REFINEMENT OF STRATEGIC GROUNDWATER SOURCE AREAS OF SOUTH AFRICA

WP11446

REFINED METHODOLOGY REPORT

RDM/NAT00/02/CON/SWSA/0225
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3.2	**RDM/NAT00/02/CON/SWSA/0225**	**Refined Methodology for Identifying and Delineating Strategic Groundwater Source Areas of South Africa Report**
3.3	RDM/NAT00/02/CON/SWSA/0126	Delineation of Strategic Groundwater Source Areas of South Africa Report
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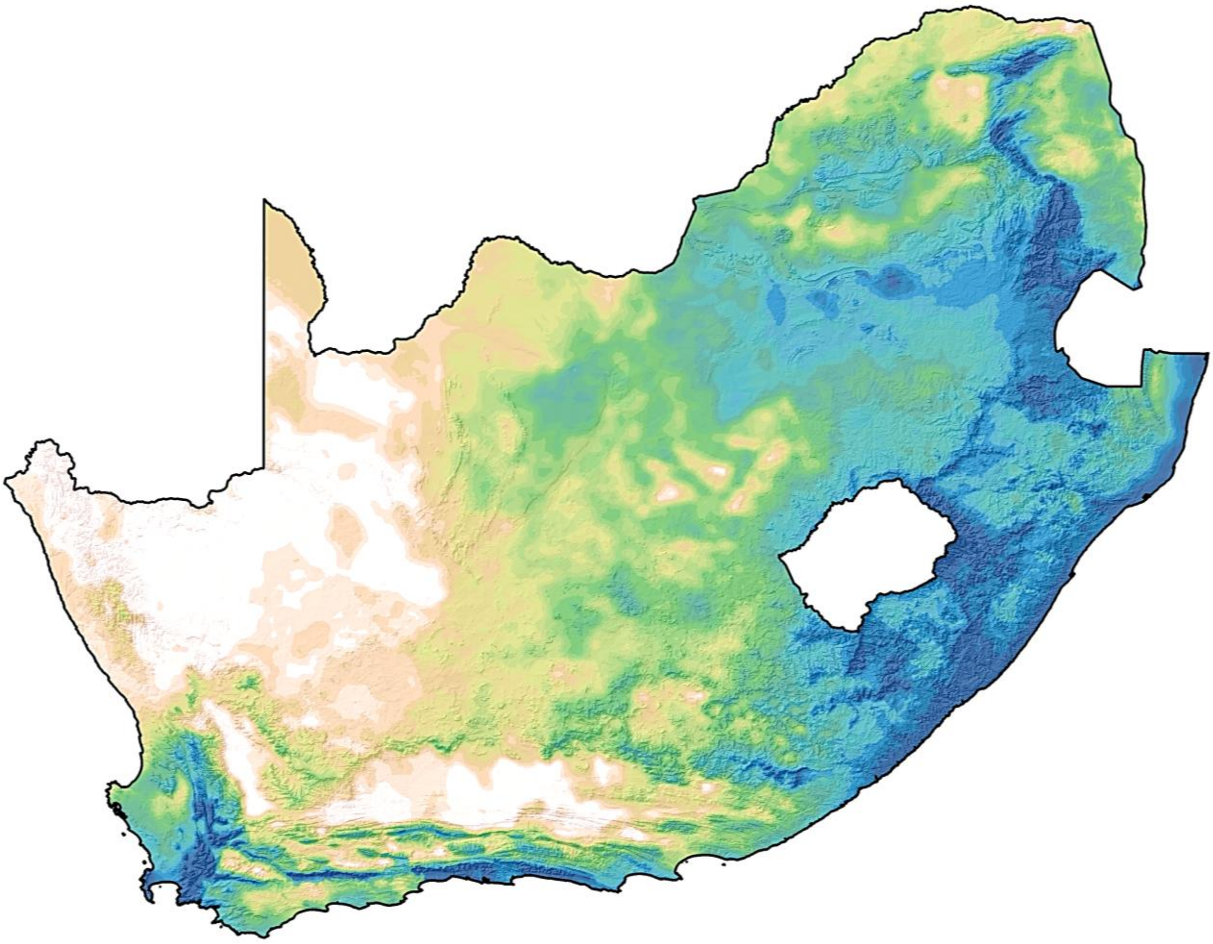
REFINEMENT OF STRATEGIC GROUNDWATER SOURCE AREAS OF SOUTH AFRICA



Refined Methodology for Identifying and Delineating Strategic Groundwater Source Areas of South Africa Report

Final

Prepared for:

Department of Water and Sanitation

Chief Directorate: Water Ecosystems Management

Executive Summary

Background & Motivation

The National Water Resource Strategy III (NWRS III), developed under the National Water Act (Act 36 of 1998), recognises the protection of Strategic Water Source Areas (SWSA) as a national priority. While a fine-scale refinement has been completed for surface water (SWSA-sw), no equivalent update had been undertaken for Strategic Groundwater Source Areas (SWSA-gw).

This project, led by the Department of Water and Sanitation's Chief Directorate: Water Ecosystems Management (DWS CD: WEM), addresses that gap by presenting a refined, aquifer-specific methodology for identifying and delineating SWSA-gw. It builds on the 2018 national assessment by Le Maitre et al. (2018), which provided a valuable baseline and national perspective, and advances the approach with higher-resolution datasets, aquifer-aligned spatial units, and a broader, more transparent spatial and evaluation framework suitable for both national and transboundary planning.

Definition Adopted

SWSA-gw are aquifers (geological bodies capable of holding and transmitting water) that can naturally supply disproportionately large volumes of groundwater per unit area and are considered of national strategic significance for water security, socio-economic development and sustainability.

Legislative Context and Drivers

The refinement aligns with the objectives of the NWRS III and the proposed National Water Amendment Bill (2023), which, importantly, introduces explicit legal recognition of strategic water source areas encompassing both land and aquifers. International practice (e.g., EU, Denmark, Western Australia, USA) emphasises aquifer-specific delineation, vulnerability mapping, and enforceable protection zones. Regionally, while policy intent exists, implementation tools are somewhat limited; this work positions South Africa to lead with a defensible, science-based framework that links technical assessment to management action.

Core Framework and Workflow

This Refined Methodology Report provides a first-generation, transparent, and modular methodology that formalises two core pillars, 1) the Enhanced Spatial Framework and 2) the Enhanced Evaluation Framework; and operationalises a Four-Part Multi-Criteria Decision Analysis (MCDA) workflow.

1. **Enhanced Spatial Framework**

   The spatial foundation shifts from a uniform 1 km grid to aquifer-specific Groundwater Resource Units (GRUs) derived from the CGS 1:250 000 geological series and the DWS 1:500 000 hydrogeological series. This anchors evaluation to specific hydrogeological boundaries, improving spatial precision, interpretability, and direct applicability for planning, protection, and licensing processes.

2. **Enhanced Evaluation Framework**

   The evaluation broadens beyond recharge and groundwater use to include groundwater availability, strategic significance, and contextual viability. Indicators are standardised to a common nominal scale and combined using MCDA with clearly documented weights and combination rules. Contextual factors (e.g., groundwater quality against Domestic Water Quality Targets, aquifer vulnerability, and development pressures) ensure priorities reflect both supply potential and water safety/resilience.

The Four-Part MCDA Workflow

1. **Groundwater Availability**

   A composite assessment integrates four parameters: recharge and baseflow (from downscaled MAP and refined recharge:MAP relationships, maintaining hydrological consistency) as well as storage capacity and potential yield (from national geological/hydrogeological datasets and updated expected-yield information). Parameters are reclassified to a common scale and merged to identify zones with consistently high potential to sustain groundwater supply.

2. **Aquifer-Specific GRU Delineation**

   High-availability zones are intersected with mapped aquifers to define GRUs. Candidate units are retained only where availability thresholds are met; aggregated availability scores are carried forward. This step effects the core shift from coarse national grids to aquifer-aligned units relevant to management and protection.

3. **Strategic Significance**

   Each GRU is assessed using socio-economic indicators (e.g., current/projected demand, reliance on groundwater for domestic and economic activities, governance context) as well as ecological indicators (e.g., groundwater-dependent ecosystems, designated recharge protection areas). Through MCDA, indicators are weighted and combined to produce a Strategic Significance Score.

4. **Additional Considerations & Contextual Adjustment**

   Preliminary rankings are refined using groundwater quality, aquifer vulnerability, current status quo assessments, and future development pressures. This adjustment ensures the final shortlist includes areas that are both strategically important and viable in terms of quality, resilience, and long-term sustainability.

Advances Relative to the 2018 Baseline

The refined methodology builds directly on the 2018 national SWSA-gw study, which provided an important baseline for identifying SWSA-gw. While the earlier work offered a valuable starting point, its uniform 1 km^2 grid and limited integration of hydrogeological, water quality, and socio-economic datasets restricted its operational value. The updated approach addresses these constraints through aquifer-specific GRUs, delivering outputs that are both hydrogeologically realistic and management-ready. The evaluation framework incorporates a richer set of indicators, covering groundwater availability (recharge, baseflow, storage, and potential yield), socio-economic and ecological significance, and contextual factors such as groundwater quality and aquifer vulnerability. Scoring and ranking are implemented through a transparent MCDA process, with clear thresholds, weights, and decision rules. Higher-resolution datasets and refined processing methods reduce artefacts from generic buffers or interpolations, improving boundary fidelity and spatial precision. The modular design ensures that parameters, thresholds, and decision rules can be updated as new datasets or higher resolution datasets become available, supporting iterative refinement without breaking the framework.

First-Generation Workflow and Next Steps

The workflow presented in this report represents the first generation of the refined methodology, established, tested, and ready for application, yet intentionally adaptable. Its design anticipates future improvements during the upcoming Delineation of Refined SWSA-gw (**Deliverable 3.3**), where sensitivity testing will be conducted on data, thresholds, classification schemes, and weighting structures. This stage will refine parameters using newly available or validated datasets, calibrate outcomes against observed aquifer performance, and incorporate local expert review to strengthen both accuracy and practical relevance. Where necessary, decision rules will be adjusted to ensure national consistency while retaining hydrogeological defensibility.

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List of Abbreviations and Acronyms

ADE	Aquifer Dependent Ecosystems
AHP	Analytic Hierarchy Process
BHN	Basic Human Need
CB	Capacity Building
CBA	Critical Biodiversity Area
CD: WEM	Chief Directorate: Water Ecosystems Management
CGS	Council for Geoscience
CMA	Catchment Management Agency
CMB	Chloride Mass Balance
CSIR	Council for Scientific and Industrial Research
DFFE	Department of Forestry, Fisheries, and the Environment
DTIC	Department of Trade, Industry and Competition.
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWQT	Drinking Water Quality Targets.
DWS	Department of Water and Sanitation
EBK	Empirical Bayesian Kriging
EBKRP	Empirical Bayesian Kriging Regression Prediction
Et al.	And Others
Etc.	Et cetera
EU	European Union
EWR	Ecological Water Requirements
GDE	Groundwater Dependent Ecosystem
GEP	Groundwater Exploitation Potential
GIS	Geographic Information System
GRA II	Groundwater Resource Assessment II
GRU	Groundwater Resource Unit
GW	Groundwater
IDP	Integrated Development Plan.
IDZ	Industrial Development Zone
IPAP	Industrial Policy Action Plan.
IWRM	Integrated Water Resource Management
K	Thousand
KBA	Key Biodiversity Area
l/s	Litres per second
l/s/km^2	Litres per second per square kilometre
LIMCOM	Limpopo Watercourse Commission
Ltd	Limited Company
m^2/h	Square meters per hour (used here as a unit of hydraulic conductivity)
m^3/a	Cubic meters per annum
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MCDA	Multi-Criteria Decision Analysis
MGB	Major Groundwater Basin
mm/a	Millimetres per annum
mm/a/km^2	Millimetres per annum per square kilometre
Mm^3/a	Million cubic meters per annum
MPA	Marine Protected Area
NGA	National Groundwater Archive
NGDB	National Groundwater Database
NGS	National Groundwater Strategy

NLC	-	National Land Cover
NSDP	-	National Spatial Development Perspective
NW&SMP	-	National Water and Sanitation Master Plan.
NWA	-	National Water Act
NWM5	-	National Wetland Map 5
NWP	-	National Water Policy
NWRS I	-	National Water Resource Strategy Frist Edition
NWRS II	-	National Water Resource Strategy Second Edition
NWRS III	-	National Water Resource Strategy Third Edition
NWRS	-	National Water Resource Strategy
ORASECOM	-	Orange-Senqu River Commission
PDWSA	-	Public Drinking Water Source Areas
PGEP	-	Potable Groundwater Exploitation Potential
PMC	-	Project Management Committee
PS	-	Public Stakeholder
PSC	-	Project Steering Committee
Pty	-	Proprietary Limited
QC	-	Quaternary Catchment
RMSE	-	Root Mean Square Error
RQOs	-	Resource Quality Objectives
RSA	-	Republic of South Africa
SADC	-	Southern African Development Community
SAEON	-	South African Environmental Observation Network
SANS 241	-	-South African National Standard 241
SAPAD	-	South African Protected Areas Database.
SAWS	-	South African Weather Service
SD	-	Standard Deviation
SEZ	-	Special Economic Zones
SGWCA	-	Subterranean Government Water Control Areas
Stats SA	-	Statistics South Africa
SWSA	-	Strategic Water Source Areas
SWSA-gw	-	Strategic Groundwater Source Areas
SWSA-sw	-	Strategic Surface Water Source Areas
TIA	-	Tripartite Interim Agreement (Incomati & Maputo Watercourses).
TMG	-	Table Mountain Group
ToR	-	Terms of Reference
TPI	-	Topographic Position Index
TPTC	-	Tripartite Permanent Technical Committee
UGEP	-	Utilisable Groundwater Exploitation Potential
US EPA	-	United States Environmental Protection Agency
WARMS	-	Water Use Authorisation & Registration Management System
WLC	-	Weighted Linear Combination
WMA	-	Water Management Area
WMS	-	Water Management System
WP	-	Work Package
WR2012	-	Water Resources of South Africa 2012
WRC	-	Water Research Commission
WRSM2000	-	Water Resources Simulation Model 2000
WSDP	-	Water Services Development Plan.

1. INTRODUCTION

1.1. Background and Motivation

Groundwater has long been recognised as a critical component of South Africa's water security. Its role in sustaining rural livelihoods, buffering drought impacts, and supporting ecological resilience has become increasingly important over the past two decades, particularly in arid and semi-arid regions where surface water availability is limited and increasingly constrained by climate variability, population growth, and land-use pressures.

The concept of Strategic Water Source Areas (SWSA) was introduced in 2013 as part of a national effort to identify regions that contribute disproportionately to the country's total surface water supply (Nel et al., 2013). While the term itself is relatively recent, the underlying principle of prioritising and protecting key water source regions can be traced back to earlier policy frameworks. For example, the National Water Resource Strategy First Edition (NWRS I; DWAF, 2004) emphasised the protection of water resources critical to economic development, ecological function, and regional supply security, particularly high-yielding catchments and aquifer systems supporting major demand centres. Although not yet formalised as "SWSA", these foundational ideas laid the groundwork for later strategic delineation efforts. The Second Edition of the National Water Resource Strategy (NWRS II; DWA, 2013) formally incorporated SWSA, as defined by Nel et al. (2013), into national planning, establishing a framework for prioritisation and investment.

Le Maitre et al. (2018) expanded the definition of SWSA to explicitly include groundwater. The resulting study delineated 37 Strategic Groundwater Source Areas (SWSA-gw) at a national scale, based on recharge potential, groundwater use, and socio-economic importance. While this represented a significant advancement in recognising groundwater as a strategic resource, the study also identified several limitations, including inconsistent groundwater use data, variability in recharge estimates, and insufficient spatial resolution to support aquifer-specific planning. As a result, the outputs, though foundational to this current study, have proven difficult to implement operationally, often under- or overestimating key hydrogeological components. These challenges were echoed in the Third Edition of the National Water Resource Strategy (NWRS III; DWS, 2023), which emphasised the need for locally actionable delineation of SWSA to support the Integrated Water Resource Management (IWRM) outline in the National Water Act (NWA; No. 36 of 1998).

Although the Department of Forestry, Fisheries and the Environment (DFFE) completed a fine-scale refinement of Strategic Surface Water Source Areas (SWSA-sw) in 2021 (Lötter and Le Maitre, 2021), this was not incorporated into NWRS III, and, more importantly, no equivalent refinement has yet been undertaken for SWSA-gw. This has left a critical gap in the national water resource planning framework, particularly given the growing reliance on groundwater for domestic supply, agricultural productivity, and ecological resilience.

In response, the Department of Water and Sanitation (DWS), through its Chief Directorate: Water Ecosystems Management (CD: WEM), initiated the "Refinement of Strategic Groundwater Source Areas of South Africa" project. The project aims to strengthen groundwater governance and improve the spatial and technical basis for national water planning.

This report, Deliverable 3.2, Refined Methodology for Identifying and Delineating Strategic Groundwater Source Areas of South Africa, builds on the insights and findings of earlier project deliverables, including the Inception (DWS, 2024a), Gap Analysis (DWS, 2024b), and Status Quo Reports (DWS, 2025). It presents a scientifically robust, aquifer-specific, and nationally scalable methodology to guide the updated identification and delineation of SWSA-gw. The refined framework is intended to serve as the technical foundation for protecting and managing South Africa's most important groundwater assets, supporting DWS's broader goals of equitable access, sustainable development, and long-term water security.

1.2. Terms of Reference

The Terms of Reference (ToR), developed by DWS (CD: WEM), define the overarching scope, objectives, and intended outcomes of this study. They establish the framework for this report and guide the overall refinement process.

The primary aim of the project is to enhance the delineation of SWSA-gw to an aquifer-specific scale, building upon the baseline information provided by the 2018 study.

The objectives for the study include:

1. Developing a scientifically sound methodology for delineating SWSA-gw for both national and transboundary aquifers/aquifer systems, incorporating considerations for groundwater quality.
2. Reviewing and refining the scale of SWSA-gw to the aquifer level.
3. Developing an approach for the protection and management of the refined SWSA-gw.

Throughout these processes, it is imperative to ensure consultative engagement, keeping all interested and affected parties, stakeholders, water users, etc., informed about developments.

By establishing this scope, the ToR position the study as a direct response to three key gaps: 1) the limitations identified in the 2018 SWSA-gw delineation (Le Maitre et al., 2018); 2) the absence of an equivalent refinement for SWSA-gw, as was undertaken for SWSA-sw by Lötter and Le Maitre (2021); and 3) the strategic priorities outlined in NWRS III (2023). This study addresses these gaps and is not only a technical exercise but also a foundational step toward integrating groundwater more effectively into national and transboundary water resource planning.

1.3. Aims and Objectives of this Report

This report constitutes Deliverable 3.2 of Phase 3 (see **Table** 1-1) and presents the Refined Methodology for Identifying and Delineating SWSA-gw in South Africa. It marks the transition from the project's foundational phases to the development of a robust, spatially explicit methodology to guide the delineation, protection, and integration of SWSA-gw into national water resource planning.

The report aims to develop a scientifically defensible, scalable methodology for identifying SWSA-gw at an aquifer-specific level, grounded in hydrogeological reality and aligned with national policy. Building on the approach by Le Maitre et al. (2018), the refined methodology addresses known limitations, improves spatial resolution, and integrates updated hydrogeological, environmental, and socio-economic metrics. It provides a transparent, modular framework that can evolve with new data, legislation, and stakeholder priorities, ensuring a consistent and policy-relevant approach at both national and transboundary scales. To support this aim, the objectives of the report are to:

1. To provide a consolidated set of definitions and guiding principles that frame the scope and intent of the methodology.
2. To describe the conceptual and methodological approach, including the rationale for the selected methods.
3. To detail the hydrogeological and strategic parameters considered, along with proposed datasets, tools, and geospatial techniques to develop and test the methodology.

While the methodology seeks to generate aquifer-specific outputs, these should be regarded as indicative at a national scale. Their application in local or site-specific decision-making requires validation with site-specific datasets, local expertise, and ground-truthing to ensure robustness.

Table 1-1 Project Deliverables and Associated Tasks for each Project Phase.

Phase 0: Project Management, Administration, Communication and Capacity Building		
P0	**P0.1** General Project Management	
	P0.2 PMC Meetings	
	P0.3 PSC Meetings	
	P0.4 PS Meetings	
	P0.5 Ad Hoc Meetings	
	P0.6 Monthly Progress Reports	
	P0.7 Capacity Building	
Phase 1: Project Inception		
P1	**D1.1**: Inception Report	**T1.1.1**: Lit Review
Phase 2: Information and Data Gathering		
P2	**D2.1**: Gap Analysis Report	**T2.1.1**: Data and Information Assessment **T2.2.1**: Inventory of Water Resource Tools
Phase 3: Refinement of SWSA-gw		
P3	**D3.1:** Status Quo SWSA-gw Report	**T3.1.1**: Status Quo SWSA-gw Assessment
	D3.2: Refined Methodology Report	**T3.2.1: Refined Methodology Assessment**
	D3.3: Delineation of Refined SWSA-gw Report	**T3.3.1**: Delineation of Refined SWSA-gw **T3.3.2**: Groundwater Quality **T3.3.3**: Transboundary Aquifers **T3.3.4**: Updated Status Quo SWSA-gw Assessment
	D3.4: SWSA-gw Protection and Management Report	**T3.4.1**: SWSA-gw Protection and Management
Phase 4: Project Closure		
P4	**D4.1**: Refined Strategic Groundwater Source Areas of South Africa Report	**T4.1.1**: Report Integration
	D4.2: External Review Summary Report	
	D4.3: Electronic Database	
	D4.4: Close Out Report	

1.4. Report Structure

This Refined Methodology for Identifying and Delineating SWSA-gw Report is organised into four main sections, supported by tables and figures that guide the reader through the methodology and its context.

