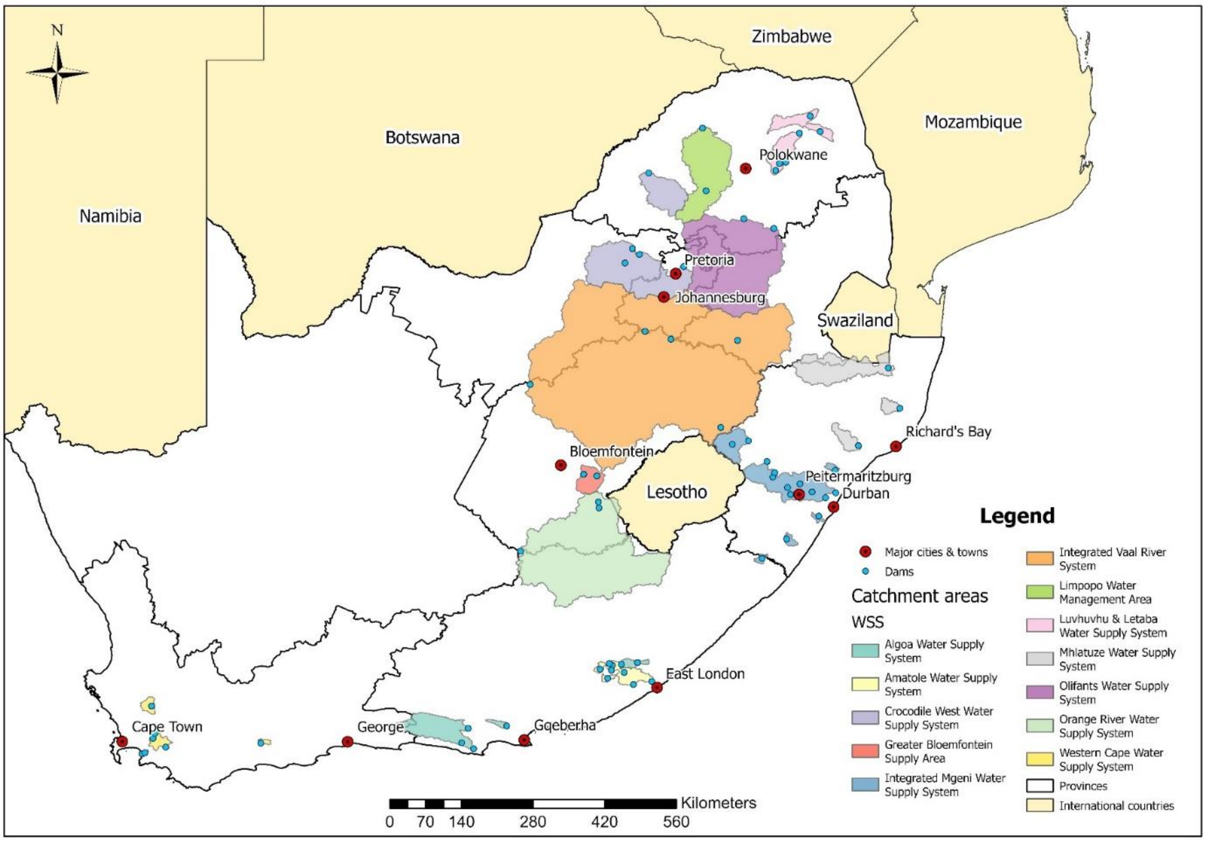


Figure 5. Spatial distribution of dams and catchment areas (coloured by WSS) included in the IAP spread and cost-effectiveness analyses.

EXTENT AND SPREAD OF IAPS

Using the IAP spread model, based on the NIAPS 2010 data (Kotzé et al., 2010), IAP coverage in 2022 was estimated to be approximately 623 000 condensed ha, which covered 2.7% of all catchment areas combined. At a spread rate of 7.5%, it was estimated to quadruple to 2.5 million condensed ha, or 10.9%, by 2050 without implementation of clearing interventions. The Amatole WSS had the highest percentage area of IAP coverage in both 2022 (22%) and in 2050 (58.22%) (**Figure 6**). Conversely, the Orange River System was estimated to have the lowest percentage area of infestation in both 2022

(0.27%) and 2050 (1.61%). No invasions were reported in the original NIAPS 2010 data for the Greater Bloemfontein Supply Area. Therefore, this WSS was excluded from any further analysis.

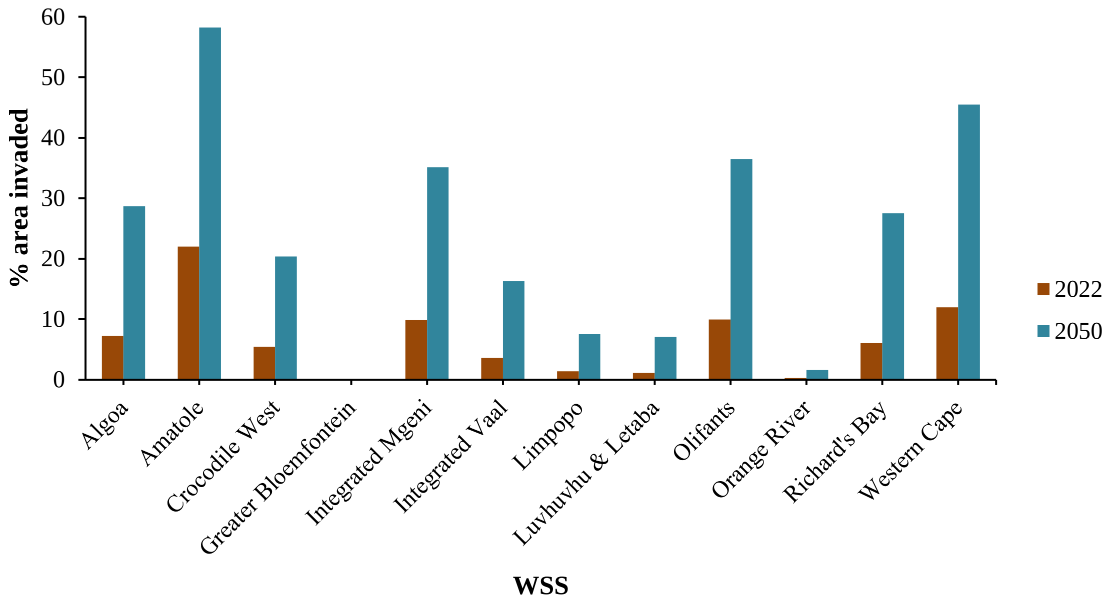


Figure 6. Present (2022) and future (2050) percentage area (condensed ha) of IAPs in each water supply system (WSS).