Section 1 introduces the motivation for the refinement process, the Terms of Reference, and the aims and objectives of this deliverable. It outlines the role of Strategic Groundwater Source Areas in national water security and sets the context for the refinement within key policy instruments such as the National Water Act (Act 36 of 1998) and the National Water Resource Strategy III (2023).

Section 2 presents the legislative context and key drivers for refinement. It traces the evolution of SWSA and SWSA-gw concepts, compares national and international definitions, reviews relevant benchmarking examples, and identifies limitations in previous approaches.

Section 3 details the Refined Methodological Framework. It begins with the conceptual overview and rationale, then describes the Enhanced Spatial Framework and Enhanced Evaluation Framework, followed by the stepwise Four-Part Workflow: 1) Groundwater Availability, 2) Aquifer-Specific Groundwater Resource Unit (GRU) Delineation, 3) Strategic Significance, and 4) Additional Considerations & Contextual Adjustment. Each part outlines the datasets used, analytical methods, classification and scoring processes, and decision rules applied. Figures and summary tables provide a visual guide to the data integration and evaluation steps.

Section 4 provides concluding remarks, summarising the purpose and technical foundation of the refined methodology and outlining how these results will inform the subsequent project phases, including the delineation and protection of South Africa’s most critical groundwater source areas.

2. LEGISLATIVE CONTEXT AND DRIVERS

2.1. Policy and Legislative Frameworks

2.1.1. National Water Policy

South Africa's National Water Policy (NWP), adopted in 1997, marked a fundamental shift in water governance (DWAF, 1997). Grounded in the 28 Fundamental Principles and Objectives for a new water law, the policy reclassified water as a national resource held in public trust, effectively abolishing private ownership and riparian rights. It introduced time-bound water use licences, decoupled from land ownership, and prioritised both the basic human need (BHN) and ecological water requirements (EWR).

At its core, the NWP promotes equity, sustainability, and efficiency, underpinned by integrated management of water quantity and quality. It supports decentralised governance through catchment management agencies (CMAs) and encourages cooperative governance across sectors. To ensure transparency and fairness, the policy also emphasises demand management, pollution prevention, and equitable cost recovery. Additionally, it provides a framework for managing shared international watercourses through cooperative agreements. Collectively, these provisions operationalised the 28 principles and laid the foundation for the National Water Act (NWA) of 1998 (Act 36 of 1998; RSA, 1998).

2.1.2. National Water Act

The NWA (Act 36 of 1998, RSA, 1998) gave legal effect to the NWP of 1997 (DWAF, 1997), creating a unified framework for the management of South Africa's water resources. It reaffirms water as a public resource, held in trust by the state, and assigns custodianship to the national government through the Minister of Water and Sanitation.

The NWA introduced a formal system for both water resource protection and regulated water use, comprising licensed allocations, general authorisations, and the recognition of existing lawful uses. Chapter 3 of the Act, the Protection of Water Resources, establishes the framework for safeguarding water resources through the Water Resource Classification System, Resource Quality Objectives (RQOs), and, most importantly, the Reserve, which ensures that water is first allocated to meet BHN and EWR before any other uses are considered.

Since its enactment, the NWA has undergone several amendments aimed at improving regulatory clarity and administrative efficiency. In the context of this study, Chapter 3 (focused on the protection of water resources) provides a basis for the inclusion and legal recognition of SWSA, as reflected in the following developments:

- The 1999 Amendment Act addressed transitional challenges by clarifying the status of existing lawful uses and refining the water use licensing process (RSA, 1999).
- The 2014 Amendment Act strengthened institutional mandates, aligned definitions with environmental legislation, and reinforced principles of transparency, public accountability, and ministerial oversight (RSA, 2014).
- The proposed 2023 amendments mark a major evolution in the legal framework by formally recognising SWSA for the first time. These amendments propose restrictions on water and land use within SWSA and seek to integrate their protection into national and catchment-level planning. This legal recognition represents a critical step in elevating SWSA from a policy concept to an enforceable instrument for securing South Africa's water future (RSA, 2023).

2.1.3. National Water Resource Strategy

The first edition of the National Water Resource Strategy (NWRS I; DWAF, 2004) established the foundational framework for implementing the NWA (Act 36 of 1998), outlining principles for the equitable and sustainable management of South Africa's water resources. However, it did not yet include the concept of SWSA.

The second edition (NWRS II; DWA, 2013) introduced the concept for the first time, drawing on the findings of Nel et al. (2013). In this edition, SWSA were recognised as national assets critical to water security, warranting coordinated management and long-term protection.

Building on this, the third edition (NWRS III; DWS, 2023) expands the strategic vision for South Africa's water and sanitation sector, establishing three overarching goals:

- Firstly, water resources must be protected, developed, conserved, managed, and controlled sustainably and equitably;
- Secondly, water and sanitation services should support development and the elimination of poverty and inequality; and
- Thirdly, water and sanitation must contribute to economic growth and job creation.

Together, these goals highlight the dual role of water as both a vital ecological resource and a driver of social and economic development. The NWRS III further expresses this vision as:

> *"The protection and management of water resources to enable equitable and sustainable access to water and sanitation services in support of socio-economic growth, development and sustained ecosystem functioning for the well-being of current and future generations."*

Chapter 12 of the NWRS III (Protecting Aquatic Ecosystems and Maintaining & Restoring Ecological Infrastructure) explicitly calls for the use of legal mechanisms to declare and protect SWSA. This marks further policy shifts toward institutionalising their protection as a central component of national water resource planning. Specifically, Section 12.4.3 (Strategic Objective 3) outlines the objectives relating to SWSA as follows:

- *Declare water source areas, critical groundwater recharge areas and aquatic ecosystems that are recognised as threatened or sensitive, as protected areas.*
- *Establish innovative ways for collective action through taking a stewardship approach to securing Strategic Water Source Areas.*
- *Monitor the impact of alien invasive plants in water security and ensure their removal from Strategic Water Resource Areas and riparian / buffer zones.*
- *Identify and use legal mechanisms to protect strategic water source areas.*
- *Invest in strategic water source areas and ecological restoration to maintain healthy ecosystems that deliver benefits (i.e. entrepreneurial opportunities in the blue-green zero waste economy).*

The NWRS III also marks the first time that Strategic Water Source Areas for groundwater (SWSA-gw) were explicitly recognised, following the work of Le Maitre et al. (2018). Within Chapter 12, Strategic Objective 3 promotes the protection and rehabilitation of ecological infrastructure, referencing both surface water and groundwater SWSA (SWSA-sw and SWSA-gw), as well as aquifer-dependent ecosystems and critical groundwater recharge zones.

While the NWRS III acknowledges the vital role of groundwater in supporting environmental sustainability, human well-being, and socio-economic development, it does not clearly define what constitutes a SWSA nor does it provide specific criteria for delineating such areas. The strategy also references the National Groundwater Strategy (NGS; DWS, 2016), which identifies a key opportunity to integrate groundwater protection zoning with the SWSA initiative. However, no technical framework or detailed guidance is provided to operationalise this integration.

2.2. The Concept of SWSA-gw

While the broader concept of SWSA has gained policy recognition over the past decade (see **Section 2.1**), the groundwater component, i.e., SWSA-gw, remains somewhat under-defined. As efforts to protect and manage groundwater resources intensify, a clear and consistent conceptual foundation and definition is needed to guide the identification, delineation, and integration of SWSA-gw into protection and management planning frameworks.

2.2.1. Evolution of Definitions and Terminology

Various government and research publications have described SWSA in slightly different ways, often reflecting evolving or specific priorities. **Table 2-1** below compares definitions across key documents, illustrating how the understanding of SWSA, particularly in relation to groundwater, has shifted over time.

The key points from these definitions are:

- The original definition (Nel et al., 2013) focused on surface water (specifically, Mean Annual Runoff).
- Water Source Areas contribute a disproportionately high amount of runoff relative to their size; they contribute 50% of the mean annual runoff within South Africa, Lesotho, and Swaziland, while occupying less than 8% of the land surface area.
- The updated definition (Le Maitre et al., 2018) includes both surface water and groundwater sources, expanding beyond the earlier surface water only definition
- SWSA are natural source areas that supply disproportionately large volumes of water per unit area
- SWSA may be national or transboundary, depending on its hydrological and planning significance
- Considered strategically significant for national water security, based on national water resource planning priorities

The proposed definition in the National Water Amendment Bill (2023) acknowledges the difference between surface water, being on the land, and groundwater, being contained in aquifers:

> *"water source area" means all land and aquifers which form the original collection point, and provide above average amounts of water to the rest of South Africa's water resources, and which meet significant social, economic and environmental water requirements."*

This is a significant shift and relevant for the development of the refined methodology.

Table 2-1 Definitions or descriptions of SWSA from key national policy and research documents.

Source	Key Points & Quotes
National Water Act 1998 (RSA, 1998)	No explicit definition of "water source" or "water source area".
Defining South Africa's Water Source Areas (Nel et al., 2013)	**Quote 1:** *Any area estimated to have ≥ 135 mm/a in its 1 x 1 minute grid cell was considered to be a water source area. These areas span South Africa, Lesotho and Swaziland and occupy 8 per cent of the land surface area in the region. Together, these areas supply 50% of the region's mean annual runoff, of which 80 per cent, 12 per cent and 8 per cent are contributed respectively by South Africa, Lesotho and Swaziland.* **Quote 2:** *The final map of water source areas was produced by grouping areas generating mean annual runoff across South Africa, Lesotho and Swaziland into percentile categories, where areas representing 50 per cent of the mean annual runoff in the region were considered to be strategic water source areas for the country. These areas in South Africa, Lesotho and Swaziland together contribute 50 per cent of the region's water supply in less than 8 per cent of the land surface area*
	Key points: • The concept, as originally described, focuses on surface water (specifically, Mean Annual Runoff). • Water Source Areas contribute a disproportionately high amount of runoff relative to their size, they contribute 50% of the mean annual runoff within South Africa, Lesotho, and Swaziland, while occupying less than 8% of the land surface area.
National Water Resource Strategy 2nd edition (DWA, 2013)	**Quote:** *Strategic Water Source Areas supply a disproportionately high amount of the country's mean annual runoff in relation to their surface area. These areas make up 8% of the land area across South Africa, Lesotho and Swaziland, but provide 50% of the water in these countries.*
	Key points: • Directly adopts the concept of SWSA from Nel et al. (2013).

<table>
<tr><th>Source</th><th>Key Points & Quotes</th></tr>
<tr><td rowspan="2">Identification, Delineation and Importance of the Strategic Water Source Areas of South Africa, Lesotho and Swaziland for Surface Water and Groundwater
(Le Maitre et al., 2018)</td><td>Quote 1:
Strategic water source areas – A subset of water source areas that are considered of strategic significance for water security. The term “strategic” is based on national water resource planning considerations and includes groundwater and surface water source areas (both national and transboundary). Criteria for identifying nationally strategic water source areas (SWSA) have been developed as part of this project. Those which are not considered nationally strategic are identified as sub-national SWSA. This study has modified the 2013 definition of SWSA and also includes groundwater, which has changed the overarching definition of a SWSA to include use and dependence on groundwater.

Quote 2:
Water source areas – Natural areas for that provide disproportionate (i.e. relatively large) volumes of surface water and/or groundwater water per unit area, or which meet critical social, economic and environmental water requirements and provide water security.

Quote 3:
Strategic Water Source Areas (SWSA) are now defined as areas of land that either: (a) supply a disproportionate quantity of mean annual surface water runoff in relation to their size and so are considered nationally important; (b) have high groundwater recharge and where the groundwater forms a nationally important resource; or (c) areas that meet both criteria (a) and (b).</td></tr>
<tr><td>Key points:
Now includes both surface water and groundwater sources, expanding beyond the earlier surface water only definition
Supply disproportionate volumes of water per unit area, whether surface water or groundwater
Significant to national water security
SWSA may be national or transboundary, depending on its hydrological and planning significance
Introduces a refined classification:
SWSA-sw for surface water,
SWSA-gw for groundwater,
SWSA as a general term
Defined based on either (a) high surface runoff yield, (b) high groundwater recharge, or (c) both.</td></tr>
</table>

Source	Key Points & Quotes
National Water Resource Strategy 3rd edition (DWS, 2023)	**Quote 1:** *Strategic Water Source Areas: The areas with greater than average rainfall per year represent strategic water source areas in South Africa, Lesotho and Swaziland. These Strategic Water Source Areas supply a disproportionately high amount of the country's mean annual runoff in relation to their surface areas. These areas occupy approximately 8% of the land surface and contribute 50% of the water supply. They are thus strategic national assets that are vital for water security and need to be acknowledged as such at the highest level across all sectors.* **Quote 2:** *Strategic Water Source: Natural source area for water resources that provides disproportionately large volumes of water per unit area and that is considered of strategic significance for water security from a national planning perspective. This includes a surface or groundwater area of national significance.*
	Key points: • Maintains the original (Nel et al. 2013) definition regarding surface-water SWSA • Acknowledges groundwater recharge areas but does not fully adopt the refined groundwater-inclusive definition or terminology from Le Maitre et al. (2018).
Accounts for Strategic Water Source Areas, 1990 to 2020 (StatsSA, 2023)	**Quote:** *SWSA are natural source areas for water that supply disproportionately large volumes of water per unit area and that are considered of strategic significance for water security from a national planning perspective, either for surface water, groundwater or both.*
	Key points: • Includes both surface water and groundwater • SWSA are natural source areas that supply disproportionately large volumes of water per unit area • Considered strategically significant for national water security, based on national water resource planning priorities

Source	Key Points & Quotes
National Water Amendment Bill 2023 (RSA, 2023)	**Quote 1:** *“water source area” means all land and aquifers which form the original collection point, and provide above average amounts, of water to the rest of South Africa’s water resources, and which meet significant social, economic and environmental water requirements*
	Key points: • Includes both land and aquifers; it's not limited to surface features, and groundwater is explicitly included • Represent the source zones for South Africa’s water supply system • They provide above-average amounts of water per unit area, whether surface water or groundwater • Significant to national water security

2.2.2. International Benchmarks

International experience provides valuable lessons for strengthening South Africa's approach to identifying and safeguarding SWSA. Across a wide range of legal and institutional contexts, many countries apply science-based, hydrogeologically grounded methods to delineate (to some degree) and manage groundwater resources. Despite varying terminology and frameworks, several common principles emerge, beginning with the identification of resources of strategic value, followed by vulnerability assessments and zoning systems that guide protection, land-use regulation, and long-term sustainability.

International Approaches to Groundwater Delineation and Protection

In the European Union (EU), the Water Framework Directive proposes the delineation of groundwater bodies based on ecological relevance (e.g. baseflow contributions to rivers or wetlands) or quantitative thresholds (e.g. abstraction rates exceeding 10 m^3/day for drinking purposes). Boundaries are drawn using hydrogeological criteria and may be adjusted as new data becomes available. Each groundwater body is assigned to a river basin district, with internal zones sometimes designated for enhanced protection or restoration (European Commission, 2003). A similar science-based approach is seen in Poland, where Major Groundwater Basins (MGBs) are designated using strict quantitative and qualitative criteria, such as discharge greater than 10,000 m^3/day and hydraulic conductivity above 10 m^2/h. These basins are protected through zones determined by vertical and lateral groundwater travel times, with four levels of protection guiding risk-based land-use management (Krogulec et al., 2021).

Denmark provides a particularly detailed example of risk-informed groundwater protection. Here, a three-step process is used: 1) hydrogeological mapping, 2) inventorying of actual and potential contamination sources, and 3) the development of a management plan that outlines regulatory land-use restrictions within delineated protection zones. The process incorporates geophysical surveys, drilling, groundwater modelling, and public engagement, enabling site-specific protection strategies based on both vulnerability and socio-economic context (Thomsen et al., 2004). A tiered zoning framework is also applied in Western Australia, where Public Drinking Water Source Areas (PDWSAs), legally designated surface water catchments or aquifers supplying urban drinking water, are designated by law and divided into three priority zones: Priority 1 (risk avoidance), Priority 2 (risk minimisation), and Priority 3 (risk management). Additional wellhead protection zones further safeguard sensitive boreholes, and all zones are supported by enforceable land-use controls (Australian Government, 2013; WEPA, 2018).

China, meanwhile, classifies its groundwater into three functional categories: Resource Function (assessing availability, recharge, and usability), Ecological Function (evaluating support for vegetation, wetlands, landscapes, and soil health), and Geological Environmental Function (addressing roles in preventing geohazards such as subsidence or seawater intrusion) (Teng et al., 2021). In the United States, the Environmental Protection Agency's Sole Source Aquifer programme designates aquifers that supply more than 50% of a region's drinking water and lack viable alternatives. Designation requires stakeholder-submitted petitions supported by hydrogeological data and risk assessments. Once approved, critical recharge zones are delineated to ensure federally funded projects do not threaten water quality (US EPA, 1987).

Despite differences in legislative and institutional settings, these countries apply evidence-based approaches to prioritise and protect groundwater resources, not only based on yield or recharge, but also in terms of water quality, vulnerability to pollution, ecological function, and land-use compatibility.

Regional Approaches to Groundwater Delineation and Protection

Within the Southern African region, most neighbouring countries have recognised groundwater protection as a policy priority, but formal implementation has been limited. Namibia's Water Resources Management Act (2013), operationalised in 2023, allows the minister to declare water protection areas in cases of significant pollution or depletion risk, although it does not specify a methodology for delineating such zones (Republic of Namibia, 2013). Zimbabwe lacks any formal legal framework for protected groundwater areas, however, their National Water Resources Master Plan (2020–2040) acknowledges that groundwater protection remains underdeveloped and provides a framework for assessing groundwater resources using Geographic Information System (GIS) and Analytic Hierarchy Process (AHP) techniques to map aquifer productivity, recharge potential, and vulnerability (Ministry of Lands, Agriculture, Water and Rural Resettlement, 2020).

Mozambique's Water Law (1991) provides legal authority for establishing groundwater protection zones where there is a risk of excessive exploitation or pollution, but none have yet been formally declared (SADC-GMI, 2019). In Lesotho, the Water Act (2008) permits the designation of catchment areas for resource protection, but no system exists for identifying or managing vulnerable aquifers specifically (Government of Lesotho, 2008). Eswatini's National Water Policy (2018) advocates for the protection of groundwater from pollution and over-abstraction, yet no formal delineation frameworks are in place (Government of the Kingdom of Eswatini, 2018). Likewise, Botswana's legislation supports groundwater sustainability in principle but has not established legal or procedural mechanisms for designating protected aquifer zones (Republic of Botswana, 2012).

Lessons to South Africa's SWSA-gw Framework

South Africa, by contrast, has taken important steps toward delineating water source areas of national strategic value, particularly under the SWSA framework, by recognising them in policy, embedding them in legal and strategic instruments, and expanding the concept to include groundwater (see **Sections 2.1** and **2.2**). While technical criteria for delineation are still evolving, these efforts are increasingly guided by science-based and hydrogeologically grounded methods. Drawing on international experience can, however, help strengthen both the scientific foundation and policy implementation of this work, particularly through the following insights:

- Delineation should prioritise aquifers with ecological and socio-economic importance, not just those with high yield or recharge. As shown in the EU and Denmark, aquifers that support baseflow, wetlands, or urban water supply require targeted protection even if they are not the most productive in volumetric terms.
- Vulnerability to contamination and land-use pressure must inform zoning strategies. Integrated vulnerability mapping, as applied in Denmark and Western Australia, strengthens the defensibility and effectiveness of land-use restrictions.
- Implementing a tiered protection framework allows for flexible, site-specific management that balances development needs with aquifer sensitivity. Denmark's approach demonstrates how zoning, linked to actual and potential pollution risks, can be spatially refined and socially negotiated.
- Formal legal designation is critical to ensure long-term enforcement. Poland and Namibia both illustrate how legal recognition provides the foundation for monitoring, regulation, and public accountability.
- Finally, delineation must be science-based and adaptive. The EU, Zimbabwe, and the United States highlight the importance of dynamic boundaries that can evolve with new data, allowing for continuous improvement and better alignment with on-the-ground realities.

Taken together, these insights offer a valuable roadmap for refining the identification and governance of South Africa's SWSA-gw. Building on current momentum, incorporating international best practices, especially those emphasising vulnerability, land-use compatibility, and legal designation, will strengthen the long-term resilience of the country's groundwater resources.

2.2.3. Envisioned Role of SWSA-gw

Legal Recognition and Formal Protection

SWSA-gw should be formally recognised and designated as protected areas under the National Water Act, through their inclusion in the proposed National Water Amendment Bill of 2023. The Bill introduces a formal definition of water source areas as land and aquifers that contribute significantly to the national water supply, thereby enabling their legal designation, protection, and long-term enforcement. Such recognition would empower the DWS to regulate land and water use within these areas, enforce compliance, and prioritise ongoing monitoring, rehabilitation, and investment.

Integration into National Planning Frameworks

The incorporation of SWSA-gw into the NWRS will enable their identification as priority areas for protection, investment, and management. This supports the implementation of key strategic objectives outlined in NWRS III, including the legal designation and rehabilitation of SWSA, integration of protection measures into water resource classification and licensing processes, and the strengthening of ecological infrastructure essential to long-term water security. Embedding SWSA-gw into national planning frameworks will also enhance alignment of monitoring, governance, and resource allocation with broader water security and climate resilience goals.