Overall, gum and wattle species were more prolific than pine species in most water catchment areas in 2022 and in 2050 (**Table 4**). Wattle species were shown to spread the most drastically by 2050, having the highest average coverage (9.53%) between all three species. The Amatole WSS's high percentage of invaded area was dominated by wattle infestation which covered 29.32% of the WSS's total catchment area by 2050.

Table 4. The percentage cover of each IAP species in catchment areas of each water supply system (WSS) in 2022 and 2050.

WSS	**% Cover in 2022**			**% Cover in 2050**		
	Gum	**Pine**	**Wattle**	**Gum**	**Pine**	**Wattle**
Algoa Water Supply System	0.49	0.87	5.23	1.27	2.87	21.92
Amatole Water Supply System	1.10	3.80	11.10	2.44	10.57	29.32
Crocodile West Water Supply System	1.89	0.09	1.65	7.66	0.31	5.61
Integrated Mgeni Water Supply System	2.95	1.16	2.50	10.28	3.57	9.71
Integrated Vaal River System	1.25	0.15	0.49	5.74	0.69	2.11
Limpopo WMA North	0.88	0.00	0.15	4.74	0.00	0.75
Luvuvhu-Letaba Water Supply System	0.52	0.19	0.11	3.19	1.20	0.71
Olifants Water Supply System	0.21	0.10	4.24	0.92	0.52	19.33
Orange River System	2.28	0.04	3.08	7.99	0.17	11.67
Richard’s Bay Water Supply System	0.09	0.04	0.10	0.56	0.33	0.52
Western Cape Water Supply System	1.50	5.49	0.84	7.06	19.55	3.15
AVERAGE	**1.20**	**1.08**	**2.68**	**4.71**	**3.62**	**9.53**

COST-EFFECTIVENESS ANALYSIS

It was estimated that the Integrated Vaal River System would have the greatest number of condensed hectares infested with IAPs by 2050 (approximately 922 000 condensed ha), resulting in the highest present value (PV) clearing cost to remove them (R4.7 billion) (**Table 5**), while the Luvuvhu-Letaba WSS was estimated to have the smallest area of invasion (approximately 25 000 condensed ha) and would therefore require the lowest allocation of EI investment for IAP removal (R71.8 million).

The amount of water that could be gained by removing IAPs from bulk water supply catchment areas increased exponentially between 2022 and 2050, resulting in an estimated total of 1 595 million m^3 of saved water (**Figure 7**). The rate at which IAPs spread is exponential by nature, which results in an exponentially increasing amount of water taken up by them. Therefore, this figure indicates the difference between water lost when IAPs are present and left to proliferate at their respective spread rates over time (i.e., no intervention takes place), and water gained over time when they are removed.

Table 5. The total condensed hectares (c.ha) that would be infested in 2050 if no clearing was pursued and the present value (PV) in 2022 Rands of the investment required to clear IAPs in existing bulk water supply infrastructure catchment areas of each relevant water supply system (WSS) between 2022 and 2050 at a discount rate of 8%.

WSS	**Area infested by 2050 without intervention (c.ha)**	**Water gained by 2050 with intervention (Mm^3)**	**PV of clearing costs (R millions)**
Algoa Water Supply System	145 657	103.88	740.80
Amatole Water Supply System	92 804	87.71	578.89
Crocodile West Water Supply System	235 377	66.50	1 414.64
Integrated Mgeni Water Supply System	227 610	303.86	1 231.66
Integrated Vaal River System	922 233	423.36	4 696.02
Limpopo WMA North	61 764	22.83	136.84
Luvuvhu-Letaba Water Supply System	24 929	11.84	71.80
Olifants Water Supply System	524 977	263.02	3 078.45
Orange River System	45 818	26.60	145.45
Richard's Bay Water Supply System	188 057	180.38	889.88
Western Cape Water Supply System	46 326	105.39	325.93
TOTAL	**2 515 554**	**1 595**	**13 310**

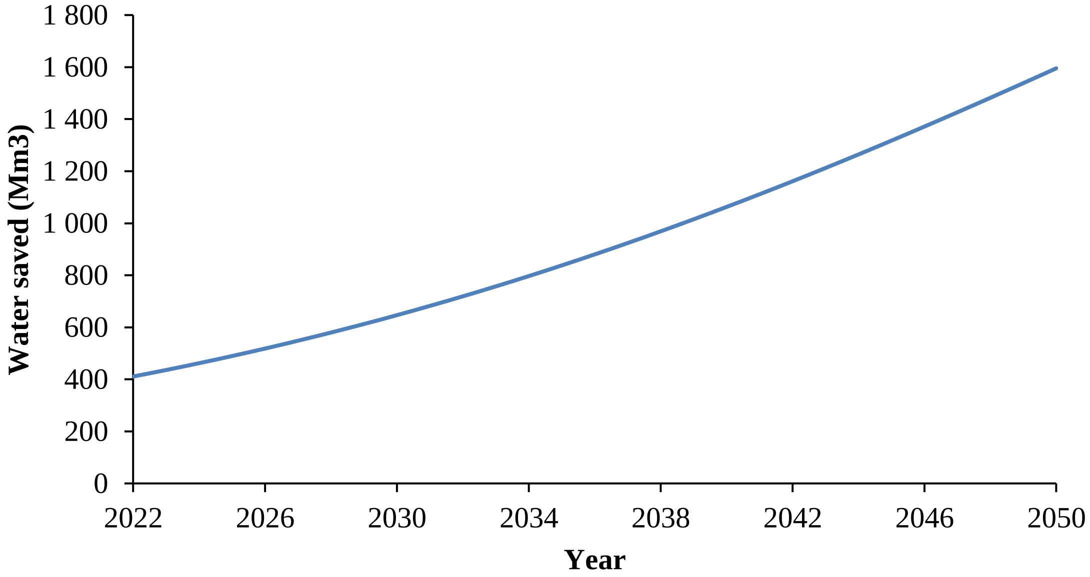


Figure 7. The amount of water (million m3) that could be gained if IAPs were cleared from all WSS catchment areas from 2022 to 2050.