Spatial Planning and Policy Alignment Across Sectors

SWSA-gw should be incorporated into national and provincial spatial planning instruments to ensure coherence across sectors such as water, land use, agriculture, and biodiversity conservation. Recommendations by Le Maitre et al. (2018) remain relevant, including the integration of SWSA-gw into biodiversity planning tools (e.g., Critical Biodiversity Areas), the prioritisation of recharge zone protection, and the restriction of land uses that may compromise groundwater quality or availability. These areas can also serve as spatial triggers for the deployment of monitoring infrastructure, pollution control interventions, and climate adaptation strategies. Intergovernmental collaboration should be strengthened, particularly around shared aquifer systems and transboundary recharge zones, to support integrated and effective governance.

2.2.4. Proposed Definition of SWSA for Groundwater

Building on previous definitions, the international examples and envisaged role of SWSA-gw, the following definition is proposed:

> *SWSA-gw are aquifers (geological bodies capable of holding and transmitting water) that can naturally supply disproportionately large volumes of groundwater per unit area and are considered of national strategic significance for water security, socio-economic development and sustainability.*

This definition builds on earlier work (Le Maitre et al., 2018; RSA, 2023) and reflects the shift toward recognising the national importance of aquifer systems in terms of both yield and strategic significance for water security and sustainability. It is aligned with the proposed 2023 amendment to the National Water Act, which formally includes aquifers as part of SWSA to be protected.

2.3. Drivers for Methodological Refinement

2.3.1. Previous Methodology

The national delineation of Strategic Water Source Areas for Groundwater (SWSA-gw), developed by Le Maitre et al. (2018), represented a key advancement in recognising the importance of groundwater to South Africa's long-term water security (see **Table 2-1**). It built on the earlier work of Nel et al. (2013) and introduced a methodology for identifying and delineating groundwater-specific components based on areas of high recharge and strategic groundwater use. At its core, the methodology is structured around two interdependent components (see **Figure 2-1**):

1. **The Spatial Framework**

   The Spatial Framework provided the national-scale geospatial foundation for assessment. It established a consistent structure for evaluating key hydrogeological datasets. A uniform 1 km × 1 km grid was applied as the standard resolution for all input datasets. This reduced spatial bias by avoiding alignment with catchment or administrative boundaries and enabled the identification of local-scale, though still coarse, groundwater "hotspots" based on observed data patterns. It also supported consistent threshold application and allowed for national comparability.

2. **The Evaluation Framework**

   The Evaluation Framework guided the assessment of groundwater availability and strategic use. It introduced a set of quantitative criteria to evaluate each grid cell and determine its inclusion in the final delineation. Each cell was assessed against five criteria: 1) Absolute Recharge, 2) Relative Recharge, 3) Licensed Use, 4) Domestic Supply Dependence and 5) Strategic and Future Use. Thresholds were tested for each criterion, and cells meeting at least three out of five were retained. The final delineation of SWSA-gw was completed in GIS using overlays of the binary outputs, which were interpreted to define continuous polygons.

Summary of the workflow for each of the 5 criteria (see Table 2-2):

- **Absolute Recharge:** National recharge (mm/a) was mapped at 1 km × 1 km resolution using the Groundwater Resource Assessment II (GRAII) dataset. A threshold of ≥65 mm/a, representing approximately 50% of the national recharge volume, was applied to retain higher-recharge grid cells.
- **Relative Recharge:** Recharge values were assessed relative to their secondary catchment means. A recharge ratio (grid cell value/catchment average) was calculated, and cells with ratios ≥1.5 were retained as local recharge hotspots.
- **Licensed Use:** Abstraction volumes from Water Use Authorisation & Registration Management System (WARMS) were converted to flow rates (l/s) and aggregated per km^2. A kernel density function was used to estimate use intensity across the 1 km^2 grid. Cells with rates ≥0.3 l/s/km^2 were retained.
- **Domestic Supply Dependence:** Towns relying on groundwater for over 50% of municipal supply (from the All Towns Studies) were identified. A 10 km buffer was applied around each town, and all intersecting grid cells were retained.
- **Strategic and Future Use**: Strategic economic zones and growth areas were sourced from the NWRS II (2013). Where available, aquifer model boundaries defined spatial extent; otherwise, a 10 km buffer or expert-defined zone was used. All intersecting grid cells were retained, as well as all Subterranean Government Water Control Areas (SGWCA).

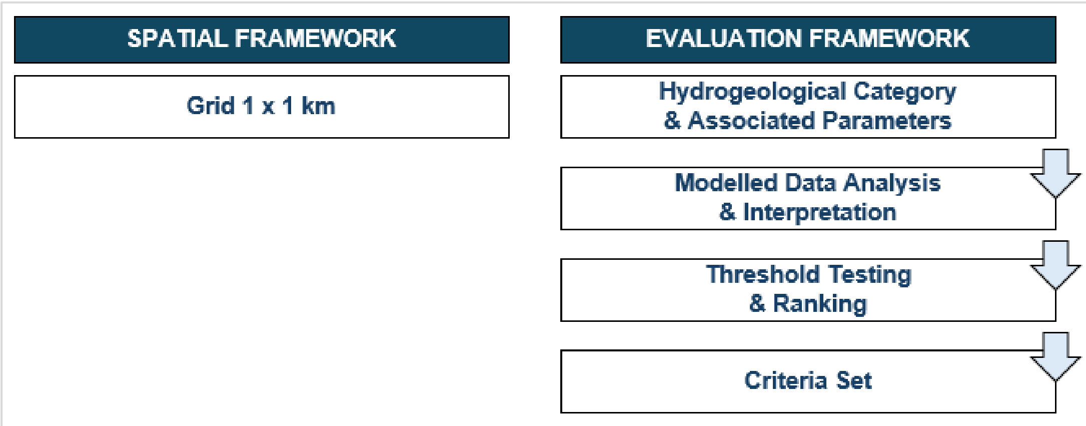


Figure 2-1 **Overview of the 2018 SWSA-gw methodology, featuring a uniform 1 km × 1 km Spatial Framework and a stepwise Evaluation Framework using hydrogeological data and criteria to identify strategic groundwater areas.**

Table 2-2 **Summary of the criteria and thresholds used by Le Maitre et al. (2018) to identify SWSA-gw.**

Category	**Recharge (Groundwater Availability)**		**Groundwater Use (Strategic Significance)**		
Sub-Category	**Absolute Recharge**	**Relative Recharge**	**Licenced Use**	**Domestic Supply**	**Strategic & Future Use**
Modelled Data	GRAII Recharge (mm/a/km^2)	Mean Recharge per Secondary Catchment (mm/a/km^2)	WARMS	DWS All Towns	NWRS II (2013) & SGWCA
Analysis	Determined the recharge rate that contributes approximately 50% of the national recharge volume	Recharge per Grid Cell vs Catchment Mean	Converted licensed volumes (m^3/a) to a flow rate (l/s) and then used a Kernel Density Function to estimate l/s/km^2.	Towns with > 50% Groundwater were considered Sole Supply towns.	26 Areas of National Economic Significance listed in NWRS II
Threshold Tested	1. > 150 2. >= 100 3. >= 65 4. >= 35	1. 1.0 (at least catchment average) 2. 1.5 (>= 150% of catchment average) 3. 2.0 (>= 200% of catchment average) 4. 2.5 (>= 250% of catchment average)	1. 0.1 l/s/km^2 2. 0.3 l/s/km^2 3. 0.5 l/s/km^2	1. Buffer 10 km Radius	1. If Aquifer Model Boundary Exists 2. If no Aquifer Boundary, Buffer Town with 10 km Radius 3. If a 10 km Buffer was deemed insufficient, then SGWCA was taken
Criteria	**Recharge**	**Recharge Ratio**	**Licenced use**	**None**	**None**
	>= 65 mm/a/km^2	**1.5**	**0.3 l/s/km^2**	**(i.e. all areas included)**	**(i.e. all areas included)**

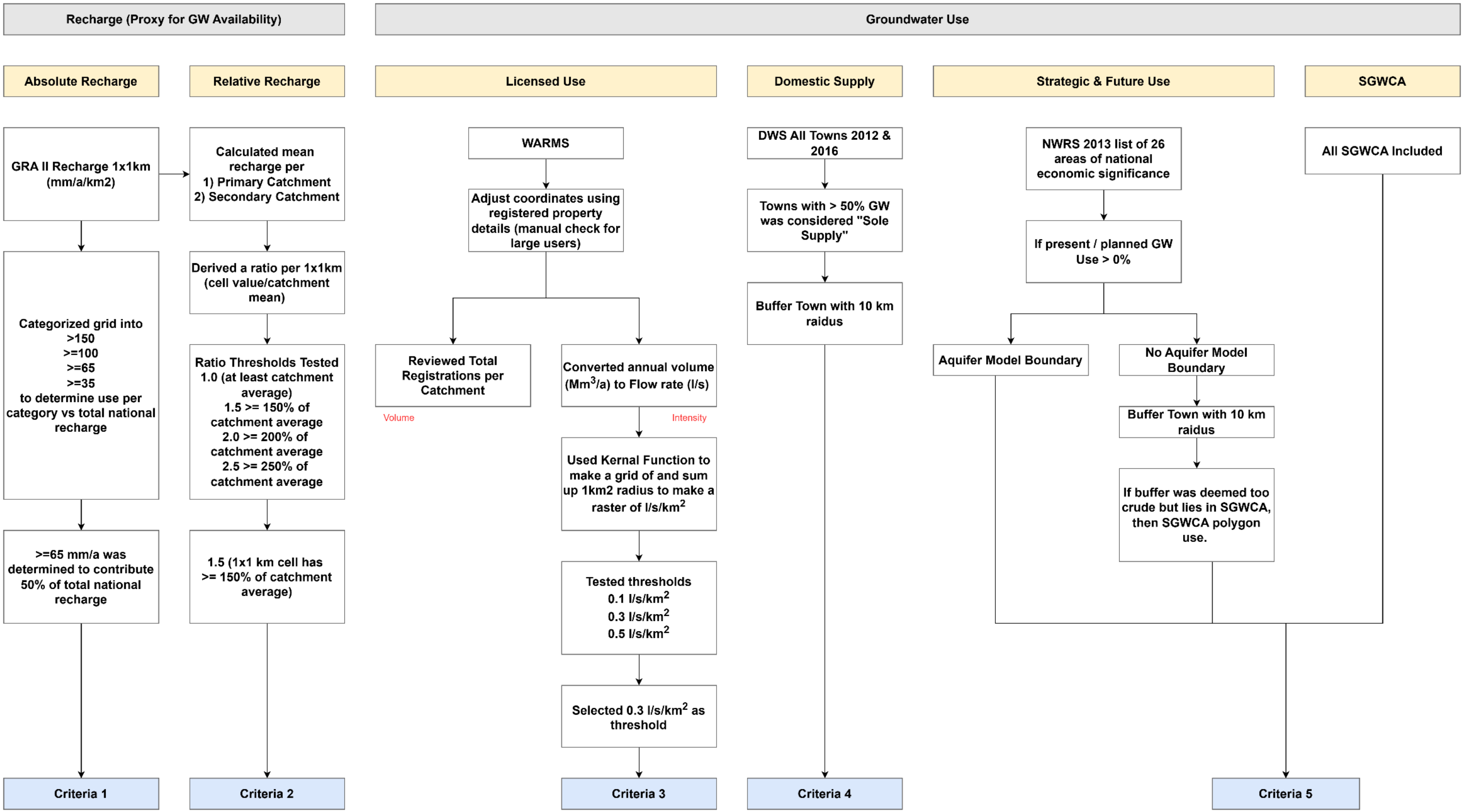


Figure 2-2 Visual representation of the Le Maitre et al. (2018) methodology.

2.3.2. Limitations of the 2018 Methodology

1. **Recharge as a Proxy for Groundwater Availability**

   Although the 2018 report (Le Maitre et al., 2018) acknowledged that recharge is not equivalent to sustainable yield, it was considered broadly proportional to natural discharge and therefore acceptable as a proxy for groundwater availability for national-scale assessment. The recharge layer (from GRAII; DWAF, 2006a; DWAF, 2006b), which was later carried through in the delineation of SWSA-gw by Le Maitre et al. (2018), served as the primary indicator of groundwater availability in the methodology. While the GRAII recharge dataset provided national coverage, several important limitations need to be noted:

   a. Recharge values were modelled at a 1 km x 1 km grid resolution, then aggregated to the quaternary catchment scale. This process masked fine-scale spatial variability, limiting its suitability for more detailed resource assessments.

   b. Groundwater recharge shows significant temporal variation, particularly in more arid regions. The dataset reflected mean annual recharge, which does not imply that recharge occurred consistently each year and does not account for intra-catchment heterogeneity, such as differences in geomorphology, soils, or hydrogeological conditions.

   c. Important recharge controls, such as rainfall intensity and duration, were not incorporated into the modelling approach.

   d. Recharge alone doesn’t fully represent groundwater availability, which is also influenced by factors like storage, baseflow, and yield.

2. **Influence of Recharge Classification**

   A key limitation of the 2018 SWSA-gw methodology was the strong influence of spatial grouping (e.g. quaternary vs. secondary catchments) on the identification of relative recharge “hotspots”.

   The approach applied a relative recharge ratio, comparing each 1 km² grid cell’s recharge to the average of its surrounding hydrological unit. However, the choice of grouping defined the spatial context, meaning the same grid cell could be classified differently depending on the unit used, as shown in **Figure 2-3**. This introduced sensitivity to the scale of analysis and affected the consistency of delineated SWSA-gw areas.

3. **Threshold Selection**

   The selection of “65 mm/a” as the recharge threshold was based on the “half-of-the-resource” principle, intended to align with the surface water SWSA threshold of “135 mm/a” MAR. While this offers conceptual symmetry between surface and groundwater designations, the selection may not reflect functional groundwater system boundaries.

4. **Baseflow Contributions**

   Although baseflow is referenced in Le Maitre et al. (2018) as a key ecosystem function supported by groundwater, it was not explicitly included as a criterion in the delineation of SWSA-gw. As a result, areas important for sustaining baseflow, particularly in ecologically sensitive or seasonally dry catchments, may not have been fully captured.

5. **Groundwater Use as a Proxy for Availability and Strategic Importance**

   Groundwater use was used inconsistently in the 2018 methodology, serving both as an indicator of aquifer productivity (availability) and of strategic significance. The underlying assumption was that high abstraction volumes indicate either productive aquifers or areas of national importance. However:

   a. High abstraction may reflect a lack of alternative water sources, not necessarily high aquifer yield.

   b. High use does not inherently indicate strategic significance, as it lacks validation through independent economic or social indicators.

   c. The WARMS database, which underpinned this analysis, is known to have spatial inaccuracies, under-reporting, and mismatches between licensed and actual use.

   These limitations reduce the reliability of abstraction data as a meaningful proxy for either aquifer potential or strategic importance.

6. **Groundwater Use Density as an indication of Strategic Significance**

   Groundwater use density was also interpreted as a proxy for strategic importance, with higher abstraction volumes assumed to indicate areas of higher national relevance. However, this assumption may not hold true in all contexts and was not supported by an independent measure of economic or social value.

7. **Interpolation Using Kernel Density Function**

   The use of a kernel density function to interpolate groundwater abstraction introduced additional uncertainty. This method creates smoothed, interpolated surfaces, even in areas without original data, and tends to generate artificial circular patterns. These artefacts were carried through into the delineation process, potentially skewing the spatial extent of identified use areas (See **Figure 2-3**).

8. **Buffering with no link to hydrogeological Units**

   For towns where more than 50% of the water supply comes from groundwater, a 10 km circular buffer was applied to represent groundwater dependence zones. In the absence of aquifer model boundaries, this method introduced significant generalisation, as it was not linked to actual hydrogeological units or aquifer extents. Similarly, areas designated as SGWCAs were buffered or interpolated without a consistent geological justification (See **Figure 2-3**).

9. **Methods of Boundary Delineation**

   The final SWSA-gw polygons were delineated manually based on overlays of binary raster layers representing the five criteria (recharge, abstraction, and groundwater dependence). These included interpolated surfaces (e.g., kernel density outputs) and buffered zones around towns or SGWCA areas. Where possible, boundaries followed known surface geology or lithostratigraphic contacts. In other cases, boundaries were smoothed or interpolated to create coherent zones.

   This semi-manual process introduced subjectivity and potential inconsistency, especially in areas with limited data or mismatched proxies. The stacking of interpolated and buffered layers, some derived from uncertain or inconsistent datasets, may have resulted in delineations that did not reflect actual aquifer behaviour or hydrogeological boundaries.

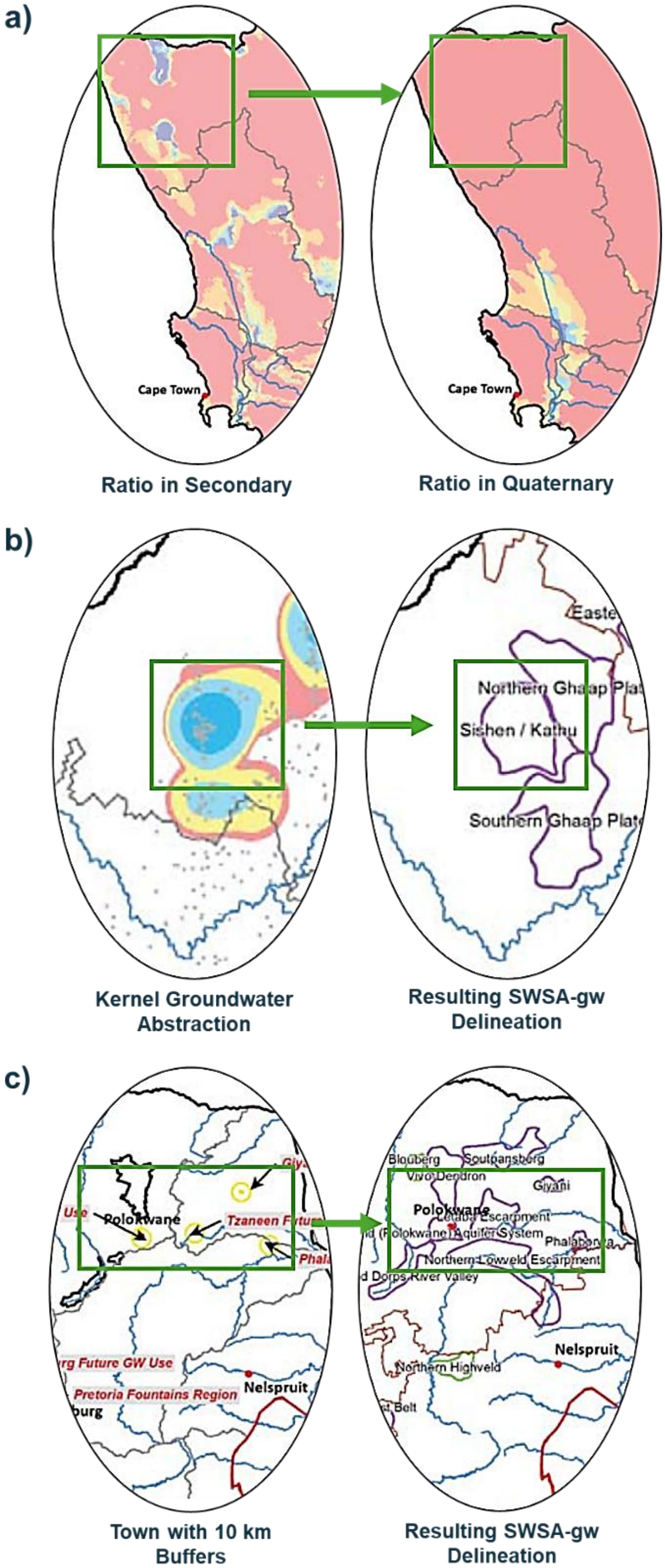


Figure 2-3 **Examples of methodological artefacts affecting SWSA-gw delineation. a) Spatial grouping affects relative recharge classification; the same area appears as high-recharge under quaternary but not secondary grouping, b) Kernel density interpolation introduces circular abstraction artefacts, carried into use area delineations (e.g. near Sishen/Kathu) and c) Generic buffers around towns with >50% groundwater use led to unnaturally rounded SWSA-gw boundaries in Giyani, Phalaborwa, and the Polokwane Aquifer System (after Le Maitre et al., 2018).**

3. REFINED METHODOLOGICAL FRAMEWORK

3.1. Overview and Rationale

The identification and delineation of Strategic Water Source Areas for Groundwater (SWSA-gw) in South Africa requires the integration of diverse geospatial and hydrogeological datasets, each varying in scale, resolution, format, and thematic focus. These datasets (described in **Section 3.3**) include raster layers (e.g., recharge grids), vector features (e.g., aquifer extents), and point-based records (e.g., boreholes and registered abstraction volumes). In addition to their spatial form, inputs also vary in data structure, encompassing continuous variables (e.g., recharge in mm/a), categorical classes (e.g., aquifer types such as major, minor, or poor), and binary indicators (e.g., boreholes and registered abstraction volumes above a specified threshold).

These differences introduce substantial analytical complexity, particularly when assessing and comparing areas across contrasting hydrogeological, climatic, and socio-economic settings. To address this complexity, the Refined Methodology adopts a Multi-Criteria Decision Analysis (MCDA) framework. MCDA provides a structured, transparent, and reproducible basis for spatial decision-making, particularly where multiple and potentially conflicting criteria must be evaluated simultaneously (Tecle & Duckstein, 1994). It enables the harmonisation of heterogeneous datasets through processes of normalisation, weighting (based on empirical or expert-derived inputs), and aggregation into composite indicators. These indicators, in turn, support the ranking, classification, and prioritisation of areas of strategic groundwater importance.