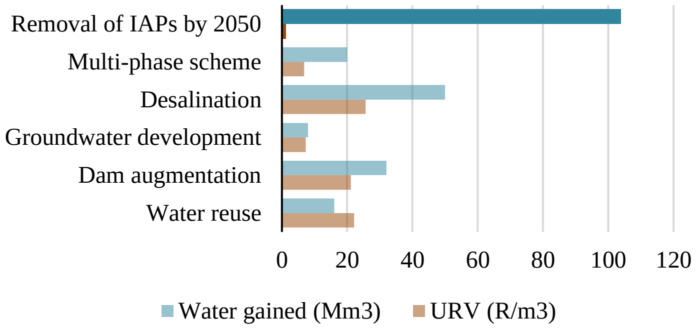
Across all 11 WSSs considered in this study, a total of 52 planned water supply projects were specified in the relevant reconciliation strategy studies between 2022 and 2050. Combined, planned built infrastructure interventions would result in an additional water yield of approximately 4 173 million m^3/a (**Table 6**). When compared to the gain in water supply through EI interventions, IAP clearing was approximately 40% of the amount of water that could be gained through implementation of all 52 built infrastructure interventions in the same time frame. If considered as a complementary intervention, this means that 100% removal of IAPs from bulk water supply catchment areas would avail an additional 1 595 million m^3/a to downstream built water supply infrastructure from 2050.

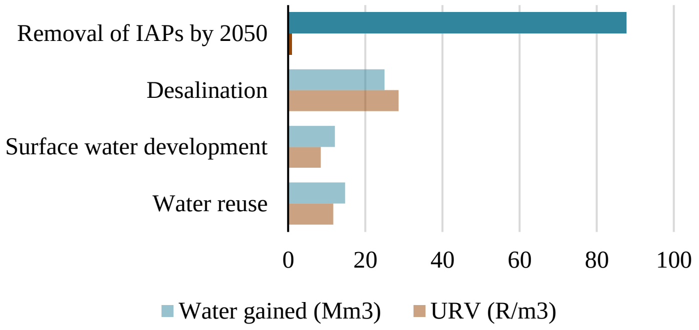
Table 6. The number of water supply projects planned for construction/implementation between 2022 and 2050 and the additional water yield that would be gained from for each WSS.

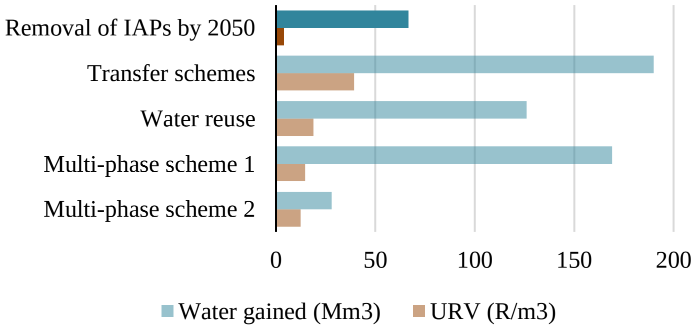
WSS	**Number of augmentation projects**	**Yield gained (Mm^3/a)**
Algoa Water Supply System	5	126
Amatole Water Supply System	3	52
Crocodile West Water Supply System	5	513
Integrated Mgeni Water Supply System	7	671
Integrated Vaal River System	3	1 144
Limpopo WMA North	1	50
Luvuvhu-Letaba Water Supply System	4	33
Olifants Water Supply System	5	361
Orange River System	3	862
Richard’s Bay Water Supply System	8	148
Western Cape Water Supply System	8	213
TOTAL	**52**	**4 173**

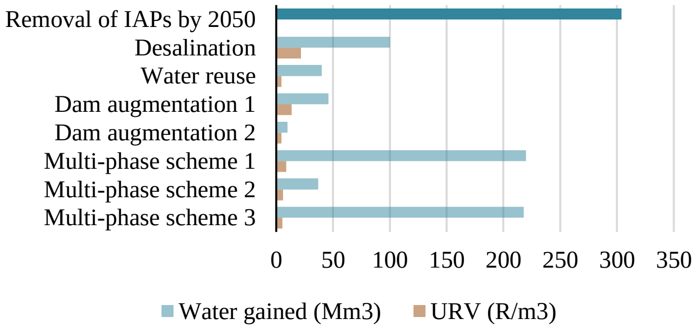
Assurance level of supply is often incorporated in water supply plans and can be simplified as the confidence in the ability to fulfil demand. Built infrastructure for bulk water supply schemes are presented at a very high assurance level of supply, generally between 99% to 99.9% (Blignaut et al., 2007) which is accounted for in the yield gains stipulated in the reconciliation strategy studies, and hence those included in **Table 6**. However, clearing IAPs for gain in water yield has a considerably lower assurance level of approximately 90% (Blignaut et al., 2007). The current IAP clearing water yield gains stipulated in **Table 5** and **Figure 7** are presented at a 100% assurance level and is therefore a slight overstatement. However, this reveals the full potential of the water gains associated with well implemented and maintained IAP clearing interventions.

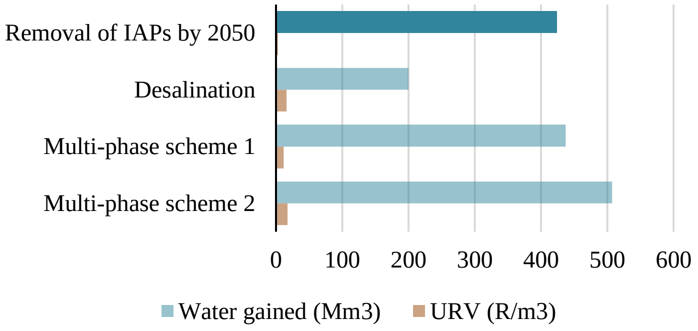
When the URVs and additional water gains of IAP clearing are compared with that of planned built infrastructure developments, it becomes clear that IAP clearing is a cost-effective intervention for securing water supply. IAP clearing was the most cost-effective water supply option for all WSSs except for the Orange River System, which showed relatively low water gains for the associated URV (**Figure 8**). Overall, IAP clearing averaged as the second most cost-effective augmentation option after multi-phased schemes. The least cost-effective augmentation scheme was groundwater development.

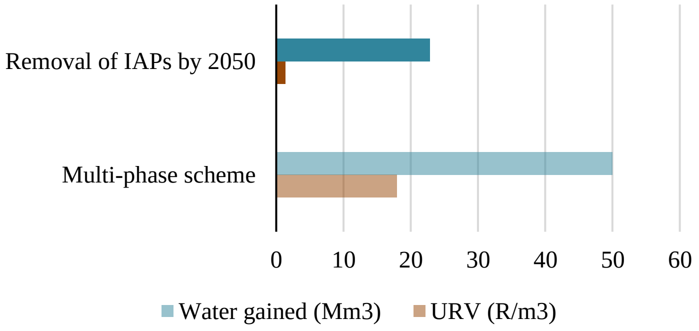

Algoa WSS

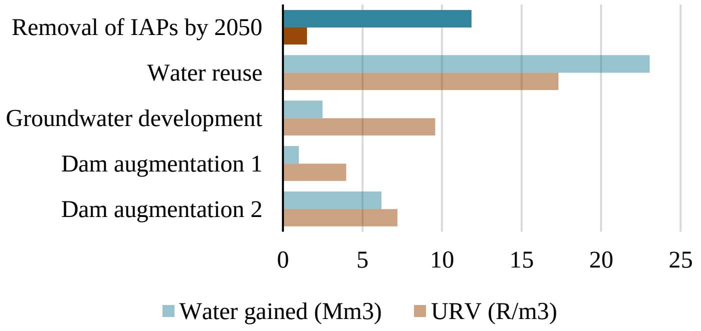

Amatole WSS

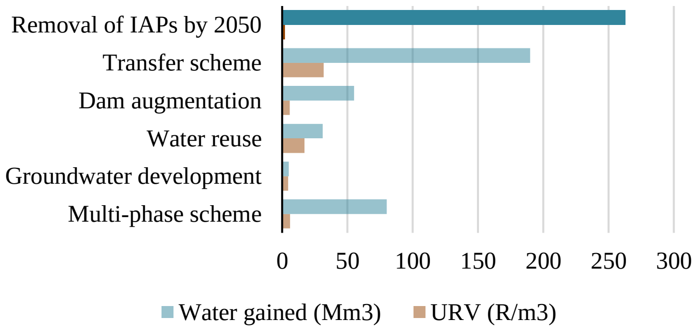

Crocodile West WSS


Integrated Mgeni WSS


Integrated Vaal River System


Limpopo WMA North


Luvuvhu-Letaba WSS


Olifants WSS

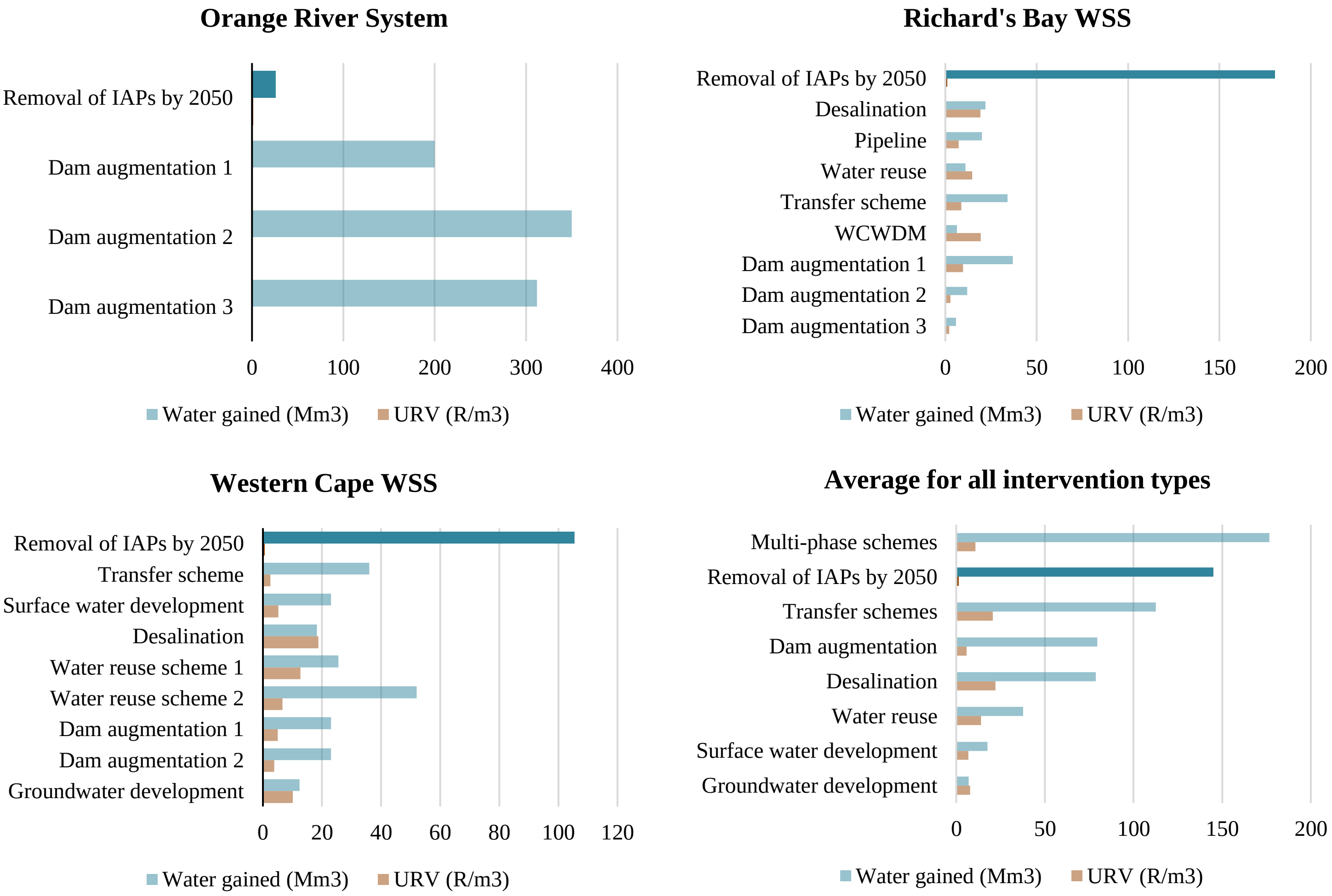


Figure 8. Unit reference value (URV) and additional water gained through implementation of various interventions for each water supply system (WSS), and finally, the average URV and water gained per intervention type.

The URVs for built infrastructure ranged from R0.48/m^3 for the new Vioolsdrift Dam augmentation project in the Orange River System (DWA, 2015), to R44.36/m^3 for the Zambezi River transfer scheme in the Crocodile West WSS (DWS, 2015), while the URVs for IAP clearing ranged from R0.53/m^3 for the Western Cape WSS to R3.86/m^3 for the Crocodile West WSS (**Table 7**). All URVs for IAP clearing were much lower than that of built infrastructure interventions, except for the Orange River System which had low levels of IAP invasion and planned built infrastructure interventions that would produce a significant amount of water.

Table 7. A summary of the overall extent of IAPs (% IAP coverage) within each water supply system (WSS) if no intervention is pursued, as well as the unit reference values (URVs) associated with built infrastructure (BI) and ecological infrastructure (EI) interventions (i.e., IAP clearing). As a comparative measure, the difference between built infrastructure and EI URVs is also shown, where positive values indicate that EI is more cost-effective, and negative values indicate the cost-effectiveness of BI. URVs are reported in 2022 Rands.