MCDA is widely applied in international water resource assessments and is increasingly utilised in the South African groundwater sector. A growing body of local applications (including national, regional, and municipal-scale studies) has demonstrated its flexibility, scalability, and relevance to groundwater planning (Pietersen, 2006; DWA, 2009; Zhang et al., 2019; Ponnusamy et al., 2022; Zenande et al., 2024; Vandala & Mahed, 2025). Collectively, these studies reinforce MCDA's role as a tested framework capable of aligning data-driven assessments with national planning and policy objectives. Its use in this methodology ensures that the assessment process remains defensible, repeatable, and aligned with the Terms of Reference (ToR) (**Section 1.2**) and relevant policy guidance (**Section 2**).

3.2. Building on Existing Frameworks

The Refined Methodology builds on the national-scale approach developed by Le Maitre et al. (2018), with structural enhancements introduced to improve spatial resolution, analytical consistency, and strategic relevance. At its core, the methodology is structured around the same two base components presented previously (see **Section 2.3.1** and **Figure 3-1** below):

1. **An Enhanced Spatial Framework**

   The Spatial Framework establishes the geospatial foundation for the assessment. It defines the geographic and hydrogeological context in which groundwater areas are evaluated and delineated. This framework provides a spatial structure based on aquifer-specific Groundwater Resource Units (GRUs), enabling consistent comparison and analysis across South Africa's diverse hydrogeological environments.

2. **An Enhanced Evaluation Framework**

   The Evaluation Framework guides the interpretation of input data and the prioritisation of GRUs as potential SWSA-gw. It introduces a structured process for assessing strategic groundwater significance, incorporating a range of hydrogeological and socio-economic indicators. The framework supports objective comparison of datasets and their application to the enhanced spatial framework.

The specific refinements made to each of these frameworks, as well as the underlying datasets used, are described in **Section 3.3**.

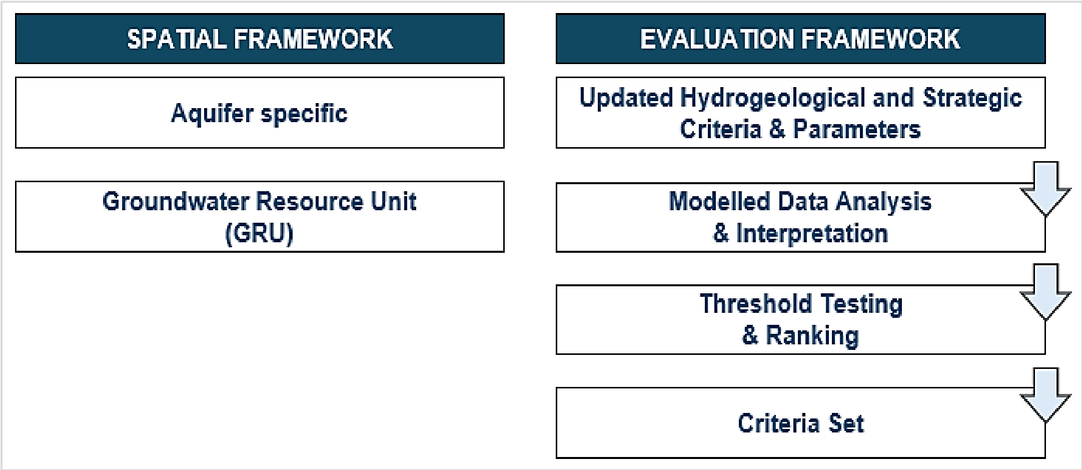


Figure 3-1 **Overview of the two core components of the Refined Methodology: the Enhanced Spatial Framework (left), structured around aquifer-specific GRUs, and the Enhanced Evaluation Framework (right), which applies updated criteria, data analysis, and threshold testing to identify and delineate SWSA-gw.**

3.3. Framework Refinement & Datasets

The refined methodology builds on the national framework developed by Le Maitre et al. (2018) (see **Section 2.3.1**), which provided an important baseline for identifying and delineating SWSA-gw. While that approach offered a consistent and nationally comparable assessment, its application revealed several areas where refinement was needed to strengthen its practical utility for groundwater planning and management.

In particular, improvements were needed in the spatial representation of groundwater systems, the range of parameters used to assess groundwater value, and the integration of socio-economic and policy dimensions relevant to strategic groundwater resources. These refinements aim to enhance both the thematic accuracy and analytical consistency of the framework, ensuring that it can support defensible, evidence-based decision-making.

The updated approach continues to rely on nationally available datasets but incorporates an updated set of parameters alongside revised analytical techniques. Where necessary, spatial processing methods such as downscaling, disaggregation, and composite indicators have been applied to ensure compatibility and consistency across datasets (described in detail in **Section 3.3.1** and **Section3.3.2**).

By introducing these refinements, the methodology maintains the national comparability of the original framework while providing greater hydrogeological and strategic relevance. This ensures that the outputs remain credible for high-level policy planning while also being meaningful for more detailed, aquifer-scale resource management.

Sections 3.3.1 and **3.3.2** describe these refinements in detail, outlining the updates made to the Spatial Framework and Evaluation Framework, respectively. Each section explains not only the datasets and methodological changes applied but also the rationale for these refinements, ensuring that the conceptual basis for each update is clearly articulated.

While the methodology generates aquifer-specific outputs, these should be regarded as indicative at a national scale. Their application in local or site-specific decision-making requires further validation with site-specific and higher-resolution datasets, local expertise, and ground-truthing to ensure robustness.

3.3.1. Enhancement of Spatial Framework

Identifying and delineating SWSA-gw requires a spatial framework that is both nationally consistent and hydrogeologically meaningful. In the original 2018 national study (Le Maitre et al., 2018), a 1 × 1 km grid was adopted as the primary analytical structure. This decision was largely driven by the format of the GRAII Recharge dataset (DWAF, 2006a; DWAF, 2006b), which at the time was the only nationally available, long-term dataset of estimated groundwater recharge. While recharge is not a direct measure of sustainable yield, it was used as a proxy for groundwater availability and served as one of the core criteria for identifying potential SWSA-gw.

To enable consistent comparison and integration across multiple datasets, other key inputs such as relative recharge (calculated within secondary catchments), licensed groundwater use (based on WARMS volumes), domestic supply dependence, and strategic or future use (e.g. groundwater reliance of towns, villages, and irrigation schemes) were all rasterised or spatially aggregated to this 1 × 1 km grid. This ensured compatibility across different data types and allowed the indicators to be overlaid and assessed uniformly at the national scale (see **Section 2.3.1** and **Figure 2-1**).

While this structure served its purpose as a first-generation national screening tool for SWSA-gw, it introduced several important limitations when viewed through a hydrogeological lens.

1. **Hydrogeological misalignment**

   The 1 × 1 km grid, although effective for standardising and aggregating diverse datasets, was not inherently tied to aquifer boundaries, hydrostratigraphic units, or groundwater flow systems. With the exception of 26 Areas of National Significance, where known aquifer boundaries were applied after areas of high recharge and groundwater use were identified, the framework lacked a direct connection to geological or hydrogeological structures. Outside of these areas, the grid-based delineation remained spatially arbitrary, limiting its utility for aquifer-scale interpretation.

2. **Surface water bias**

   The framework aligned more closely with surface water planning units (e.g. quaternary and secondary catchments), which are designed for surface runoff processes rather than subsurface flow. This made it difficult to represent groundwater systems that span catchment divides or behave independently of topography. Grid cells, in isolation, do not adequately reflect groundwater flow paths, hydrostratigraphic variability, or the natural geometry of aquifer systems.

3. **Loss of thematic resolution and spatial flexibility**

   The exclusive use of a uniform grid, without anchoring it to a hydrogeological framework, limited the ability to reflect local-scale heterogeneity, particularly in complex geological terrains where groundwater conditions can vary significantly over short distances. While several hydrogeological datasets (such as geology, aquifer type, and yield class) were reviewed as part of the analysis, they were not used to structure the delineation or define base spatial units. Instead, these layers were assessed in parallel or used to inform threshold selection but were not spatially integrated into the core delineation framework. Outside of the 26 Areas of National Significance, where known aquifer boundaries were applied, the delineation remained decoupled from the structure and function of the underlying aquifers.

4. **Hybrid spatial logic**

   Although the 1 × 1 km grid formed the main analytical base in the 2018 study, some indicators, particularly Relative Recharge, were assessed using secondary catchments as the reference unit. This introduced a “hybrid” spatial logic where both gridded and catchment-based components influenced evaluation. While this helped contextualise regional patterns, it also complicated interpretation at the aquifer scale, as neither unit was directly aligned with the natural geometry of groundwater systems.

Transition to the Enhanced Spatial Framework

Recognising the spatial limitations of the 2018 approach, the refined methodology introduces a new spatial framework that integrates updated climatic inputs, higher-resolution raster layers, and aquifer-specific hydrogeological boundaries to improve the delineation of SWSA-gw.

A key development underpinning this transition was the 2021 national refinement of surface water Strategic Water Source Areas (SWSA-sw) by Lötter and Le Maitre (2021), which introduced a 90 × 90 m spatial resolution based on a downscaled mean annual precipitation (MAP) surface. The MAP layer was developed using a MAP surface by Lynch (2004) as well as data from more than 12,000 rainfall stations, combined with regression-based topographic modelling, and significantly improved the spatial representation of rainfall across South Africa. Although this refinement focused on surface water, the study explicitly recognised important groundwater–surface water interactions (particularly where groundwater sustains baseflow or supports groundwater-dependent ecosystems [GDEs]) and recommended the refined MAP layer as a foundational dataset for future SWSA delineation work.

Groundwater recharge is fundamentally driven by precipitation. In the original 2018 study, recharge (as derived from the GRAII dataset) was used as a broad proxy for groundwater availability. The GRAII model itself used MAP as a core climatic input, among other factors. However, rather than remodelling recharge from first principles, the refined methodology applies GRAII-based recharge-to-MAP ratios to the updated MAP surface from Lötter and Le Maitre (2021). This enables recharge to be estimated at 90 × 90 m resolution, providing a spatially refined input layer within the broader groundwater assessment.

In contrast to the 2018 approach, where recharge served as a standalone proxy for groundwater availability, the refined methodology constructs a dedicated groundwater availability dataset by integrating multiple hydrological and geological parameters. Baseflow is derived from the updated recharge estimates using baseflow ratios obtained from the original GRAII recharge–baseflow relationships, applied consistently across the updated MAP grid. This, in combination with additional layers such as potential yield and aquifer storage capacity, forms a composite dataset that more directly represents groundwater availability. This layer can now be used as a primary input, rather than relying on recharge alone as a proxy. When linked to geology and aquifer type maps, this composite layer supports the delineation of aquifer-specific GRUs.

In the context of this study, GRUs are defined as spatial units that represent coherent aquifer domains based on groundwater availability and other hydrogeologic features. They are delineated at a scale of 1:250 000, based on hydrostratigraphic and geological boundaries, and serve as the primary spatial units for groundwater assessment within this methodology. Input datasets can then be aggregated to align with GRU boundaries, depending on their resolution and data structure. Where resampling is not appropriate, layers are retained at their native scale and integrated transparently, with treatment details documented.

This refined spatial architecture retains the national comparability of the original framework, while improving its hydrogeological relevance and spatial fidelity. By combining updated MAP-derived inputs with aquifer-specific GRUs, the methodology allows for improved interpretation of groundwater conditions at both local and national levels, supporting more effective groundwater planning, resource protection, and strategic decision-making.

The details of this workflow are described further in **Section 3.4**.

Table 3-1 Input datasets used in the Refined Methodology, summarising key groundwater availability and hydrogeological parameters, including dataset sources, resolution, and descriptions relevant to composite layer development and spatial analysis.

Dataset Category	Parameter	Datasets Used for Composites / Masks	Working Resolution*	Source	Description (how used in this report)
Groundwater Availability	**Recharge**	Downscaled MAP surface; GRAII recharge surface (for calibration via refined Recharge : MAP ratios); WR2012 MAP (long-term reference)	90 × 90 m (working); 1 × 1 km (calibration)	Lötter & Le Maitre (2021); DWAF/DWS GRAII (2006); MAP from WR2012 or Lynch (2004)	90 m recharge surface derived from MAP using refined Recharge : MAP relationships; preserves hydrological consistency and national comparability. Forms Set A in the composite.
	Baseflow	Derived from recharge using established recharge–baseflow relationships applied to the 90 m recharge surface	90 × 90 m	Derived in this study from above	Provides a discharge-oriented complement to recharge; reclassified to common 5-class scale and combined with Recharge in Set A.
	Storage Capacity	Lithostratigraphic classes mapped to storage indices; aquifer type & storativity ranges	90 × 90 m (rasterised from vectors)	CGS 1:250k geology; DWS 1:500k Hydrogeological Map Series; NGA (selected attributes)	Vector sources rasterised to 90 m and reclassified to a 5-class storage index; combined with Potential Yield in Set B.
	Potential Yield	Expected Borehole Yield classes (disaggregated to 1:250k geology); Groundwater Exploitation Potential (UGEP/PGEP)	90 × 90 m (disaggregated); 1 × 1 km (GRAII)	DWS Hydrogeological Map Series (1:500k); DWAF/DWS GRAII (2006)	Yield classes from hydro maps are disaggregated using CGS geology to improve spatial fidelity; merged with GEP to produce a 5-class potential-yield surface (Set B).
Hydrogeological Overlays	**Geology (bedrock/lithology)**	National geological polygons	1:250k (vector; rasterised to 90 m as needed)	Council for Geoscience (CGS) 1:250k & SADC/IGRAC (2020) Transboundary Dataset	Base framework for aquifer segmentation, yield disaggregation, and structural interpretation.
	Aquifer Type & Extent	Aquifer type, expected yield classes, hydrogeological boundaries	1:500k (vector)	DWS Hydrogeological Map Series & SADC/IGRAC (2020) Transboundary Dataset	Provides aquifer system context; intersected with suitability mask from Part 1 to delineate GRUs.
	Faults / Structural Features	Faults, lineaments	1:250k (vector)	CGS 1:250k	Used as ancillary interpretation for aquifer connectivity and potential preferential flow; informs GRU boundary QC.
	Spatial Framework Grids	90 m national grid; 1 km legacy grid (for comparability); aquifer grid	90 × 90 m; 1 × 1 km	Derived in this study (from MAP base and aquifer masks)	Working grids for raster analysis and cross-scale checks; 90 m is the analysis grid; 1 km used for benchmarking and traceability.

3.3.2. Enhancement of the Evaluation Framework

Identifying SWSA-gw requires not only a Spatial Framework that reflects aquifer-specific boundaries, but also an Evaluation Framework capable of capturing the multiple hydrological, ecological, and strategic roles that groundwater plays across South Africa. The Evaluation Framework provides this analytical structure, supporting the assessment and prioritisation of areas based on both groundwater availability and strategic significance.

In the original 2018 study (Le Maitre et al., 2018), five binary indicators were applied to each 1 × 1 km grid cell, including 1) Absolute Recharge, 2) Relative Recharge, 3) Licensed Use, 4) Domestic Supply Dependence, and 5) Strategic/Future Use (see **Section 2.3.1**). These were overlaid spatially, and grid cells meeting three or more criteria were flagged as candidate SWSA-gw. While this approach facilitated consistent national application, it introduced several limitations that constrained the method's analytical depth and hydrogeological sensitivity.

1. **Reliance on Recharge Alone as a Proxy**

   Groundwater availability was assessed using recharge estimates from the GRAII dataset, which the original study acknowledged as a proxy rather than a direct measure of sustainable yield. This limited the assessment's ability to reflect the functional behaviour of aquifer systems, as other important parameters such as baseflow, aquifer storage, or yield potential were not incorporated into the evaluation.

   While baseflow was discussed in the 2018 report as a key groundwater function, particularly for supporting river systems and GDEs, it was not used as a discrete evaluation criterion. This omission potentially excluded areas of ecological importance or groundwater–surface water connectivity from being identified as strategic.

2. **Sensitivity to Spatial Units and Thresholds**

   The Relative Recharge indicator was calculated as a ratio between grid cell recharge and the mean recharge of its associated secondary catchment. Although this approach helped identify local recharge 'hotspots', it introduced spatial inconsistencies, as outcomes varied significantly depending on the catchment unit used. The report itself noted that results differed when using quaternary or primary catchments, highlighting the method's sensitivity to the selected spatial frame.

   Additionally, the threshold for Absolute Recharge (≥65 mm/a) was conceptually aligned with the "half-the-resource" principle used in surface water delineation. However, this threshold was not based on empirical hydrogeological criteria, potentially leading to the exclusion of aquifers with lower recharge but high storage or yield capacity.

3. **Binary Scoring and Lack of Flexibility**

   Each indicator was applied using a fixed binary threshold (either included or excluded), which limited the framework's sensitivity to gradation and masked important transitional zones. Moreover, the framework did not include provisions for future expansion or adjustment of criteria, despite the evolving policy and climate contexts that influence groundwater management.

   Some indicators, such as Licensed Use and Strategic/Future Use, were generalised at a national scale and decoupled from underlying hydrogeological units. For instance, a 10 km buffer was applied around towns with high groundwater reliance, regardless of aquifer extent or geometry. Only in the 26 Areas of National Significance were aquifer boundaries explicitly used to delineate SWSA-gw zones; elsewhere, delineation remained grid or buffer-based and spatially arbitrary.

Transition to the Enhanced Evaluation Framework

The refined methodology addresses the limitations of the 2018 approach by introducing a more structured, transparent, and hydrogeologically grounded Evaluation Framework. It expands the suite of input parameters, refines the classification logic, and adopts a Multi-Criteria Decision Analysis (MCDA) approach to integrate, weight, and rank indicators (see **Section 3.4**). Importantly, all evaluation outputs are now aligned with the aquifer-specific GRUs introduced in **Section 3.3.1**. This alignment ensures that the analysis reflects the geometry and function of real aquifer systems, thereby improving its interpretability and decision-making value for groundwater planning and protection.

1. **Groundwater Availability: A Composite Approach**

   In contrast to the 2018 methodology, which relied on recharge alone as a proxy for groundwater availability, the refined framework introduces a dedicated composite dataset that more accurately represents the hydrological and geological components of groundwater systems. Recharge remains a core input but is now modelled using updated 90 × 90 m resolution MAP surfaces derived from downscaled national precipitation data. From this, baseflow is estimated using GRAII-derived recharge–baseflow ratios applied directly to the refined recharge grid. This allows for the spatial representation of baseflow contributions, particularly important in sustaining ecological flows and GDEs. In addition, the evaluation incorporates aquifer storage and potential yield, drawing from national groundwater datasets and expert-reviewed classifications. Together, these components form a groundwater availability composite that more realistically captures the physical functioning and resource potential of aquifer systems. This composite is used as a core evaluation input, replacing the former reliance on recharge as a singular proxy.

2. **Strategic Significance: Expanded and Thematically Structured**

   The refined Evaluation Framework also introduces a broader and thematically structured suite of indicators that reflect the strategic significance of groundwater. These parameters are grouped into five key themes: 1) Current Demand, 2) Socio-Economic and Development Context, 3) Governance and Policy Alignment, 4) Environmental and Ecological Significance, and 5) Additional Considerations related to resource condition and future use.

   Under current demand, the framework assesses licensed groundwater use (from WARMS), domestic sole supply areas, and the level of groundwater dependence within settlements and sectors. The socio-economic theme includes economic importance, water services backlog, and the identification of strategic or future use zones such as irrigation schemes or development nodes, including Special Economic Zones (SEZs). Governance alignment considers areas designated as Subterranean Government Water Control Areas (SGWCAs), as well as obligations under international water treaties, particularly where transboundary aquifers are present. Environmental significance is assessed through the presence of GDEs and ecologically sensitive sites or wetlands. Finally, additional considerations account for aquifer status (e.g., stressed or over-allocated systems), groundwater quality (including both natural groundwater quality and fitness-for-use), and the potential for artificial recharge or the use of groundwater as a climate adaptation measure.

   Each indicator has been reviewed, updated, and in cases of incomplete national coverage, supplemented through proxy modelling techniques. Where appropriate, indicators were resampled or disaggregated to align with the spatial resolution of the GRUs. Classification thresholds were informed by statistical methods such as quantile breaks, natural breaks (Jenks), or standard deviation intervals, reducing subjectivity and ensuring interpretability across diverse hydrogeological contexts.

The details of this workflow are described further in **Section 3.4**.

Table 3-2 Input datasets used in the Refined Methodology, summarising key Strategic Significance & Additional Considerations parameters, including dataset sources, resolution, and descriptions relevant to composite layer development and spatial analysis.

Dataset Category	Parameter	Datasets Used for Composites	Working Resolution*	Source	Description (how used in this report)
Strategic Significance	Current Demand	Groundwater Use	Points/schemes 90 m grid; GRU summary	DWS WARMS (latest version: licensed volumes, sector)	Baseline of lawful abstraction by purpose/volume; cleaned, normalised to 90 m (no KDE), summarised per GRU for MCDA.
		Level of Dependence	Settlement polygons 90 m; GRU summary	DWS Water-Dependent Towns; CSIR Green Book (Settlement Water Source, population)	Proportion of total supply from groundwater at settlement/municipal scale; upweights GRUs with higher reliance.
		Domestic Sole Supply	Settlement/town features GRU flag	DWS (2024); CSIR Green Book 2022	Binary flag for towns predominantly supplied by groundwater; rolled up as a reliance indicator.
	Socio-Economic & Development Context	Economic Importance	Town/settlement polygons 90 m; GRU summary	NSDP (2006) ; Total GVA for groundwater & conjunctive-use settlements	Flags nodes where groundwater supports nationally important economic activity/value.
		Water Services Backlog	Small-area / ward/settlement 90 m	Stats SA Census 2022 (water access/backlog)	Highlights unmet domestic water needs that increase the strategic role of groundwater.
		Strategic & Future Use Zones	National polygons 90 m	DWS (2023) NWRS III priority zones; development nodes/irrigation schemes	Identifies nationally prioritised growth areas likely to drive future GW demand.
		Special Economic Zones (SEZs)	National polygons 90 m	DTIC (SEZ Act 16 of 2014); IPAP 2018/19–2020/21	Nationally designated SEZs; indicator of strategic economic activity and potential demand/pressure.
	Governance & Policy	Subterranean Government Water Control Areas (SGWCA)	National polygons 90 m	DWA (2013) NWRS II SGWCA listings	Legacy groundwater control designations indicating management priority; combined in a governance composite.
		International Water Treaties / Transboundary Obligations	Basin masks & treaty nodes 90 m	ORASECOM; TPTC; LIMCOM; SADC Protocol; WRC (2006) overview, & SADC/IGRAC (2020) Transboundary Dataset	Transboundary obligations used to elevate GRUs within affected basins/nodes in the governance composite.
	Environmental & Ecological Significance	Groundwater-Dependent Ecosystems (GDEs)	30 m raster 90 m; GRU overlay	Global GDE Map v1.2.0 (Rohde et. al., 2024) supplemented with NFEPA rivers/wetlands (Nel et. al., 2011); National Wetland	Probability/certainty surfaces for GDE likelihood; normalised to 5-class scale for ecological composite.

Dataset Category	Parameter	Datasets Used for Composites	Working Resolution*	Source	Description (how used in this report)
				Map (SANBI/CSIR, 2024); and ADE/GDE (Colvin et al 2007).	
		Ecologically Sensitive Sites	National polygons 90 m	Ramsar sites; SAPAD (protected areas); KBAs; provincial CBAs; NFEPA rivers/wetlands (Nel et. al., 2011); National Wetland Map (SANBI/CSIR, 2024)	Site-based significance where groundwater sustains high ecological value; harmonised, de-duplicated (cell-wise max).
		Wetlands (proxy signal)	Raster/polygons 30m and 1:50k – 1:250k	National Wetland Map (SANBI/CSIR, 2024); NFEPA rivers/wetlands (Nel et. al., 2011); SANLC (GeoTerraImage for SANBI/DFFE. 2018–2020) - QA/validation only; not used for wetland extent.	Definitive national wetland extent and Priority status and connectivity for freshwater ecosystems.
Additional Considerations & Adjustment	Current Status Quo	Stressed / Over-allocated Systems; Pollution Hotspots	Polygons/points GRU summary	SWSA-gw Status Quo Report, complimented by WARMS (licenced abstraction volumes), GRAII Recharge and NGA Groundwater Levels.	Elevates borderline GRUs experiencing high existing pressure; applied as +1 adjustment where Class ≥ 4.
	Groundwater Quality	Natural Groundwater Quality	National raster 90 m; GRU summary	WMS (2025)	Baseline geogenic constraints informing viability relative to DWQT/application classes.
		Fitness-for-Use	National raster 90 m; GRU summary	WMS (2025)	Screens fitness for intended use; applied as ± adjustment to Part-3 scores.
	Future Development Options	Potential for Artificial Recharge (MAR)	National screening 90 m tags; GRU	Pietersen (2006); DWA (2009); Zhang et al. (2019); Ponnusamy et al. (2022); Zenande et al. (2024); Vandala & Mahed (2025)	Literature-based evidence for hydrogeologic settings favourable to MAR; flags GRUs for opportunity/risk.
		Use as a Climate-Adaptation Measure	National index 90 m; GRU summary	DART Index (Depth-to-Water change, Aquifer Type, Recharge, Transmissivity) per Dennis & Dennis (2012)	Gauges potential for groundwater to buffer climate variability and supply shocks; ± adjustment.

3.4. Four-Part Workflow

The Refined Methodology for identifying and delineating Strategic Water Source Areas for Groundwater (SWSA-gw) is structured around a four-part analytical workflow. This framework enables the integration of diverse spatial, hydrogeological, and socio-economic datasets into a consistent, reproducible process that supports evidence-based groundwater planning at a national scale. The workflow progresses through four sequential stages—from initial groundwater availability screening to aquifer-level delineation of Groundwater Resource Units (GRUs), strategic importance filtering, and final prioritisation. Each part builds on the outputs of the previous stage, applying clearly defined spatial rules and Multi-Criteria Decision Analysis (MCDA) techniques. While designed for national application, the approach also allows flexibility for refinement based on local context, future data inputs, or stakeholder priorities (see **Figure 3-2**).

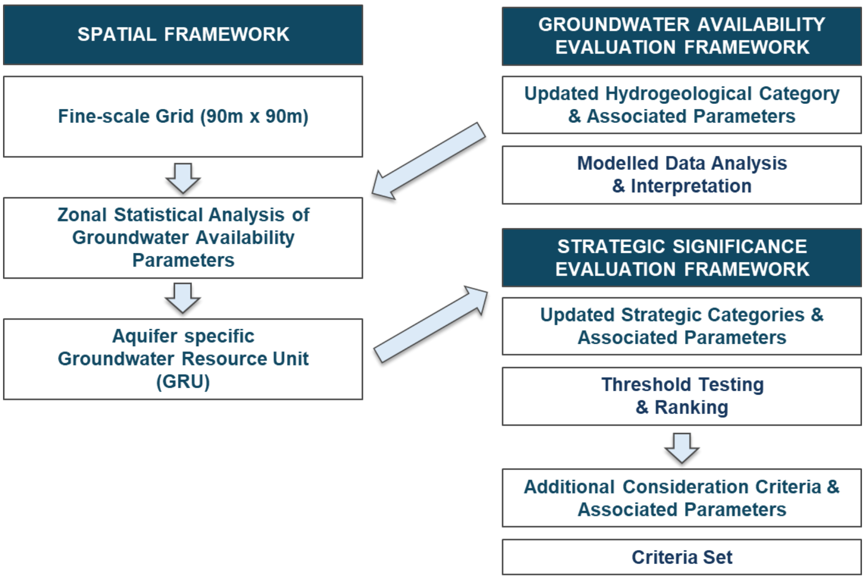


Figure 3-2 Simplified flow diagram of the refined methodology for identifying and delineating SWSA-gw, showing the integration of the spatial framework, groundwater availability evaluation, and strategic significance assessment into a sequential, four-part workflow.

1. **Part 1: Groundwater Availability**

   Establishes a composite measure of groundwater availability by integrating four national raster datasets: recharge, baseflow, storage capacity, and potential yield. These layers are grouped by hydrogeological role—input and discharge (recharge and baseflow) versus retention and abstraction potential (storage and yield). Each dataset is normalised to a five-class ordinal scale and combined using a Weighted Linear Combination (WLC) to produce two intermediate composites. These are merged to generate national groundwater availability surfaces, forming the spatial basis for GRU delineation.

2. **Part 2: Aquifer-Specific GRU Delineation**

   Uses the availability composites from Part 1 to define GRUs—spatially coherent zones that reflect both hydrogeological structure and groundwater availability. The composite surfaces are overlaid and grouped into zones of similar hydrogeological conditions (e.g., aquifer types and geology). Contiguous high-suitability areas are delineated as candidate GRUs. These are refined through merging, spatial filtering, and topological cleaning to produce a final GRU layer for strategic evaluation.

3. **Part 3: Strategic Significance Evaluation**

   Assesses the national importance of each GRU using two sets of thematic indicators: Set 1 captures socio-economic demand, current groundwater use, service delivery backlogs, governance zones (e.g. Subterranean Government Water Control Areas – SGWCAs), and development priorities such as Special Economic Zones (SEZs). Set 2 captures environmental and ecological value, including the distribution of groundwater-dependent ecosystems (GDEs) and ecologically sensitive areas. All indicators are normalised and combined into composite rasters or vector layer. Thematic buffers are applied to highlight strategic zones, and GRUs intersecting these zones are assigned a Strategic Significance Score.

4. **Part 4: Contextual Adjustment and Final Prioritisation**

   Applies a final refinement based on contextual pressures or opportunities not captured in earlier steps. These include aquifer stress, pollution hotspots, groundwater quality constraints, and the potential for artificial recharge and use of groundwater as a climate change mitigation measure. Each theme is translated into a binary adjustment layer and combined to form a single adjustment. GRUs intersecting high-pressure or opportunity zones receive a +1 score adjustment, ensuring that high-need or high-risk areas are retained in the final shortlist.

Together, these four parts form a progressive MCDA-based workflow that transforms heterogeneous spatial data into a refined, nationally consistent shortlist of SWSA-gw areas. This shortlist supports scenario testing, sensitivity analysis, and long-term groundwater investment planning. Table 3-1 summarises this workflow, outlining key inputs, processing logic, outputs, and associated MCDA principles. Detailed methods for each part are presented in **Sections 3.4.1** to **3.4.4**.

Table 3-3 Summary of the Four-Part Workflow including key inputs, analytical steps, and outputs used to identify and prioritise SWSA-gw.

Part	Purpose / Focus	Key Inputs	Analytical Steps	Key Outputs

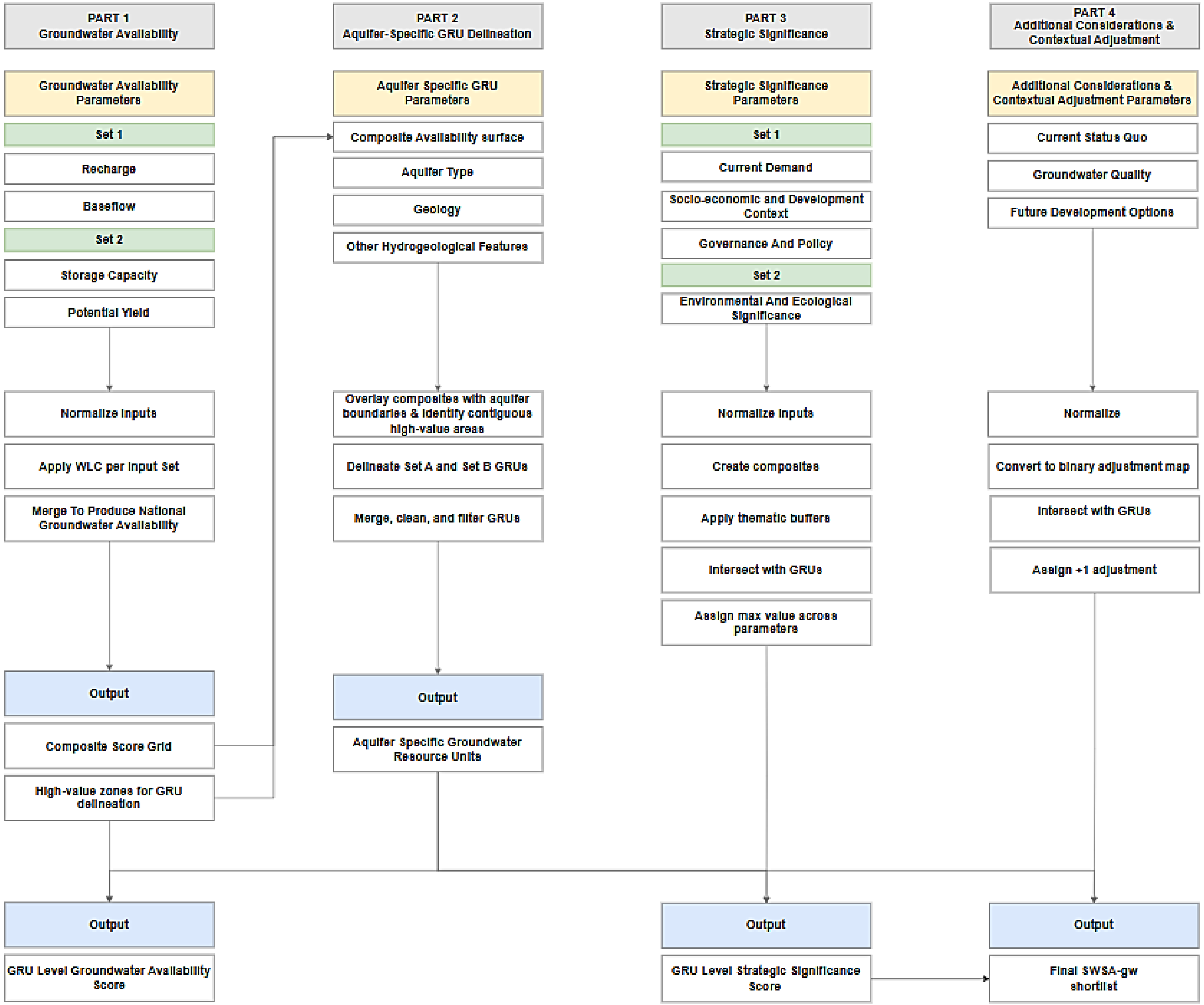
Part 1: Groundwater Availability	Quantify where groundwater is naturally available and abundant.	• Recharge
		• Baseflow
		• Storage Capacity
		• Potential Yield
			• Normalise each input (1–5 classes)
			• Group into:
			  ○ Input/Discharge: Recharge & Baseflow
			  ○ Retention/Abstraction: Storage & Yield
			• Apply WLC for each group
			• Merge to produce national Groundwater Availability
				• Four normalised parameter layers
				• Two composite surfaces (Set A and Set B)
				• Groundwater Availability Score per cell

Part 2: Aquifer-Specific GRU Delineation	Define aquifer-specific GRUs based on availability and hydrogeological structure.	• Composite score surfaces • Aquifer type • Geology • Other hydrogeological features	• Overlay availability scores with aquifer boundaries • Identify contiguous high-value zones • Delineate Set A and Set B GRUs • Merge, clean, and filter GRUs • Retain GRUs with spatial and geological coherence	• National GRU layer • GRU-level groundwater availability attributes

Part 3: Strategic Significance	Evaluate the national importance of each GRU from demand, governance, and ecological perspectives.	**Set 1 – Socio-economic & governance**
		• Current Demand
		  ○ Licensed use
		  ○ Level of Dependence
		  ○ Domestic Sole Supply
		• Socio-Economic and Development
		  ○ Economic Importance
		  ○ Water service status
		  ○ Strategic and Future Use
		  ○ SEZs
		• Governance and Policy
		  ○ SGWCAs
		  ○ Transboundary Treaty's
		Set 2 – Environmental
		• GDEs
		• Ecologically Significant Sites
			• Normalise parameters (1–5)
			• Apply thematic buffers
			• Create composite raster per set using WLC
			• Intersect GRUs with each composite
			• Assign highest score across sets as Strategic Significance Score
				• Strategic zones map
				• GRU-level Strategic Significance Score

Part 4: Contextual Adjustment	Refine prioritisation based on stress, water quality, and future groundwater development value.	• Current Status Quo
		  ○ Stressed, Over Allocated Aquifer
		  ○ Pollution hotspots
		• Groundwater Quality
		  ○ Natural quality
		  ○ Fitness for Use
		• Future Development Options
		  ○ Potential for Artificial Recharge
		  ○ Groundwater as a mitigation measure for Climate Change
			• Normalise to five classes
			• Convert to binary adjustment grid
			• Overlay GRUs with adjustment zones
			• Add +1 score to intersecting GRUs (max score = 5)
			• Final score = Strategic + Adjustment
				• Adjustment map
				• Final SWSA-gw GRU shortlist with prioritised scores

Figure 3-3 Conceptual flow diagram of the refined methodology – Schematic data flow from raw inputs to ranked GRUs.



3.4.1. Part 1 – Groundwater Availability

Part 1 of the methodology focuses on generating a composite indicator of groundwater availability using four national raster datasets: 1) recharge, 2) baseflow, 3) storage capacity, and 4) potential yield. To enable direct comparison across these datasets—which differ in units, distributions, and thematic focus—all layers are reclassified onto a standard five-class ordinal scale (Class 1 = Low to Class 5 = High), using statistically derived breaks based on the value distribution of each dataset. The layers are then grouped according to their hydrogeological role:

- Set A includes recharge, the primary indicator of groundwater input, and baseflow, a supplementary indicator of sustained groundwater discharge to surface water—often associated with well-connected and replenished groundwater systems.
- Set B comprises storage capacity and potential yield, which together indicate where groundwater is likely to be retained or accessed within the subsurface.

Each dataset is initially retained at its native spatial resolution: 90 × 90 m for Set A, and 1 × 1 km for Set B. Where appropriate, Set B layers may be resampled to 90 × 90 m, provided this does not diminish information content. Within each set, the two layers are assigned an initial equal weight (1:1) and combined using a cell-wise maximum function, resulting in one composite raster per set. Although equal weighting is used in this baseline application, the methodology is explicitly designed to support adjustable weighting, allowing for future refinement through expert judgement, stakeholder input, or formal techniques such as the Analytic Hierarchy Process (AHP). The two composites are then merged—again using the cell-wise maximum—to produce a final Groundwater Availability layer, assigning a score to every grid cell.

A binary suitability mask is then applied: cells scoring 4 or 5 are classified as “suitable”, while those scoring 3 or below are considered “not suitable”. The suitable cells represent high-value “seeds” that are carried forward into Part 2 for the delineation of aquifer-specific Groundwater Resource Units (GRUs). Importantly Groundwater Availability Score is also aggregated and averaged per GRU post GRU delineation.

MCDA Principles Embedded in Part 1

The approach applied in Part 1 reflects a simplified yet robust implementation of key Multi-Criteria Decision Analysis (MCDA) principles, adapted for spatial hydrogeological evaluation:

- Normalisation for comparability: All input layers are reclassified to a common ordinal scale, enabling integration across heterogeneous data types and thematic indicators.
- Hydrogeological grouping of criteria: Indicators are grouped into conceptually coherent sets—those representing groundwater inputs (Set A) and those representing storage or yield potential (Set B). This thematic structuring provides clarity in interpretation and supports a transparent aggregation process.
- Weighted combination of criteria: Within each set, an equal-weight (1:1) aggregation is performed using a non-compensatory operator (cell-wise maximum). While simple, this approach avoids trade-offs between strong and weak indicators and ensures that areas of highest hydrogeological potential are retained. The framework is purposefully designed to accommodate custom weighting schemes should future applications require sensitivity testing or expert-driven prioritisation.
- Threshold-based classification: The use of a binary suitability mask (≥ 4 = suitable) represents a constraint-based decision rule, commonly used in spatial MCDA to support screening, prioritisation, or exclusion.

Together, these techniques establish a transparent and scalable MCDA framework that provides a hydrogeologically meaningful basis for evaluating groundwater availability. The approach serves both as a standalone assessment and as a critical input to downstream components of the refined methodology, including GRU delineation and strategic significance analysis.

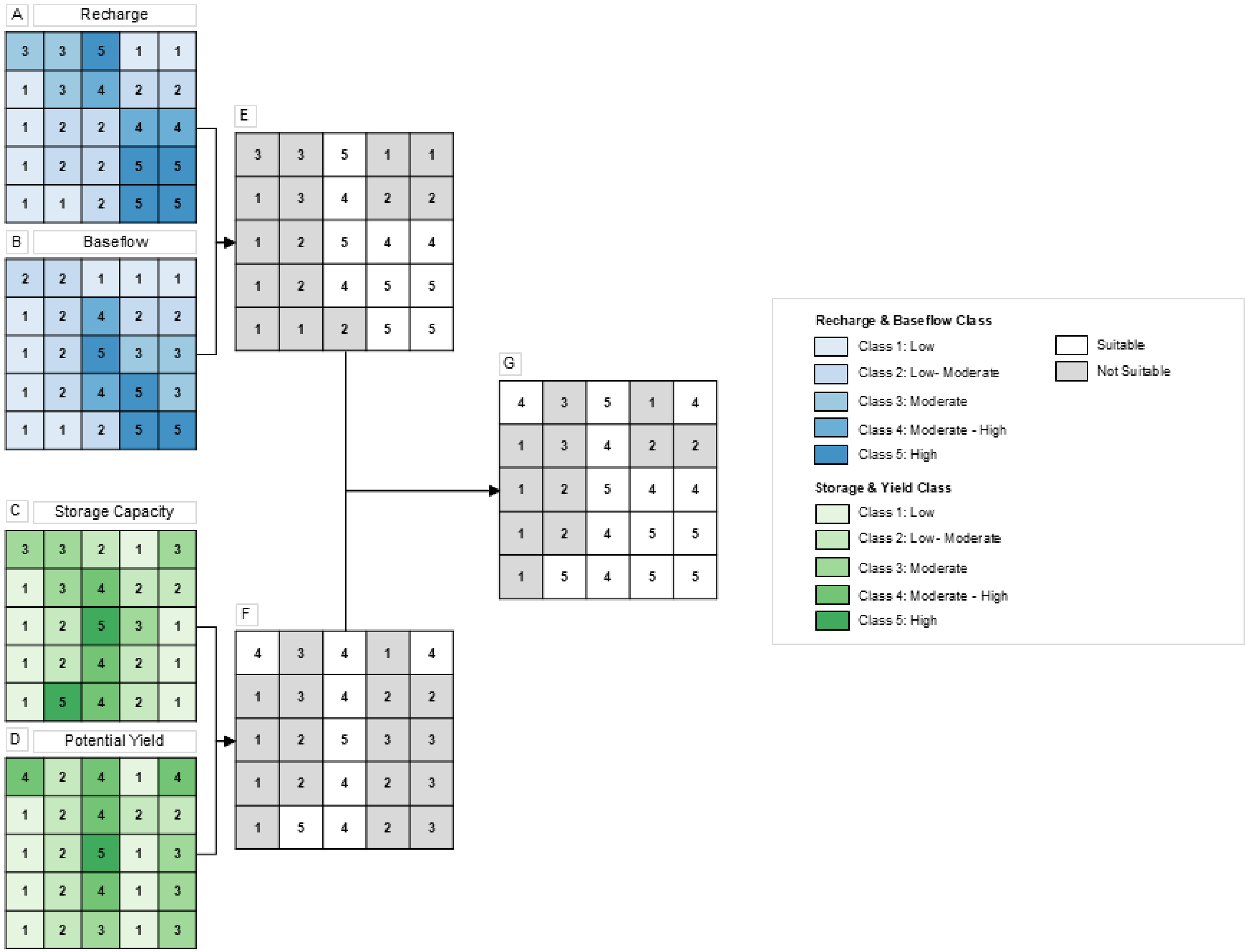


Figure 3-4 **Conceptual flow diagram for Part 1 – Groundwater Availability. Panels A (Recharge) and B (Baseflow) and panels C (Storage Capacity) and D (Potential Yield) show the four input rasters after re-classification to a five-class scale (Class 1 = Low; Class 5 = High). Within each dataset pair the layers are combined at equal weight with a cell-wise maximum, producing the Set A composite in E and the Set B composite in F; cells scoring ≥ 4 are (suitable), those ≤ 3 (not suitable). A second cell-wise maximum merges E and F to give the final Groundwater Availability Score in G. White cells in G serve as the “seed” locations carried forward to Part 2 for delineating GRUs. Blue tones represent recharge/baseflow classes, green tones storage/yield classes, while the white-and-grey overlay indicates suitability.**

3.4.1.1. Recharge

Datasets and Resolution

Recharge estimation in this study will draw on three complementary national datasets: the Groundwater Resource Assessment Phase II (GRA II) recharge surface, the Water Resources of South Africa 2012 (WR2012) or Lynch (2004) Mean Annual Precipitation (MAP) surface, and the high-resolution downscaled MAP surface from Lötter & Le Maitre (2021). Together, these will provide the national calibration, temporal coverage, and fine-scale spatial variability needed to produce a recharge layer suitable for both national and local assessments.