WSS	**% IAPs**		**Range of BI URVs (R/m^3)**	**EI URV (R/m^3)**
	2022	**2050**		
Algoa Water Supply System	7.26	28.68	6.77 – 25.62	1.26
Amatole Water Supply System	22.00	58.22	8.46 – 28.66	0.96
Crocodile West Water Supply System	5.43	20.35	12.38 – 44.36	3.86
Integrated Mgeni Water Supply System	9.84	35.12	4.54 – 21.91	0.70
Integrated Vaal River System	3.61	16.30	11.80 – 17.61	2.22
Limpopo WMA North	1.40	7.50	*17.95	1.36
Luvuvhu-Letaba Water Supply System	1.14	7.10	**3.98 – 17.32	1.49
Olifants Water Supply System	0.27	1.61	4.50 – 31.92	2.08
Orange River System	6.03	27.50	0.48 – 0.84	1.32
Richard's Bay Water Supply System	9.96	36.51	2.22 – 19.36	0.99
Western Cape Water Supply System	11.97	45.49	2.57 – 18.77	0.53

*Only one planned BI intervention.

**Values based on the average URVs of similar projects due to deficient data.

DISCUSSION

Using South Africa as a case study to investigate the financial viability of investing in EI compared to built infrastructure revealed that IAP clearing in catchment areas of large dams is a cost-effective approach to secure water supply. Broadly, the total water gained from clearing IAPs equates to approximately 30% of the capacity of the Gariep Dam, the largest dam in South Africa (**APPENDIX A**). Of all the 11 WSSs analysed, only the Orange River System produced a URV for IAP clearing that was less cost-effective than for planned built infrastructure options for the region. Overall, the higher the potential coverage of IAPs within the catchment areas of a WSS, the greater the potential yield of additional water would be available with IAP clearing. Therefore, it can be argued that the cost-effectiveness of IAP clearing as an EI intervention is greater when the levels of invasion are high, as demonstrated by the Amatole, Western Cape, and Richard's Bay WSSs. However, this does not hold true for the converse argument, where the lower the potential coverage of IAPs, the lower the potential water yield and the less cost-effective the clearing intervention. This is clearly demonstrated by the Orange River System, which was estimated to have relatively high levels of invasion by 2050 (27.50), but still had a higher EI URV (1.32). A likely explanation for the mismatch in yield gains and cost could be the density of invasion within a particular catchment area as density affects the number of person-days required to clear a given catchment area, which in turn affects the cost. Although the scope of this study did not consider IAP density as a significant determinant of the cost-effectiveness of IAP clearing, it is acknowledged as a confounding factor that warrants further investigation and consideration in future studies.

Despite the confounding effects of density, the promising prospects IAP clearing as an approach to EI investments presents an opportunity to delay construction of more expensive built infrastructure options. This should be regarded as an attractive opportunity as built augmentation options become progressively more expensive due to the cheaper interventions being implemented first (Roderiquez et al., 2012). Additionally, water management costs are likely to become more costly over time as storage space in existing impoundments decreases due to sedimentation (Mander et al., 2017). WSPs should therefore plan for IAP clearing ahead of other augmentation interventions as the suite of benefits associated with postponing construction of bulk water supply infrastructure can be significant. It must be noted that there are a number of ecological and built infrastructure costs and benefits that are not accounted for in the URVs presented in this study but provide additional valuable insight into each approach (Mander et al., 2017). For example, removal of IAP species not only leads to additional water gains but allows for indigenous regrowth, which significantly reduces sediment mobilisation (Acreman et al., 2021). On the other hand, built infrastructure such as dams can worsen the effects of sediment mobilisation, leading to sediment accumulation and reduced water quality in downstream impoundments and rivers which carries further management costs down the line (Mander et al., 2017).

Other economic and environmental benefits of investing in EI can include improved water quality, restoration and protection of biodiversity, increased health of downstream aquatic ecosystems, wildfire and flood risk reduction, job creation, and potential for value added products (Turpie et al., 2008; Hughes et al., 2018; Seddon et al., 2020; Acreman et al., 2021; Turpie et al., 2021). Furthermore, climate change is recognised as a serious threat to water security where declines in rainfall and increases in temperatures and evaporation have been predicted (Engelbrecht, 2005). Infrastructure that is fixed in position and capacity may lack the resilience necessary to cope with such changes, particularly with the added pressure of rising water demand (Wertz-Kanounnikoff et al., 2011; Vogl et al., 2017). Ecosystem-based adaptation is nested within NbS approaches, hence, EI investment through the adaptive management of catchment areas offers a potential solution for the need to increase the resilience of current water supply. Although investing in EI does not stand as a full substitute for built infrastructure approaches, it must be emphasized for its complementary potential, particularly in the context of climate change (Marais and Wannenburgh, 2008; Palmer et al., 2015).

Despite the recognition of ecological and built infrastructure as being mutually supportive of built infrastructure by the DWS (DWS, 2013), there is still a general lack of initiative for the EI investment movement in South Africa. Only two of the eleven WSSs have formally acknowledged and incorporated catchment restoration as a key intervention for securing water supply in the long-term. These include the Integrated Mgeni WSS, managed by Umgeni Water, and the Western Cape WSS, managed by the City of Cape Town and Overberg Water. Umgeni Water in the Integrated Mgeni WSS is involved in the ‘uMngeni Ecological Infrastructure Partnership’ (UEIP) which is an initiative dedicated to exploring the role and potential of EI investments in supplementing and/or substituting built infrastructure to improve water security in the uMngeni River catchment (Pieterse et al., 2017). Since the UEIPs inception in 2013, the initiative has gained over 20 signatories from government, academia, civil society and business, and has led to the development of an Ecological Infrastructure Investment Plan which will feed into future reconciliation strategy study updates (Pieterse et al., 2017).

Similarly for the City of Cape Town in the Western Cape WSS, the Greater Cape Town Water Fund (GCTWF) was initiated in 2018 with a core purpose of pooling financial support from public and private water users to restore the integrity of EI in catchment areas that supply water to the Western Cape WSS (Turpie et al., 2019). IAP clearing is formerly included as a prioritised augmentation option in the latest reconciliation strategy study for the Western Cape WSS (Tlou et al., 2021). The net URV of R1.20/m^3 outlined in the reconciliation strategy is higher than the URV of R0.53/m^3 estimated in this study. However, the reconciliation strategy value is still significantly lower than the range of URVs determined for built infrastructure augmentation options in the WSS (R2.57/m^3 – R18.77/m^3) and was also the most financially viable augmentation option explored in the strategy (Tlou et al., 2021). Another study completed for the GCTWF set out to determine priority areas for catchment restoration in the Greater Cape Town area and estimated a URV range of R0.30/m^3 – R0.80/m^3 to clear IAPs in the top seven priority sub-catchments (Turpie et al., 2019). The Western Cape WSS URV determined in this study falls in the middle of this range.

Other South African studies have also evaluated IAP clearing as an EI investments approach to securing water supply. These studies were also done at finer, catchment-level scales including the Olifants River catchment in Limpopo (Morokong et al., 2016), Baviaanskloof-Tsitsikamma catchment area in the Easten Cape (Mander et al., 2017), and the uMngeni catchment area in KwaZulu-Natal (Mander et al., 2017). The findings of this study agree with the outcomes of these case studies, where the EI investment approach was found to be a considerably cheaper option for securing water supply than the built infrastructure alternatives. However, the results of Mander et al. (2017) highlight that the severity of degradation can play a large role in increasing EI investment costs as more expensive approaches may be necessary to address the specific conditions of the area. In a comparison between the uMngeni and Baviaanskloof-Tsitsikamma catchment areas, uMngeni had more severe levels of degradation which consequently resulted in a higher EI URV (R2.50/m^3) than the Baviaanskloof-Tsitsikamma (R1.17/m^3) due to expensive measures needed to re-vegetate the area at a large-scale (Mander et al., 2017). Nonetheless, the R2.50/m^3 URV still falls far below the range of built infrastructure URVs determined for the region in this study.

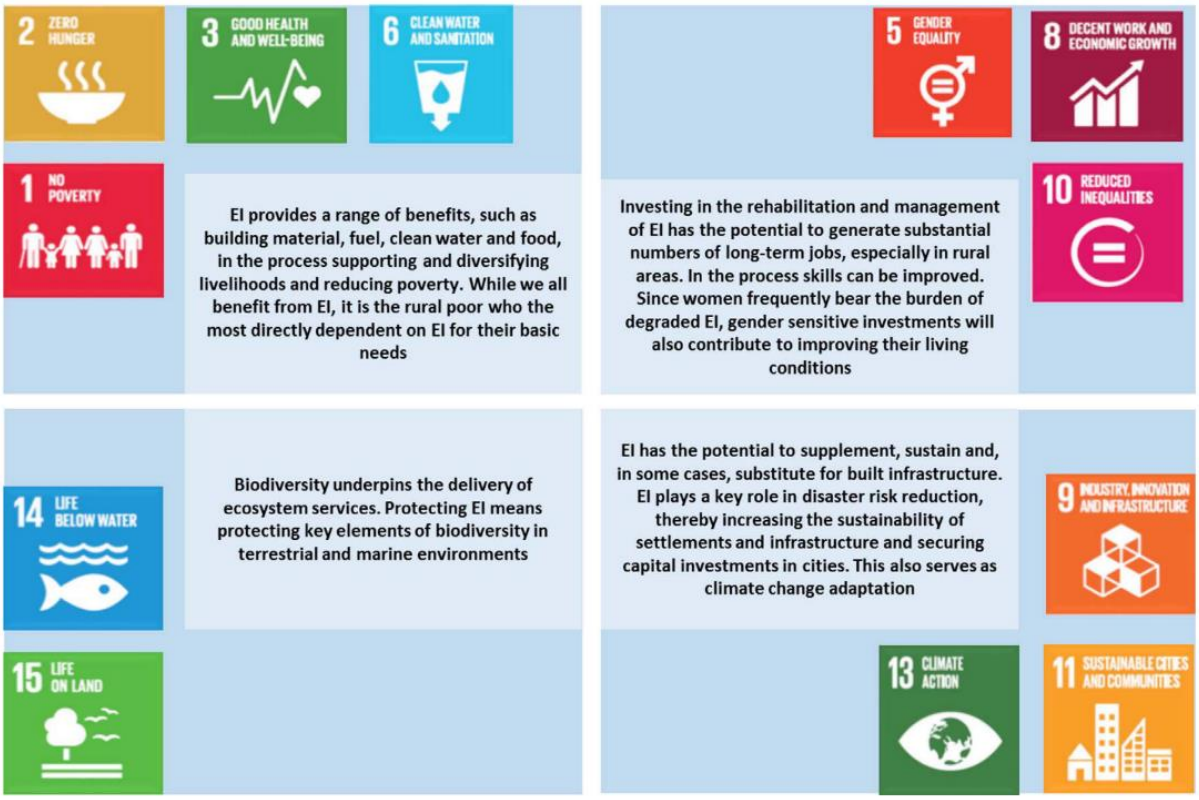
The lack of participation in hydrological EI investments can be a result of three main barriers identified and reviewed by Vogl et al. (2017). These include ‘institutional failure’, ‘information failure’ and ‘market failure’. Here, I will focus on the relevance of institutions and information, given the scope of the study. Given the institutional landscape of South Africa’s water sector, the weight of responsibility to plan and implement EI interventions would be carried by the regional institutional level of governance. This includes water boards, catchment management agencies and regional water utilities. Water boards are considered the key stakeholders of WSS management and are responsible for the provision of water services in the form of bulk potable water to other water service institutions within their areas of supply, such as local municipalities (DWS, 2014). Although DWS compiles the reconciliation strategy studies focused on bulk infrastructure options for each water supply system, it is the responsibility of the water boards to ensure that sufficient water is delivered to their jurisdictional regions through the efficient management of that infrastructure. Therefore, water boards would bear the responsibility of ensuring the effective implementation of EI investments to meet their specific water supply goals. It is recognised that different nations have different institutional landscapes, but it is imperative that the responsibility to carry out key actions are appointed to specific institutions at the appropriate level. EI investment frameworks should be built for the specific institutional landscape of the nation to ensure that each institution is held accountable for the tasks appointed to it. At the same time, EI investments are a multi-institutional, multi-discipline approach which requires coordination between responsible institutions to ensure sufficient interaction, collaboration, and negotiation for smooth running of the operation as a whole. The same is recommended for countries with a similar governing body to uphold responsibility within the institutional landscape.

As the interest in EI investments has grown, so has the demand for tools that can model the potential outcome of conservation interventions regarding return on investments (Vogl et al., 2017). It is well known that funding for conservation is thinly stretched and has also been a significant barrier to the implementation of conservation programmes, particularly in developing countries (Seddon et al., 2020; Mbopha et al., 2021). However, the need for restoration, maintenance, conservation and protection of EI to be prioritized is becoming more apparent than ever as research on the state of environmental health continues to emerge. South Africa's government remains the primary source of conservation funding in the country, however other partnerships and funds, like the UEIP and GCTWF, have great potential to create momentum in the EI investments scene.