- **Recharge from GRA II**

  GRA II estimated natural (undeveloped) groundwater recharge for South Africa using a GIS-based modelling approach (DWAF, 2006a; DWAF, 2006b) on a 1 km × 1 km grid, with outputs aggregated to the quaternary catchment (QC) scale. The methodology combined Chloride Mass Balance (CMB) analysis, empirical rainfall–recharge relationships, a spatial "layer" model, and cross-calibration with field measurements. Key inputs included a national MAP dataset, potential evapotranspiration, land cover, and generalised soil and aquifer properties from 1:1 000 000 & 1:500 000 geological and hydrogeological maps. Calibration drew on streamflow separation (baseflow), tracer studies, and prior local-scale recharge assessments. The national "undeveloped" recharge volume was estimated at ~30.52 km^3/a (~ 5.2 % of MAP), with higher uncertainty in complex hydrogeological settings such as karst and highly fractured aquifers.

- **MAP from WR2012**

  The WR2012 study produced a national MAP surface as part of its integrated hydrological-modelling framework (WRC, 2015a; WRC, 2015b), using the WRSM2000/Pitman rainfall–runoff model. It incorporated long-term rainfall records from the South African Weather Service (SAWS) and other regional stations for the 1920–2009 baseline period. The MAP layer was interpolated at the QC scale and presented in the WR2012 Book of Maps. Although coarser than the 1 km GRA II grid, WR2012 provides the temporal depth and national coverage required for long-term hydrological modelling and calibration. Since Lötter & Le Maitre (2021) draw on the Lynch (2004) rainfall dataset, the 1 km MAP compiled in the South African Atlas of Agrohydrology (Schulze, 2008) from the same primary dataset will also be used in a sensitivity run as an alternative rainfall baseline to enhance consistency with the 90 m product.

- **Downscaled MAP from Lötter & Le Maitre (2021)**

  This high-resolution MAP surface covered South Africa, Lesotho, and eSwatini (Lötter & Le Maitre, 2021; CSIR, 2021). It was derived from over 12 000 rainfall stations (8 319 after quality control) using Empirical Bayesian Kriging Regression Prediction (EBKRP) with predictors such as altitude, latitude, continentality, Topographic Position Index (TPI) at 50 km and 250 km scales, and Mean Annual Runoff (MAR), all at 90 m resolution. Interpolation zones followed SAWS Rainfall District boundaries. Model performance, with a Root Mean Square Error (RMSE) = 68 mm, exceeded both Simple Kriging (78 mm) and Empirical Bayesian Kriging (EBK) without regression (74 mm). This dataset was also a key climatic input in the fine-scale SWSA-sw delineation.

Processing to Derive Fine-Scale Recharge (90 m × 90 m)

Groundwater recharge will be a critical input to this study and was the primary dataset in the previous SWSA-gw delineation (**Section 2.3.1**). For this refinement and in order to enhance the Spatial and Evaluation framework (**Section 3.3**), the aim will be to produce a 90 m recharge layer that retains national calibration while incorporating fine-scale rainfall variability. Re-modelling recharge for the entire country will be beyond the project scope, so a pragmatic downscaling approach will be applied.

In GRA II, recharge and MAP were integrated within the model, but the GRA II MAP dataset was only available as aggregated QC-scale values, with the underlying gridded rainfall inputs unreleased. This made cell-level calculations impossible and risked boundary artefacts if applied directly.

To overcome this, the gridded WR2012 MAP dataset will be used as the rainfall baseline at ~1 km resolution, comparable to the GRA II recharge dataset, with a sensitivity run using the 1 km Schulze (2008) MAP (derived from Lynch, 2004) to test consistency with the Lötter & Le Maitre (2021) surface. For each 1 km cell, a recharge-to-MAP ratio will be calculated by dividing the GRA II recharge value by the corresponding WR2012 MAP value. This will provide a nationally consistent measure of the proportion of rainfall converted to recharge in each cell, preserving GRA II's spatial patterns and calibration. These ratios will then be applied to the high-resolution (90 m × 90 m) 2021 MAP raster from Lötter & Le Maitre (2021), scaling the fine-scale rainfall data to match the national recharge calibration. The result will be a 90 m × 90 m groundwater recharge surface that is hydrologically consistent, spatially detailed, and suitable for both national-scale screening and local-scale decision-making. Results from the sensitivity run will be compared at QC and local scales. Any material systematic difference will be documented and, if warranted, the Schulze-based ratios will be adopted.

This downscaling method was selected as it preserves the integrity of the nationally recognised GRA II recharge calibration while leveraging the enhanced spatial detail of the 2021 MAP dataset. Unlike statistical interpolation alone, which risks distorting recharge patterns in areas with limited station density or complex hydrogeology, this ratio-based approach will maintain hydrogeological realism by anchoring fine-scale variability to an established, modelled recharge baseline. It will also avoid the considerable time and resource demands of re-modelling recharge across the entire country, while still producing outputs that are consistent, comparable, and defensible for both strategic planning and local assessment.

Normalisation and Integration into MCDA Workflow

To ensure compatibility with other indicators used in the four-part MCDA, the fine-scale recharge grid (expressed in mm/a) will be converted to a five-class ordinal scale. This transformation will allow recharge to be directly compared and combined with other datasets in the workflow, regardless of their original units or distributions (see **Section 3.4.1** Part 1 description and **Figure 3-4** Part 1 Conceptual Diagram). Several classification approaches will be considered to determine the most appropriate method for representing recharge values:

- Equal Count (Quintile) – Will divide the dataset into five classes containing equal numbers of cells. This will ensure the full value range is represented and maintain balanced class sizes, but the resulting boundaries may not correspond to meaningful hydrological thresholds.
- Logarithmic Scale – Will apply a log transformation to reduce the influence of high outlier values and enhance variation in the lower range. This can better represent low-recharge areas, though the resulting thresholds may be less intuitive to interpret.
- Natural Breaks (Jenks) – Will group values to minimise variance within classes and maximise variance between them, producing boundaries that align with natural patterns in the data. While effective for identifying inherent regimes, it may limit comparability between regions.
- Standard Deviation – Will set class boundaries relative to the mean recharge value, highlighting areas that deviate significantly above or below average. This method will be useful for identifying anomalies but assumes a quasi-normal distribution, which may not always be the case.
- Percentage Volume Contribution per Zone – Will rank cells according to their contribution to total recharge within defined zones (e.g., climate regions, moving windows, secondary catchments). This will highlight local recharge hotspots but may be sensitive to the choice and scale of the zones, which can affect national comparability.

The final classification method will be selected to achieve a balance between statistical robustness, hydrogeological interpretability, and cross-context comparability. Once classified, recharge will be incorporated into Part 1: Groundwater Availability of the MCDA workflow, grouped with baseflow in Set A. Both recharge and baseflow will be given equal weighting to form the Set A composite score. A binary mask will then be applied to retain only cells scoring 4 or 5, representing areas of relatively high groundwater availability. This filtered Set A output will then be combined with the Set B composite (storage capacity and potential yield) in Part 2: Aquifer-Specific GRU Delineation, where recharge will play a role in refining GRU boundaries in relation to underlying aquifer characteristics.

3.4.1.2. Baseflow

Datasets and Resolution

Baseflow estimation in this study will be based on outputs from the GRA II, which simulated and separated baseflow at the QC scale for South Africa under undeveloped conditions (DWAF, 2006a; DWAF, 2006b). While recharge datasets from GRA II were available at a 1 km × 1 km resolution, baseflow outputs were provided only at the aggregated QC scale, reflecting the model's catchment-based calibration and the spatial resolution of flow gauging data.

- **Baseflow from GRA II**

  In GRA II, baseflow was derived from naturalised daily streamflow simulated using the WRSM2000/Pitman rainfall–runoff model, calibrated individually for each QC. The model was run under pre-development conditions (i.e., with anthropogenic abstractions and land-use changes removed) to capture natural hydrological functioning. Baseflow separation was then applied to the simulated daily hydrographs using digital filtering techniques (notably the Lyne–Hollick filter) to distinguish sustained groundwater discharge from quickflow components. Outputs were expressed in mm/a for each QC. Baseflow volumes incorporated both diffuse groundwater contributions to streams and delayed interflow, making them a broader indicator of groundwater–surface water interaction. However, at the QC scale, these values were influenced by catchment geology, topography, and climate variability, and may mask fine-scale heterogeneity in fractured or karstic aquifers.

- **Recharge from GRA II**

  To relate baseflow to recharge, this study will use the national GRA II recharge grid (DWAF, 2006a; DWAF, 2006b) at 1 km × 1 km resolution. The dataset represents natural (undeveloped) recharge, derived through a GIS-based modelling approach that integrates multiple methods, including CMB, empirical rainfall–recharge relationships, and calibration against field measurements (see **Section 3.4.1.1**).

Processing to Derive Fine-Scale Baseflow (90 m × 90 m)

Baseflow will be a critical measure of groundwater availability, indicating the sustained contribution of groundwater discharge to river systems under natural conditions. As with recharge, the aim will be to produce a fine-scale (90 m × 90 m) baseflow layer that retains the national calibration from GRA II while integrating the finer spatial variability provided by the 2021 high-resolution MAP dataset (Lötter & Le Maitre, 2021). Because GRA II baseflow outputs are only available at the QC scale, a downscaling process will be required. First, the 1 km × 1 km GRA II recharge layer (**Section 3.4.1.1**) will be aggregated to mean values per QC, enabling direct comparison with the QC-scale baseflow dataset. The relationship between baseflow and recharge in each QC will then be expressed as a fixed proportion, capturing the share of recharge that emerges as sustained baseflow under undeveloped conditions. These proportions will then be applied to the 90 m × 90 m groundwater recharge surface (developed in Section **3.4.1.1**), effectively transferring the GRA II-calibrated recharge–baseflow relationship onto the higher-resolution surface.

Normalisation and Integration into MCDA Workflow

The fine-scale baseflow layer (mm/a) will be normalised to a five-class ordinal scale for direct comparability with other indicators (see **Section 3.4.1** Part 1 description and **Figure 3-4** Part 1 Conceptual Diagram). Classification options under consideration will match those evaluated for recharge (**Section 3.4.1.1**), and selected based on balancing statistical performance, hydrogeological interpretability, and national comparability. Within the MCDA, baseflow will form part of Part 1: Groundwater Availability, grouped with recharge in Set A. Equal weighting will be applied to normalised baseflow and recharge scores to create the Set A composite. A binary mask (Classes 4–5) will then be applied to retain only areas with relatively high groundwater inflow and discharge potential. This filtered Set A output will be combined with Set B (storage capacity and potential yield) for Part 2: Aquifer-Specific GRU Delineation.

3.4.1.3. Storage Capacity

Datasets and Resolution

Storage capacity estimation in this study will draw on three national-scale datasets: the Aquifer Storage and Aquifer Thickness layers from the GRA II, and the National Storage Capacity layers from the Artificial Recharge Strategy (DWAF, 2007) and the Potential Artificial Recharge Areas study (DWA, 2009). These datasets collectively provide volumetric groundwater storage estimates, thickness-based plausibility checks, and targeted artificial recharge capacity mapping, which together will form the basis for evaluating subsurface storage potential in the Four-Part MCDA workflow.

- **Aquifer Storage from GRA II**

  The GRA II aquifer storage dataset quantified the volumetric capacity of aquifers at a national scale, mapped on a 1 km × 1 km grid (DWAF, 2006a; DWAF, 2006b). Storage was calculated using aquifer-specific parameters — specific yield for unconfined aquifers and storativity for confined aquifers — applied to mapped aquifer extents and saturated thickness. Aquifer extent and type were derived primarily from the 1:500 000 national hydrogeological map series, supplemented with 1:250 000 geological mapping in certain regions. Parameter values were sourced from the National Groundwater Database (NGDB) borehole records, supplemented by literature values for similar aquifer types. The output was a continuous grid of estimated groundwater storage capacity (m^3) for each cell, providing a nationally calibrated baseline for volumetric groundwater potential.

- **Aquifer Thickness from GRA II**

  The GRA II aquifer thickness layer provided saturated thickness values (m) for each aquifer unit at 1 km × 1 km resolution (DWAF, 2006a). Estimates were derived from NGDB borehole lithological logs, geological cross-sections, and regional hydrogeological maps (1:250 000 and 1:500 000). This dataset enabled verification of volumetric capacity estimates by identifying areas where high storage values coincided with substantial saturated thickness. It also helped identify geologically constrained areas where storage may have been volumetrically limited despite favourable aquifer parameters.

- **National Storage Capacity from DWAF (2007) and DWA (2009)**

  The Artificial Recharge Strategy (DWAF, 2007) and Potential Artificial Recharge Areas study (DWA, 2009) produced a “storage” layer quantifying the maximum theoretical volume of water that could be stored within aquifers favourable for artificial recharge. Storage volume was calculated as: *Storage Volume (m^3) = Area (m^2) × Saturated Thickness (m) × Storage Coefficient*. For unconfined aquifers, the storage coefficient equalled specific yield; for confined aquifers, storativity values (orders of magnitude smaller) were used. Aquifer thickness and type were sourced from national hydrogeological maps (1:500 000 scale) and refined using NGDB borehole logs. The spatial extent of “favourable” aquifer zones was defined using yield thresholds and permeability criteria. Outputs were summarised per Water

Management Area (WMA) and sub-WMA, providing a coarser but nationally consistent layer for planning artificial recharge interventions.

Processing to Derive Composite Layer at 1 km

Storage capacity will be represented at its native 1 km resolution as a composite GIS layer integrating the datasets listed above. Inputs will be harmonised in terms of units, spatial extent/grid, and projections. Cross-checking will be carried out using aquifer thickness to flag implausible high-storage values, ensuring internal consistency across datasets. The combination rule will not be fixed at this stage. Candidate methods under consideration will include: weighted overlays (e.g., giving more influence on certain datasets based on confidence levels), rule-based intersections (e.g., requiring minimum thresholds in both thickness and storage), and non-compensatory operators (e.g., minimum or conjunctive approaches to avoid overestimation).

A potential 90 m downscaling approach may be piloted in the next phase of the project only if testing demonstrates that volumetric integrity is preserved and that additional fine-scale detail is hydrologically defensible. Until then, the 1 km composite will remain the working resolution for analysis and integration.

Normalisation and Integration into MCDA Workflow

The composite storage capacity layer will be normalised to a five-class ordinal scale for comparability with other MCDA indicators. Class-break methods under review will mirror those in the recharge section (**Section 3.4.1.1**), including equal count, logarithmic, natural breaks, standard deviation, and percentage volume contribution per zone. The final method will be selected following sensitivity testing and expert review to balance statistical robustness, hydrogeological interpretability, and national comparability.

Within the Four-Part MCDA workflow, storage capacity will form part of Set B (storage capacity & potential yield) in Part 1: Groundwater Availability. Initial weighting between storage capacity and potential yield will be equal, subject to later sensitivity testing. A binary mask consistent with the chosen classification approach (e.g., retaining Classes 4–5) will be applied to the Set B output before combining it with the filtered Set A (recharge & baseflow) in Part 2: Aquifer-Specific GRU Delineation, ensuring that storage capacity is assessed within correct aquifer boundaries and alongside inflow/discharge potential (see **Section 3.4.1** Part 1 description and **Figure 3-4** Part 1 Conceptual Diagram).

3.4.1.4. Potential Yield

Datasets and Resolution

Potential yield in this study will draw on two complementary national datasets: the Aquifer Type and Yield maps from the national hydrogeological mapping programme, and the Groundwater Exploitation Potential (GEP) products from the GRA II. Together, these will provide geological context and a nationally calibrated estimate of sustainable abstraction potential.

- **Aquifer Type and Yield Maps**

  The national hydrogeological map series (primarily 1:1 000 000, with 1:500 000 coverage in selected regions) compiled lithostratigraphic and structural information (Council for Geoscience, CGS) and borehole yield data (National Groundwater Database, NGDB) into a merged Aquifer Type and Yield layer. Aquifer types reflected dominant groundwater occurrence (e.g., intergranular, fractured, intergranular–fractured, karst), while expected borehole yield classes were provided as ranges (e.g., <0.1 L/s, 0.1–0.5 L/s, 0.5–2 L/s, 2–5 L/s, >5 L/s). These classes represented typical sustainable abstraction under average conditions (not single-test maxima) and have been widely used for national/regional screening, licensing context, and feasibility scoping.

- **Groundwater Exploitation Potential (GEP) from GRA II**

  GEP (DWAF, 2006a; 2006b) provided a nationally consistent estimate of sustainable abstraction at regional scale under natural (undeveloped) conditions. Two variants were reported: Potable GEP (PGEP) for aquifers meeting potable standards and Utilisable GEP (UGEP) where non-potable sources were included. GEP integrated long-term recharge, aquifer storage/parameters (e.g., transmissivity, storativity, thickness, type), hydrogeological boundaries, and management constraints (e.g., ecological reserve/flow considerations) to produce sustainable yield estimates. Original outputs were summarised at QC level (with underlying 1 km layers informing parameters), reported as annual volumes (e.g., Mm^3/a) and/or relative to recharge. Average-condition national totals were higher than drought-condition equivalents, with PGEP > UGEP in quality-constrained areas.

Processing to Derive Composite Layer at 1 km

Potential Yield will be represented at 1 km × 1 km resolution as a composite of: (1) Expected Borehole Yield, disaggregated and updated to 1:250 000 geology, and (2) GEP downscaled from QC with geological constraints.

The supplied Aquifer Type and Yield product will be split into independent Aquifer Type and Yield layers to integrate more clearly with other geological datasets and avoid conflating lithological controls with performance classes. Newly available 1:250 000 national geology from the CGS will be adopted as the base framework, with existing DWS yield classes (<0.1 L/s, 0.1–0.5 L/s, 0.5–2 L/s, 2–5 L/s, >5 L/s) reassigned to updated aquifer polygons based on lithology/structure equivalence and mapped continuity. The DWS yield classes will be retained without national re-modelling; where supported by NGA syntheses or regional studies, additional classes (e.g., 5–10 L/s, >10 L/s) may be incorporated in a future update.

GEP (PGEP/UGEP) will be downscaled from QC to 1 km through proportional allocation constrained by the spatial distribution of Expected Borehole Yield classes, ensuring higher proportions align with more productive aquifers (e.g., fractured/karst high-yield units) and unsuitable zones are excluded. Harmonisation steps will include spatial, extent, mask, and unit checks. The final combination rule is not fixed at this stage; candidate approaches — weighted overlays (confidence-weighted), rule-based intersections (e.g., requiring a minimum yield class and non-zero GEP), and non-compensatory operators (e.g., minimum) — will be tested during delineation phase. The working resolution will remain 1 km for consistency with input datasets, with 90 m refinement considered only if downscaling preserves yield class meaning and avoids artefacts across geological boundaries.

Normalisation and Integration into MCDA Workflow

To ensure compatibility with other indicators in the Four-Part MCDA workflow, the composite potential-yield surface will be normalised to a five-class ordinal scale (see **Section 3.4.1** Part 1 description and **Figure 3-4** Part 1 Conceptual Diagram). Class-break methods under consideration will mirror those used for recharge/baseflow (Equal Count; Logarithmic; Natural Breaks; Standard Deviation; % Contribution per Zone – see **Section 3.4.1.1**). The final choice will balance statistical soundness, hydrogeological interpretability, and national comparability after sensitivity and expert review.

Within the Four-Part MCDA workflow, Potential Yield will form Set B with Storage Capacity in Part 1: Groundwater Availability. Initial equal weighting will be applied (subject to sensitivity testing) to produce the Set B composite. A binary mask (retaining Classes 4–5 under the selected classification) will then be applied before combining Set B with the filtered Set A (Recharge & Baseflow) in Part 2: Aquifer-Specific GRU Delineation, ensuring potential yield is evaluated alongside inflow (recharge), discharge (baseflow), and storage within correct hydrogeological boundaries.

3.4.2. Part 2 – Aquifer-Specific GRU Delineation

Part 2 builds directly on the outputs generated in Part 1 (**Section 3.4.1**): the two composite groundwater availability rasters (Set A and Set B) and the associated binary suitability mask. The objective of this step is to transform the raster-based indicators into spatially coherent, aquifer-specific Groundwater Resource Units (GRUs)—the core spatial units used in subsequent prioritisation.

For each composite raster (Set A: recharge & baseflow and Set B: storage capacity & potential yield), delineation begins by intersecting the raster with mapped hydrostratigraphic domains—primarily aquifer type, which is then refined by geology and other hydrogeological features. Within each domain, the full range of raster values (Classes 1–5) is preserved, and contiguous groups of similar-value cells (i.e., low-to-low or high-to-high) are grouped to identify initial GRU areas (for Set A these areas are based on Recharge and Baseflow only). This allows for the delineation of GRUs that reflect both high and low groundwater availability conditions (based on Recharge and Baseflow only), consistent with the spatial logic shown in the composite layers.

This process is repeated independently for Set A and Set B, producing two parallel sets of initial GRU areas. These are then merged, with overlapping or adjacent polygons dissolved to create a single consolidated layer of a preliminary GRUs. Polygons that fail hydrostratigraphic coherence checks or fall below the high value thresholds are discarded. Remaining GRUs are considered suitable for evaluation in Part 3: Strategic Significance.

Each retained GRU polygon is then cleaned topologically to remove slivers, overlaps, and voids, resulting in a national GRU shapefile. The composite Groundwater Availability Score from Part 1 is then spatially aggregated within each GRU, producing an intrinsic availability value.

Spatial and MCDA Principles Embedded in Part 2

Although Part 2 shifts from pixel-based scoring to polygon-based delineation, it remains grounded in key spatial and MCDA principles:

- Hydrostratigraphic constraint logic: GRU boundaries are restricted to mapped aquifer and geological domains, ensuring hydrogeological validity—consistent with domain-constrained decision units in MCDA.
- Full-range suitability grouping: Rather than using only high-value cells (e.g., ≥ 4), delineation considers the full value range, grouping cells of similar class to represent both high and low availability areas. The binary mask is used only later to flag GRUs to take forward to the next phase, aligning with class-based zoning in spatial MCDA.
- Multi-perspective candidate merging: By delineating Set A and Set B separately before merging, the method accounts for different groundwater dimensions (inputs vs. storage/yield), reflecting a parallel evaluation framework often used in MCDA.
- Topological validation and spatial generalisation: Post-processing ensures spatial coherence and removes artefacts, reflecting decision unit cleaning commonly applied in MCDA-based GIS workflows.
- Zonal aggregation: Groundwater Availability Scores are aggregated per GRU using spatial summary statistics, representing a transition from cell-based indicators to unit-based evaluation for downstream analysis.

Together, these steps create a GRU layer that is hydrogeologically meaningful, spatially coherent, and analytically aligned with the broader MCDA framework.

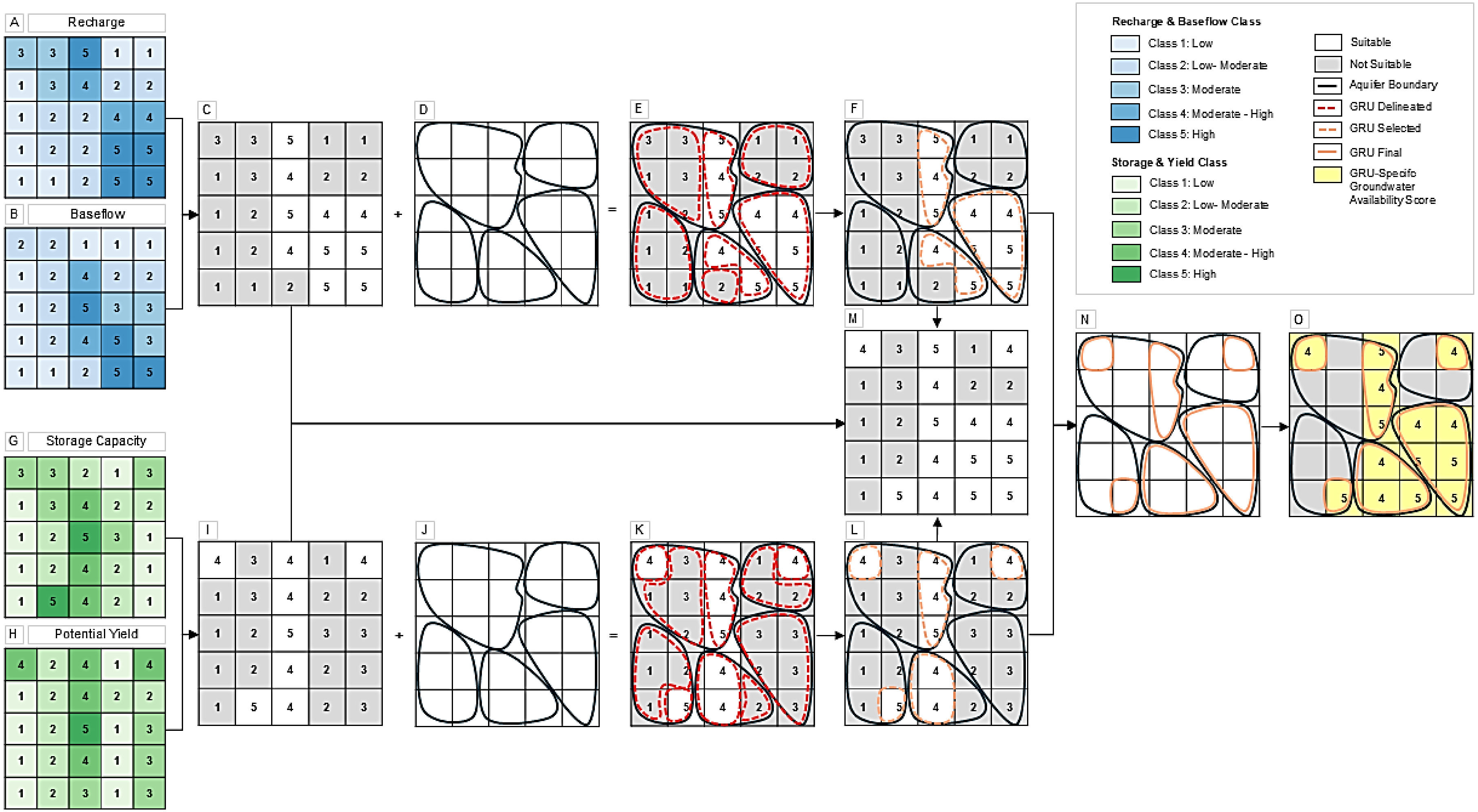


Figure 3-5 **Conceptual flow diagram for Part 2: Delineation of GRUs. Set A's composite (C) and Set B's composite (I) are each intersected with the aquifer grid (D, J) to outline preliminary GRUs (red dashed polygons in E and K). Applying the Part 1 suitability mask retains only GRUs with enough suitable cells, shown by orange dashed boundaries in F and L. The two candidate areas are merged and dissolved into a single layer to which groundwater availability scores can be assigned (M). The surviving GRUs are finalised (solid orange outlines in N) and assigned their aggregated Groundwater Availability Score from Part 1 (yellow values in O). This national GRU shapefile is the starting point for the Strategic Significance evaluation in Part 3.**

3.4.2.1. Aquifer Type

The Aquifer Type dataset in this study will originate from the disaggregated Aquifer Type and Yield layer prepared in Part 1 (**Section 3.4.1.4**). In Part 1, the original DWS national hydrogeological product — which combined lithological aquifer classification with expected borehole yield ranges — was separated into independent Aquifer Type and Expected Borehole Yield layers to improve analytical clarity and avoid conflating geological properties with productivity estimates. The Aquifer Type layer (1:500 000 scale) represents lithology–structure-based categories including: Intergranular aquifers (primary porosity in unconsolidated sediments), Fractured aquifers (secondary porosity in consolidated rock units), Intergranular–fractured aquifers (dual porosity systems), Karst aquifers (solution-enhanced permeability in carbonate rocks), and Low-yield aquifers and non-aquifer formations (minimal storage and transmissivity).

While this national-scale dataset provides a coherent classification framework, its resolution means mapped boundaries may diverge from actual hydrogeological limits, particularly in structurally complex or lithologically heterogeneous areas. These limitations will be addressed through integration with higher-resolution geological data.

3.4.2.2. Geology

The geological dataset for Part 2 will be derived from the 1:250 000 national geological mapping produced by the Council for Geoscience (CGS), South Africa's statutory geoscience agency (Geoscience Act 100 of 1993, amended 2010). This product represents the most detailed national-scale mapping currently available at the national scale, with substantially greater spatial accuracy than the 1:500 000 base used in the national Aquifer Type dataset. The 1:250 000 mapping provides: High-resolution lithostratigraphic boundaries with accurate polygon geometry, detailed lithological descriptions (rock type, composition, weathering), Chronostratigraphic information (geological age, formation, and group assignments), Structural features such as faults, folds, shear zones, and intrusive contacts, and Explanatory notes and mapping reports that contextualise aquifer potential, permeability, and storage characteristics.

This enhanced resolution and thematic detail allow direct reassignment of geological polygons to aquifer types using lithology, stratigraphy, and structural context — supported by CGS explanatory notes, regional hydrogeological studies, and published literature. The CGS mapping is accessible via the CGS Geoportal and Data Catalogue (CGS, 2022).

Processing and Integration into MCDA Workflow

In Part 2, the Aquifer Type layer developed in Part 1 at 1:500 000 scale will be refined through integration with the 1:250 000 geology dataset produced by the CGS. This refinement will begin by overlaying the existing Aquifer Type polygons with the higher-resolution geological polygons. Where spatial boundaries differ, the geometry from the 1:250 000 mapping will take precedence due to its superior positional accuracy and lithostratigraphic detail. Each 1:250 000 geological polygon will then be reassigned an aquifer type classification using a combination of lithological composition, depositional environment, chronostratigraphic position (formation and group), and structural controls on permeability such as fault density and folding intensity. Known hydrogeological behaviour documented in CGS explanatory notes and region-specific literature will also guide this reclassification.

Once reclassified, the updated Aquifer Type map will be integrated with the outputs from Part 1 by intersecting it with the filtered Set A (Recharge and Baseflow) and Set B (Storage Capacity and Potential Yield) layers. This ensures that aquifer delineation is informed not only by geological classification but also by empirical measures of groundwater inflow, discharge, and storage potential.

The result of this integration will be a refined Aquifer Type–Geology composite, which will serve as the primary spatial mask for defining Groundwater Resource Units (GRUs). Only areas where favourable aquifer types coincide with high Set A and Set B scores will be retained as candidate GRUs. These candidate units will then undergo further boundary refinement to ensure alignment with mapped geology and hydrostructural features.

Within the Four-Part MCDA framework, this integration step provides the critical bridge between Part 1's indicator-based resource quantification and Part 3's GRU evaluation. By anchoring resource indicators in an accurate geological and hydrostructural context, the method ensures that high-scoring resource areas correspond to realistic and hydrologically defensible aquifer systems, thereby improving both the technical robustness and the practical utility of the final GRU delineations.

3.4.3. Part 3 – Strategic Significance

Part 3 builds on the GRUs delineated in Part 2 (**Section 3.4.2**) to assess their strategic importance at the national level. The aim is to identify GRUs that are not only hydrogeologically favourable (i.e., with high groundwater availability) but also critical from a demand, socio-economic, governance, environmental, or ecological perspective. This is achieved through the application of two analytical sets of thematic indicators, each structured as a composite raster.

- Set 1 includes a suite of indicators reflecting direct or indirect groundwater reliance across socio-economic, demand, and governance dimensions. Current demand is represented by groundwater use, level of groundwater dependence, and domestic sole-supply areas. These are complemented by indicators reflecting the broader socio-economic and development context—namely economic importance, water services backlog, strategic or future-use areas, and Special Economic Zones (SEZs). Lastly, governance and policy alignment are captured through Subterranean Government Water Control Areas (SGWCAs) and obligations under transboundary water treaties.
- Set 2 captures environmental and ecological importance, focusing on groundwater reliance in sensitive natural systems. This includes the distribution of groundwater-dependent ecosystems (GDEs) and ecologically significant sites such as priority wetlands and biodiversity zones.

All input rasters (from both Set 1 and Set 2) are normalised to the common five-class ordinal scale (Class 1 = Low to Class 5 = High), consistent with the framework established in Part 1 (Section 3.4.1). Within each set, layers are assigned equal weight (1:1) and combined using a cell-wise maximum function to produce one composite raster per set. The framework remains weight-agnostic at this stage of the Refined Methodology, allowing for future refinement through expert judgement, stakeholder engagement, or formal MCDA techniques such as the Analytic Hierarchy Process (AHP).

A binary suitability mask is then applied to each composite raster, where cells scoring ≥ 4 are flagged as suitable, while those scoring ≤ 3 are considered not suitable.

To translate these suitability scores into spatially meaningful zones of influence, a buffering process is applied to each composite raster. The purpose of this step is to account for the functional reach or influence of each type of strategic value, recognising that socio-economic demand nodes and environmental receptors differ in how and where they interact with groundwater resources. Two distinct buffering strategies are applied for Set 1 and Set 2 to reflect these differences in hydro-functional logic:

- Set 1 buffering: Contiguous clusters of suitable cells are buffered using a 10 km radius, consistent with the 2018 SWSA methodology (see **Section 2.3.1**), though this may be refined based on other thematic considerations, such as proximity to alternative surface water sources. This step accounts for demand centres—such as communities or productive zones—that could feasibly source groundwater from nearby high-availability GRUs.
- Set 2 buffering: A more localised buffer is applied to reflect that GDEs and wetlands typically draw on direct, underlying groundwater, rather than from distant sources. This justifies the use of a distinct buffering approach tailored to ecological connectivity.

The buffered polygons from both sets are overlaid onto the GRU layer from Part 2 (i.e., GRUs with high groundwater availability). Any GRU intersected by either buffer is considered strategic and assigned the highest-class value present within the intersecting raster cells, generating a preliminary Strategic Significance Score.

GRUs that fall entirely outside both buffered zones are excluded at this stage as candidate SWSA-gw. The remaining GRUs, each carrying a Strategic Significance Score, are carried forward into Part 4 (**Section 3.4.4**) for further refinement and classification.

Spatial and MCDA Principles Embedded in Part 3

Part 3 continues the application of spatial and MCDA principles, now incorporating additional thematic indicators related to socio-economic demand, governance, and ecological value:

- Multi-criteria integration: Each analytical set combines diverse indicators into a single evaluation surface, enabling integrated decision-making across economic, policy, and ecological dimensions—an approach aligned with composite MCDA scoring.
- Normalisation and comparability: All input indicators are normalised to a common ordinal scale, ensuring comparability across datasets with different units and formats—core to any MCDA framework.
- Equal weighting and flexible structure: The use of equal weights provides a baseline aggregation method, while the weight-agnostic design allows future tailoring through expert-driven or stakeholder-led processes, supporting transparent and adaptable decision rules.
- Non-compensatory aggregation (cell-wise maximum): Within each set, the cell-wise maximum function ensures that high importance in any one criterion is preserved—this reflects a non-compensatory logic, preventing dilution of high-priority areas.
- Constraint-based masking and buffer logic: The binary suitability mask and thematic buffers represent a form of spatial constraint logic, commonly used in MCDA to exclude or prioritise areas based on thresholds or influence zones.
- Zonal tagging and score assignment: Intersecting GRUs with buffered zones and assigning them the highest-class value mirrors zonal aggregation and attribute transfer principles often applied in spatial MCDA for unit-based evaluation.

Together, these principles provide a structured and transparent basis for identifying GRUs of strategic national importance—both for current and future groundwater management.

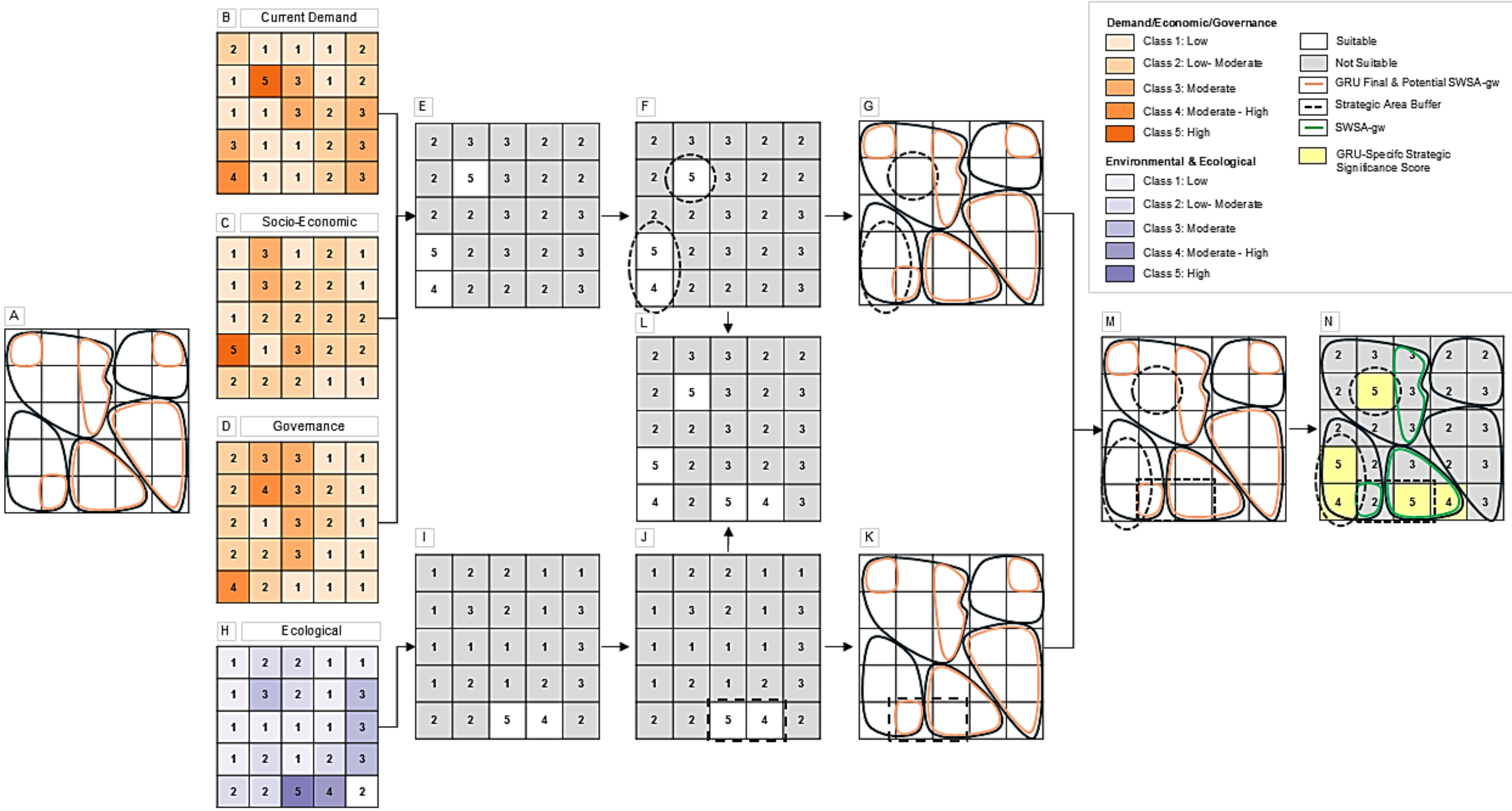


Figure 3-6 **Conceptual flow diagram Part 3: Strategic Significance. Panel A locates the GRUs produced in Part 2. Socio-economic layers—Current Demand (B), Socio-Economic context (C) and Governance (D)—are rescaled to the common five-class scale and merged by cell-wise maximum to give composite E. Cells scoring ≥ 4 are flagged suitable in F and buffered by 10 km; the overlap with GRUs defines socio-economic strategic units (orange outlines) in G. The ecological layer (H) is treated the same: composite I, suitability mask J and a local buffer yield the ecological overlay in K, which is converted to GRU scores in L. Buffers from both themes are combined (M); any GRU intersecting either buffer is tagged strategic and assigned the highest intersecting class, producing the Strategic Significance Score (yellow, Class 4–5) in N. Grey cells indicate scores ≤ 3 (not suitable); green outlines mark the existing SWSA-gw footprint carried for reference.**

3.4.3.1. Current Demand

Datasets and Resolution

Current groundwater demand estimation in this study will draw on three complementary national-scale datasets: the Water Authorisation and Registration Management System (WARMS) maintained by the DWS, the CSIR Green Book settlement-level water source classifications, and supplementary municipal planning records from Water Services Development Plans (WSDPs) and Integrated Development Plans (IDPs). Together, these will provide a robust combination of lawful abstraction records, spatially explicit settlement-level dependence data, and locally validated source information. Combined, these datasets will allow for a multi-dimensional view of groundwater demand—capturing lawful abstraction volumes, the proportion of settlements dependent on groundwater, and the degree to which domestic supply is solely reliant on this resource—providing the necessary resolution and thematic coverage for integration into Part 3 of the MCDA.