Lack of funding, or interest to invest, is often due to a lack of information, termed 'information failure' (Vogl et al., 2017; Mbopha et al., 2021). Decision-makers require sound information about the feasibility and likelihood of maximising return-on-investment for an intervention before they are willing to invest. To date, there has been limited reliable evidence on the impacts of IAP clearing for securing water supply. This study has helped to provide this evidence and encourages further research into the potential and viability of investing in catchment restoration in other nations as well as at finer scales within South Africa. Moreover, water boards (or similar institutions) are encouraged to direct and facilitate research into determining priority areas for catchment restoration, specifically at the sub-catchment level. This will ensure that limited funds are directed to areas that will have the highest return on investment, offering an opportunity to address some of the sources of uncertainty and risk related to funding that inhibits WSPs and government from establishing EI investment initiatives.

South Africa proved to be a good case study for assessing the cost-effectiveness of EI investments as it revealed the financial viability of investing in catchment restoration to enhance supply from water resources, the complications around institutional responsibility for management of such interventions, and also the usefulness of having a governmental programme dedicated to restorative work in natural systems, namely the Working for Water programme (Marais and Wannenburgh, 2008). Having such an initiative creates opportunity to realize the development goals of the country in an integrative way. South Africa is also a signatory of the United Nations (UN) 17 Sustainable Development Goals (SDGs) which address development towards achieving overall human and environmental well-being in developed and developing nations, an objective that aligns well with South Africa's National Development Plan (UN, 2015; Cumming et al., 2017). The country has a strong development agenda that recognises environmental sustainability and resilience as an important part of economic development and the role it plays in ensuring human well-being (Cumming et al., 2017). More holistic approaches to development are likely to become even more crucial in the next decade as the UN has declared 2021 – 2030 the "UN Decade on Ecosystem Restoration" to encourage global efforts towards restoring ecosystems (UNEA, 2013). Therefore, there is growing pressure to prioritise research and initiatives that pursue socio-economic development in innovative ways.

NbS are highly esteemed for presenting avenues to achieve development goals in adaptive, resilient and efficient ways (Seddon et al., 2020). The EI investments branch of NbS is one such approach that is in direct alignment with SDG15, which aims to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" (Cumming et al., 2017). By investing in catchment restoration, South Africa, and other nations with similar vision, would be effectively pursuing a development strategy with the aim of securing water supply, whist benefitting from a suite of other related SDG targets, as shown in **Figure 9.** (Cumming et al., 2017).



EI provides a range of benefits, such as building material, fuel, clean water and food, in the process supporting and diversifying livelihoods and reducing poverty. While we all benefit from EI, it is the rural poor who the most directly dependent on EI for their basic needs

Investing in the rehabilitation and management of EI has the potential to generate substantial numbers of long-term jobs, especially in rural areas. In the process skills can be improved. Since women frequently bear the burden of degraded EI, gender sensitive investments will also contribute to improving their living conditions

Biodiversity underpins the delivery of ecosystem services. Protecting EI means protecting key elements of biodiversity in terrestrial and marine environments

EI has the potential to supplement, sustain and, in some cases, substitute for built infrastructure. EI plays a key role in disaster risk reduction, thereby increasing the sustainability of settlements and infrastructure and securing capital investments in cities. This also serves as climate change adaptation

Figure 9. Investing in ecological infrastructure (EI) can support a range of the Sustainable Development Goals (SDGs). Source: Cumming et al. (2017).

LIMITATIONS

The accurate quantification of catchment degradation is challenging. Despite the abundance of literature regarding IAPs in South Africa, an updated, recent spatial dataset of national IAP coverage was not available. While acknowledging the privilege of having access to the NIAPS 2010 dataset, using outdated data about dynamic phenomena creates likelihood for over- or underestimation of current and future estimates of IAP coverage. It must also be noted that new introductions and clearing of IAPs up until the present were not accounted for in the model.

The original purpose of this study was to seek better understanding of the risks and uncertainties that WSPs face in EI investment, leading to a lack in participation in such approaches to securing water supply in South Africa. However, in reaching out to the relevant institutions (at the water board level), there was an astounding lack in willingness and drive to participate in interviews that would inform the research, despite following the necessary avenues of communication. This remains a major limitation to understanding the lack of participation in EI investments from the institutional side and can only inhibit progress towards developing an EI investment framework that addresses persisting uncertainty and risk. Given the number of EI investment benefits demonstrated in this study, government institutions are strongly encouraged to participate in research that seeks to move forward in this field.

CONCLUSIONS

The water supply sector is greatly threatened by increasing water demand driven by human population growth and the effects of climate change. The pursuit of more eco-centric strategies to both secure and maximize water supply from source areas should therefore be a priority. There is evidence that the concept of EI investments aligns with this idea, presenting a ‘win-win-win’ scenario of mutual benefit for the economy, nature and people (Cumming et al., 2014; Cumming et al., 2017). This study goes beyond valuing ecosystem services by highlighting an opportunity cost incurred by only investing in built infrastructure. The study’s findings add to the growing body of literature that advocates for EI investments to secure hydrological ecosystem services by showing that such approaches are comparable with, and can be more financially and economically viable than, built infrastructure development options. The emphasis here is on development of future augmentation options, as it has been noted that EI interventions would not be able to replace, but rather enhance existing built infrastructure.

This case study showed that IAP clearing in catchment areas should be considered a formal intervention for securing future water supply alongside built infrastructure options in almost all of South Africa’s water supply systems. IAP clearing would lead to an astounding total water gain of 1 595 million m^3 by 2050, equivalent to over 40% of the of the water gains through implementation of built infrastructure interventions in the same time frame. However, despite the promising prospects of EI investments for securing future water, WSPs have been reluctant to participate in water supply schemes that are restoration-based. Understanding the reasons behind such hesitation would provide useful insight into the best method to proceed with planning and implementation of EI investments going forward. Therefore, further research is needed to better understand perspectives of water service providers and quantify the uncertainty and risk involved in EI investments.

While erosion and bush encroachment are also recognised as problematic causes of catchment degradation, this study has focused on the effects of IAPs on water supply. Further research should be directed towards quantifying the viability of investing in the rehabilitation of eroded land as well as addressing bush encroachment in catchment areas to secure additional water supply.

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APPENDICES

APPENDIX A

Table A.1. List of the large dams included in this study to determine the cost of investing in ecological infrastructure to secure hydrological ecosystem services. The dam's name, capacity in million m^3, province and water supply system in which it occurs, and the water service provider responsible for its management are listed.

Dam name	**Capacity (Mm^3)**	**Province**	**Water Supply System**	**Water Service Provider**
Albert Falls Dam	289.20	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Berg River Dam	126.40	Western Cape	Western Cape Water Supply System	Overberg Water
Binfield Park Dam	36.83	Eastern Cape	Amatole Water Supply System	Amatole Water
Bloemhof Dam	1 218.10	Free State	Integrated Vaal River System	Rand Water
Bospoort Dam	18.20	North West	Crocodile West Water Supply System	Magalies Water
Cata Dam	12.10	Eastern Cape	Amatole Water Supply System	Amatole Water
Churchill Dam	35.70	Eastern Cape	Algoa Water Supply System	*NMBM
De Hoop Dam	351.00	Limpopo	Olifants Water Supply System	Lepelle Northern Water
Debe Dam	6.00	Eastern Cape	Amatole Water Supply System	Amatole Water
Doorndraai Dam	44.20	Limpopo	Limpopo Water Management Area	Lepelle Northern Water
Duiwenhoks Dam	6.00	Western Cape	Western Cape Water Supply System	Overberg Water
Ebenezer Dam	70.00	Limpopo	Luvuvhu & Letaba Water Supply System	Lepelle Northern Water
Flag Boshielo Dam	104.00	Limpopo	Olifants Water Supply System	Lepelle Northern Water
Gariep Dam	5 342.93	Free State	Orange River Water Supply System	Bloem Water
Glen Alpine Dam	18.90	Limpopo	Limpopo Water Management Area	Lepelle Northern Water
Goedertrouw Dam	301.30	KwaZulu-Natal	Richard's Bay Water Supply System	Mhlathuze Water
Groendal Dam	12.40	Eastern Cape	Algoa Water Supply System	NMBM
Grootdraai Dam	356.00	Mpumalanga	Integrated Vaal River System	Rand Water
Groothoek Dam	1.30	Free State	Greater Bloemfontein Supply Area	Bloem Water
Gubu Dam	8.79	Eastern Cape	Algoa Water Supply System	Amatole Water
Hazelmere Dam	17.90	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Henley Dam	5.40	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Hluhluwe Dam	25.90	KwaZulu-Natal	Richard's Bay Water Supply System	Mhlathuze Water
Impofu Dam	106.90	Eastern Cape	Algoa Water Supply System	NMBM
iMvutshane Dam	3.10	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Inanda Dam	251.70	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Knellpoort Dam	136.20	Free State	Orange River Water Supply System	Bloem Water
Kouga Dam	128.50	Eastern Cape	Algoa Water Supply System	NMBM
Laing Dam	19.90	Eastern Cape	Amatole Water Supply System	Amatole Water
Ludeke Dam	14.50	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Magoebaskloof Dam	4.80	Limpopo	Luvuvhu & Letaba Water Supply System	Lepelle Northern Water
Mearns Dam	5.54	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Mhlabatshane Dam	1.60	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water

Middle Lataba dam	173.00	Limpopo	Luvuvhu & Letaba Water Supply System	Lepelle Northern Water
Midmar Dam	175.10	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Mnyameni Dam	2.00	Eastern Cape	Amatole Water Supply System	Amatole Water
Moloko Dam	146.00	Limpopo	Crocodile West Water Supply System	Lepelle Northern Water
Nagle Dam	24.60	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Nahoon Dam	19.20	Eastern Cape	Amatole Water Supply System	Amatole Water
Nandoni Dam	164.00	Limpopo	Luvuvhu & Letaba Water Supply System	Lepelle Northern Water
Nsami's Dam (Giyani)	29.50	Limpopo	Luvuvhu & Letaba Water Supply System	Lepelle Northern Water
Nungwane Dam	2.40	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Pongolapoort Dam	2 267.07	KwaZulu-Natal	Richard’s Bay Water Supply System	Mhlathuze Water
Roodekoppies Dam	102.60	North West	Crocodile West Water Supply System	Magalies Water
Roodeplaat Dam	1.40	Gauteng	Crocodile West Water Supply System	Magalies Water
Rooikrantz Dam	5.00	Eastern Cape	Amatole Water Supply System	Amatole Water
Rustfontein Dam	71.20	Free State	Greater Bloemfontein Supply Area	Bloem Water
Sandile Dam	27.50	Eastern Cape	Amatole Water Supply System	Amatole Water
Spioenkop Dam	272.30	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Spring Grove Dam	139.50	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Steenbras Lower Dam	3.50	Western Cape	Western Cape Water Supply System	City of Cape Town
Steenbras Upper Dam	32.50	Western Cape	Western Cape Water Supply System	City of Cape Town
Sterkfontein Dam	2 617.00	Free State	Integrated Vaal River System	Rand Water
Theewaterskloof Dam	480.40	Western Cape	Western Cape Water Supply System	Overberg Water
Tzaneen Dam	157.30	Limpopo	Luvuvhu & Letaba Water Supply System	Lepelle Northern Water
Vaal Barrage Dam	55.40	Gauteng	Integrated Vaal River System	Rand Water
Vaal Dam	2 609.80	Free State	Integrated Vaal River System	Rand Water
Vaalkop Dam	56.10	North West	Crocodile West Water Supply System	Magalies Water
Voëlvlei Dam	168.20	Western Cape	Western Cape Water Supply System	Overberg Water
Wagendrift Dam	55.90	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Welbedacht Dam	11.70	Free State	Orange River Water Supply System	Bloem Water
Wemmershoek Dam	58.80	Western Cape	Western Cape Water Supply System	City of Cape Town
Woodstock Dam	373.30	KwaZulu-Natal	Integrated Mgeni Water Supply System	Umgeni Water
Wriggleswade Dam	93.20	Eastern Cape	Algoa Water Supply System	Amatole Water

*NMBM = Nelson Mandela Bay Metropolitan

APPENDIX B

Table B.1. Factors for the quantity of water saved (million m^3 per condensed hectare) based on estimated flow reduction and extent of IAP invasion in South African primary catchment areas. Source: Table 2 in Le Maitre et al. (2016).

Primary catchment	**Estimated extent of IAP invasion (c.ha)**	**Estimated flow reduction (Mm^3)**	**Quantity of water saved (Mm^3/c.ha)**
A	86510	24.44	0.0003
B	123328	61.79	0.0005
C	138557	64.25	0.0005
D	54383	31.57	0.0006
E	4825	3.65	0.0008
F	795	0	0.0000
G	92970	111.36	0.0012
H	45164	126.21	0.0028
J	25438	11.69	0.0005
K	60951	102.51	0.0017
L	24228	10.86	0.0004
M	23662	11.64	0.0005
N	39906	0.89	0.0000
P	12432	3.31	0.0003
Q	30385	4.83	0.0002
R	45414	42.92	0.0009
S	59130	46.58	0.0008
T	220942	321.96	0.0015
U	111698	154.35	0.0014
V	81139	100.87	0.0012
W	154984	148.66	0.0010
X	58025	59.19	0.0010