- **Groundwater Use**

  Groundwater use estimation in this study will draw primarily on the Water Authorisation and Registration Management System (WARMS), maintained by the Department of Water and Sanitation (DWS). WARMS is the official national register of lawful water use under the National Water Act (Act 36 of 1998), recording both licensed abstractions and registered existing lawful use. For groundwater, it typically records the purpose of use (e.g., irrigation, domestic, industrial, municipal supply), authorised abstraction volumes (m^3/a) linked to specific use categories, source classification (borehole, wellfield, spring, scheme), and spatial location, which can range from individual borehole coordinates to scheme centroids or administrative polygons.

  National in coverage, WARMS provides a critical baseline for lawful groundwater abstraction, yet the spatial density of records is highly variable. This variation reflects historical groundwater development patterns, uneven licensing uptake, and inconsistencies in registration completeness across provinces. Large-scale municipal and agricultural schemes are generally well represented, whereas rural domestic supply, small-scale irrigation, stock watering, and informal or unregistered abstractions are often absent or under-reported.

  Several inherent limitations must be acknowledged before WARMS can be used directly for current-demand mapping. Firstly, it records legal entitlements rather than metered abstraction, meaning actual volumes may differ due to under-utilisation or over-abstraction. Secondly, spatial precision is inconsistent, with some records only geolocated to a scheme centroid or administrative area, limiting site-specific accuracy. Thirdly, temporal accuracy can be an issue, as expired, suspended, or superseded authorisations may still be present. Lastly, there are sectoral biases, with municipal, industrial, and large-scale irrigation uses often over-represented relative to small-scale or dispersed rural abstraction.

  In this study, WARMS will be used as the baseline lawful abstraction dataset but will undergo further enhancement through spatial validation, removal of inactive or duplicate entries, and integration with complementary datasets (e.g., municipal supply scheme inventories, borehole census data) to improve accuracy and representativeness. Current-demand estimates will further be cross-checked against settlement-level indicators (Stats SA Census 2022) of households reliant on groundwater, and triangulated through targeted consultations with regional experts (DWS and municipal planners) in priority aquifer regions, recognising that comprehensive ground verification is beyond the projects scope.

- **Level of Dependence**

  Estimation of groundwater dependence will draw on the CSIR Green Book settlement-level water-source dataset, specifically the Settlement Water Source layer published via the Green Book ArcGIS MapServer. This dataset classifies each settlement's primary water supply as Groundwater, Surface Water, or Combination (interpreted as conjunctive use). Settlement polygons include attributes such as Settlement Name, Province, Municipality Code, and

Municipality Name, enabling robust joins with other spatial and tabular datasets. The classification is based on CSIR's integrated assessment of settlement-level water source reliance, which synthesises scheme-level infrastructure data, regional hydrology, and service delivery information. Recognising that domestic sole-supply dependence may be under-represented in the CSIR Green Book, these classifications may be complemented with Stats SA Census 2022 indicators on main household water source and a targeted review of recent research/municipal reports for data-scarce areas.

The dataset covers the entire country, with geometry derived from the Green Book's Settlement Footprint layer, ensuring alignment with other settlement-scale products. Spatial resolution is at the settlement polygon level rather than gridded cells, enabling population aggregation and cross-tabulation by water-source category. To quantify the human dimension of groundwater reliance, the Settlement Water Source layer will be coupled with population estimates from the Green Book's settlement growth workstream. These estimates are derived by downscaling district-level demographic projections to individual settlement footprints using a population-potential modelling approach. The result is a set of baseline and scenario population datasets (e.g., ~2030 and ~2050 horizons) that can be spatially joined to each water-source category, providing population counts for settlements dependent on groundwater, surface water, or conjunctive supply at present and in future projections.

This settlement-level mapping and, where available, settlement-level Census 2022 water-source attributes, will serve as the baseline for quantifying both the extent and population-weighted significance of groundwater reliance, and will be refined through spatial validation, integration with municipal scheme data and census-derived attributes.

- **Domestic Sole Supply**

  Assessment of domestic sole reliance on groundwater will be based primarily on the CSIR Green Book settlement-level water-source classifications, supplemented where possible by municipal Water Services Development Plans (WSDPs) and Integrated Development Plans (IDPs) to verify and update supply-source information.

  In the Green Book Settlement Water Source layer, settlements classified with "Groundwater" as the primary source are interpreted in this study as potential cases of domestic sole supply, meaning no viable or operational surface-water source is available or in use. The classification is mapped at the settlement polygon level using the Green Book's Settlement Footprint dataset, with attributes that include both baseline and projected population estimates. These population fields enable calculation of the total number of people potentially reliant solely on groundwater.

  The Green Book also provides groundwater vulnerability indicators—most notably Groundwater Pressure Risk and Recharge Potential—which can be used to strengthen the inference of true sole reliance. Settlements classified as Groundwater and also flagged with high or extreme groundwater pressure risk are strong candidates for confirmed sole-dependence. However, limitations must be noted. The "Groundwater" designation may indicate primary rather than exclusive reliance, with supplementary surface-water sources potentially unrecorded. Risk flags are modelled indicators rather than direct measures of supply reliability. The baseline period (2016–2019) may not reflect recent infrastructure developments, changes in abstraction behaviour, or the commissioning of new conjunctive schemes.

  To address some of these gaps, WSDPs and IDPs will be used to verify water-source information for Groundwater-classified settlements, update source status where necessary, and capture planned infrastructure changes. This cross-referencing will allow for reclassification of settlements transitioning away from sole reliance, as well as adding qualitative context on source security. The resulting dataset will therefore combine the spatial coverage and vulnerability insights of the Green Book with more recent and locally informed intelligence from municipal planning documents, ensuring an up-to-date basis for mapping Domestic Sole Supply in Part 3 of the MCDA.

Processing and Integration into MCDA Workflow

Processing of the Current Demand indicators will focus on harmonising the three datasets—WARMS, Green Book settlement water source classifications, and WSDP/IDP updates—into spatially and thematically consistent national layers suitable for integration into Part 3 of the MCDA.

For Groundwater Use, WARMS records will first be filtered to remove expired, suspended, or duplicate authorisations. Location accuracy will be improved by spatial validation against borehole coordinates, scheme boundaries, and settlement footprints. Records with coarse spatial referencing (e.g., municipal centroid) will be flagged and either refined using ancillary datasets or excluded from fine-scale analysis. Where available, municipal supply scheme datasets will be cross-checked to verify sectoral attribution and abstraction volumes. The cleaned and validated WARMS dataset will then be aggregated to a settlement and grid scale, producing two complementary surfaces: (1) absolute authorised volume (m^3/a) and (2) normalised demand (e.g., $m^3/a/km^2$) for comparability across regions of varying size.

For Level of Dependence, the Green Book Settlement Water Source layer will be joined with Green Book baseline and projected population datasets to quantify present-day and future groundwater-dependent populations at settlement level. Settlements classified as "Combination" (conjunctive use) will be retained as a separate category but weighted according to the proportion of groundwater input where this can be inferred from municipal infrastructure data. Where municipal records or WSDPs/IDPs indicate a change in primary water source since the Green Book baseline (e.g., surface-water scheme connection), settlement classifications will be updated accordingly.

For Domestic Sole Supply, the subset of settlements classified as "Groundwater" in the Green Book will be further screened using settlement-level Groundwater Pressure Risk indicators to prioritise high and extreme pressure-risk settlements. WSDPs and IDPs will then be consulted to confirm sole reliance, remove settlements with recent surface-water connections, and note planned transitions to conjunctive or alternative supply. Population totals for confirmed sole-supply settlements will be calculated for baseline and future time horizons (as per GreenBook estimates).

Once processed, all three Current Demand indicators will be normalised to a five-class ordinal scale to ensure comparability with other MCDA components. Normalisation methods under consideration include equal count, natural breaks, and standard deviation, with selection based on preserving meaningful thresholds for demand intensity.

Within the Four-Par MCDA workflow, the three Current Demand indicators (Groundwater Use, Level of Dependence, and Domestic Sole Supply) will be normalised to a common five-class ordinal scale, weighted equally, and combined to form the Part 3: Current Demand composite raster. A binary mask will then be applied to retain only areas scoring in the upper classes (≥ 4), representing relatively high current demand.

To account for the functional reach of demand centres—reflecting that high-demand nodes may source groundwater from adjacent high-availability GRUs rather than from directly underlying aquifers—contiguous clusters of suitable cells will be buffered using a 10 km radius, consistent with the 2018 SWSA methodology. This buffer distance may be refined based on thematic considerations such as proximity to alternative surface-water sources or known bulk-supply conveyance infrastructure.

The buffered polygons will be overlaid with the Part 2 GRU layer, ensuring that any GRU intersecting the buffered zones is flagged as strategically significant from a demand perspective. This approach preserves both spatial accuracy in high-demand zones and the hydro-functional logic of supply reach, ensuring that delineation prioritises aquifers with favourable hydrogeological potential and substantial current demand within a realistic abstraction catchment (see **Section 3.4.3** Part 3 description and **Figure 3-6** Part 3 Conceptual Diagram).

3.4.3.2. Socio-economic & Development Context

This component captures where groundwater intersects materially with people and the economy. It focuses on settlement-scale economic signal and service provision, strategic planning signals for future water use, and national Special Economic Zones (SEZs). Together, these indicators complement the demand metrics in **Section 3.4.3.1** by highlighting places where groundwater underpins economic activity or service delivery, and where policy or planned development implies strategic future dependence. All inputs are prepared as nationally consistent layers suitable for normalisation and integration into the Part 3 composites.

- **Economic Importance**

  Economic importance will combine the CSIR Green Book settlement-level water-source classification with the sub-national Gross Value Added (GVA) data to identify economically significant settlements that rely on groundwater.

  The Green Book's Settlement Water Source layer classifies each mapped settlement as Groundwater, Surface water, or Combination (conjunctive use) and provides attributes for settlement identifiers and municipal codes, enabling robust joins to other datasets. Spatial geometry follows the Green Book Settlement Footprint polygons (national coverage).

  Limitations include that the "Groundwater" category denotes the primary source rather than exclusive reliance, and the baseline reflects the Green Book reference period (approximately 2016–2019). For the economic signal, the Green Book Economy layers providing GVA (current prices at the time of the study - 2021) by mesozone and related sub-national units will be used. These include total and sectoral GVA fields suitable for aggregation or weighting by settlement footprint. Spatial resolution is finer than province/district and is appropriate for overlay with settlement polygons

- **Water Services Backlog**

  Water services backlog will be quantified from Statistics South Africa (Stats SA) Census 2022 indicators of household with and without access to piped/tap water and main source of drinking water, reported at ward and municipal levels. These tables provide counts and proportions of households by service category, allowing computation of backlog as the complement of minimum service standards (e.g., households without piped water in dwelling / yard / or within 200 m).

  Spatial reporting is national and recent (2022). The usual census caveats apply self-reporting and classification differences, boundary changes relative to earlier censuses, and the need for areal interpolation when assigning ward-level attributes to settlement polygons. Where beneficial for consistency and settlement geometry alignment, CSIR Green Book settlement-scale vulnerability/service-risk layers may be used in support of population-weighted backlog measures, acknowledging their 2016–2019 baseline.

- **Strategic and Future Use**

  Strategic and future use will be inferred from DWS planning instruments that identify growth nodes, supply-mix changes, and priority interventions. These include the National Water Resource Strategy (NWRS-3, 2023), which sets national priorities and flags demand growth regions and strategic interventions; the National Water and Sanitation Master Plan (NW&SMP, 2018 with subsequent updates), which lists priority programmes and augmentation schemes relevant to groundwater or conjunctive options; and the Reconciliation Strategy Studies (large systems and All Towns), which indicate future deficits, option portfolios, and planned groundwater schemes at city-system and town scales.

  Because these sources differ in spatial granularity and update cycles, they will be treated as planning-status flags (strategic nodes/corridors/towns) rather than precise demand magnitudes.

- **Special Economic Zones (SEZs)**

  SEZs will be sourced from the Department of Trade, Industry and Competition (DTIC), drawing on the Special Economic Zones Act 16 of 2014 and official DTIC SEZ programme publications listing designated zones and locations.

  The DTIC SEZ brochure enumerates designated zones (e.g., Coega IDZ, Richards Bay IDZ, East London IDZ, Saldanha Bay IDZ, Dube TradePort SEZ, Maluti-a-Phofung SEZ, OR Tambo IDZ, Musina-Makhado SEZ, Nkomazi SEZ, Atlantis SEZ) with provincial context. Boundaries or centroids will be digitised/validated against the latest DTIC documentation and associated gazettes to ensure currency.

Processing and Integration into Part 3

All four indicators will be normalised to the common five-class ordinal scale (Class 1–5), with transformation choices consistent with Part 1 methods to maintain comparability.

- Economic Importance will be computed by intersecting settlements classified as Groundwater or Conjunctive with GVA mesozone values and producing a population-weighted economic signal at the settlement polygon (e.g., GVA scaled by the share of settlement population in groundwater-reliant categories), then normalised.
- Water Services Backlog will be derived by assigning Census 2022 ward-level access metrics to settlement polygons via areal interpolation, computing the proportion of households below minimum service standards per settlement, and normalising the resulting backlog percentage.
- Strategic and Future Use will be represented as a planning-status layer by encoding NWRS-3/NW&SMP/Reconciliation-study nodes, corridors, and towns as categorical or ordinal classes reflecting strategic priority, then normalised.
- SEZs will be represented as a binary/categorical layer (designated SEZ present/absent or proximity-weighted where appropriate) and normalised to the five-class scale.

Within Part 3, these socio-economic and development context indicators will join the other Set 1 themes (Current Demand and Governance & Policy). Consistent with the Refined Methodology, Set 1 layers will be combined with equal weights and a non-compensatory cell-wise maximum to preserve high values in any individual criterion. A binary suitability mask (≥ Class 4) will then be applied. To reflect the functional reach of demand and development nodes, contiguous suitable clusters will be buffered by 10 km, consistent with the 2018 SWSA approach. The buffered Set 1 polygons will be overlaid with the GRUs from Part 2; any GRU intersected will inherit the highest class value present within the intersecting cells as its Socio-economic & Development Context score for use in Part 4 (see **Section 3.4.3** Part 1 description and **Figure 3-6** Part 3 Conceptual Diagram).

3.4.3.3. Governance & Policy

Datasets and Resolution

This component will capture legal and institutional contexts that elevate or constrain groundwater use. Two national themes are included: legacy Subterranean Government Water Control Areas (SGWCAs) and transboundary treaty obligations. Together they represent domestic statutory controls and international commitments that influence where groundwater development is permissible or strategically sensitive. Additional governance datasets may exist (e.g., current groundwater restrictions, protection zones, gazetted reserve determinations). The project team is engaging the DWS to secure authoritative gazettes, listings, and any companion spatial layers for incorporation in subsequent iterations.

- **Subterranean Government Water Control Areas (SGWCAs)**

  Subterranean Government Water Control Areas (SGWCAs) are legally declared management zones that originated under South Africa’s Water Act (Act 54 of 1956) to regulate drilling and abstraction in sensitive groundwater systems; they continue to be referenced under the National Water Act (Act 36 of 1998) as legacy management units. Declarations and amendments were/are effected by Government Gazette notices, with boundaries and conditions specified per area (e.g., the Ventersdorp Eye SGWCA notice, issued via Government Printing Works).

In parallel, technical and policy reviews (e.g., WRC knowledge series) describe SGWCA purpose and evolution and note their application to high-risk aquifers (e.g., karst springs, artesian basins). Source material is heterogeneous: gazette PDFs (geometry as maps or legal descriptions), DWS holdings, and WRC documentation; spatial coverage is national but discontinuous, and provenance varies by notice date and publisher.

- **Transboundary Treaty Obligations**

  South Africa's international water obligations derive from basin-specific agreements and the regional SADC framework. Core instruments include:

  - SADC Revised Protocol on Shared Watercourses (2000) — establishes principles for cooperation, information exchange, and equitable utilisation across the SADC region.
  - ORASECOM Agreement (2000) — establishes the Orange–Senqu River Commission among Botswana, Lesotho, Namibia, and South Africa to advise on development, utilisation, and conservation of the system.
  - LIMCOM (2003) — establishes the Limpopo Watercourse Commission among Botswana, Mozambique, South Africa, and Zimbabwe to advise on Limpopo basin management.
  - Tripartite Interim Agreement (TIA) on the Incomati & Maputo Watercourses (2002) — between Mozambique, South Africa, and Eswatini (Swaziland), an operational framework for protection and sustainable use pending a permanent instrument.

  Spatial representation will use basin masks for the Orange–Senqu, Limpopo, Incomati and Maputo watercourses; where treaty annexes provide specific nodes/works, those will be tagged. Resolution is basin/sub-basin scale, nationally complete in overlap zones; update cycles follow treaty body publications.

Processing and Integration into Part 3

SGWCA extents will be compiled from gazettes and DWS holdings, digitised where only legal descriptions exist, and validated where scanned maps are available. Polygons will be harmonised to the project projections, cleaned for topology, and rasterised to the Part-3 working grid.

Normalisation to the five-class scale will assign higher classes within SGWCA footprints (Class 5 where explicit restrictions apply; Class 4 where designation is advisory), with transitional treatment along uncertain legacy boundaries documented for transparency.

Transboundary obligations will be mapped to their relevant basin footprints. Where agreements specify critical nodes (e.g., works, control points), those locations will be buffered and merged with the basin masks. A governance raster will then be created and normalised such that areas under multiple or stricter obligations are elevated (e.g., Class 5 for overlapping commissions/agreements; Class 4 for single-agreement areas; Class 1 for non-transboundary basins).

Both SGWCA and Transboundary Obligation layers will be combined into the Set 1 (governance/policy) composite using equal weighting and a cell-wise maximum to preserve high-priority signals. Consistent with Part 3, contiguous suitable clusters (classes ≥ 4) will receive a 10 km buffer to reflect the functional management reach of these instruments. The buffered Set 1 composite will then be overlaid with GRUs from Part 2; any intersecting GRU will inherit the highest intersecting class as its preliminary Strategic Significance Score for governance/policy, before roll-up with other Part-3 sets (see **Section 3.4.3** Part 3 description and **Figure 3-6** Part 3 Conceptual Diagram).

3.4.3.4. Environmental & Ecological Significance

Datasets and Resolution

This component will capture groundwater's role in sustaining sensitive natural systems and ecologically important areas. Two national themes are included: (i) Groundwater-Dependent Ecosystems (GDEs), and (ii) Ecologically Significant Sites (wetlands, biodiversity priorities, protected areas). Together they will provide both a process-based signal of groundwater reliance and a site-based signal of conservation significance. All inputs will be normalised to the common five-class ordinal scale used across Part 3.

- **Groundwater-Dependent Ecosystems (GDEs)**

  A global GDE likelihood product has been released by The Nature Conservancy and the Desert Research Institute, derived using machine-learning methods applied to multi-sensor satellite data at 30 m resolution (Rohde et al., Nature, 2024; Global GDE Map v1.2.0). The dataset includes: (i) a "classification" band (1 = likely GDE, 2 = not likely GDE, 0 = out of model domain) and (ii) a "probability" band (0–100), with a companion certainty layer.

  Although global in extent, the model domain focuses on drylands and semi-arid regions where groundwater reliance is more detectable from earth observation; local validation is recommended where cloud cover, vegetation seasonality, or surface-water adjacency could confound signals. For South Africa, the product provides a nationally consistent screening of potential groundwater reliance at 30 m, suitable for settlement- and GRU-scale overlay once subset and masked to national boundaries.

  To sharpen ecological interpretation, the GDE raster will be complemented by national freshwater ecosystem datasets: the National Wetland Map (current SANBI release; hydrogeomorphic classes encompassing valley-bottom wetlands, seeps, floodplains, pans, and peatlands), the National Freshwater Ecosystem Priority Areas (NFEPA) river/wetland layers identifying reaches and wetlands of high conservation value, as well as GDE potential as mapped by Colvin et al. (2007) describing aquifer dependent ecosystems in key hydrogeological type settings in South Africa. Where available, mapped springs, tufa formations, and karst outlets will be incorporated to aid identification of point-source GDEs. These products collectively provide thematic context (ecosystem type, priority status) at scales suitable for GRU overlay.

- **Ecologically Significant Sites**

  Ecologically significant places relevant to groundwater will be represented using a suite of nationally curated layers: (i) Ramsar Sites (DFFE; official polygons of wetlands of international importance), (ii) the South African Protected Areas Database (SAPAD) and formally protected wetlands within it, (iii) Key Biodiversity Areas (KBA; BirdLife South Africa/SANBI national compilation), and (iv) provincial Critical Biodiversity Areas (CBAs) from Biodiversity Sector Plans aggregated via SANBI's BGIS where national layers require augmentation.

  NFEPA priority rivers and wetlands will provide additional freshwater-specific significance and connectivity. These datasets vary in nominal scale (typically 1:50 000–1:250 000 for wetlands and protected area boundaries; KBAs compiled from multiple sources) but together offer robust, nationally consistent coverage of sites where groundwater-related ecological value is likely to be high. Limitations include differing vintages and update cycles among sources, occasional boundary generalisation (especially legacy polygons), and heterogeneous criteria across provinces for CBAs; these will be documented and handled through harmonisation and confidence notes.

Processing and Integration into Part 3

All inputs will be harmonised to the project scale, integrated to the Part-3 working grid, and clipped to the national boundary. The GDE product will be subset to South Africa and converted to a five-class ordinal surface by scaling the probability band (e.g., quantile- or threshold-based reclassification guided by the product's certainty layer). Wetland and river priority layers will be used to up-class GDE-probability cells that intersect NFEPA priorities, mapped springs, or peatland/valley-bottom wetland HGM types, thereby emphasising groundwater-reliant ecosystems of known conservation importance.

Ecologically Significant Sites (Ramsar, KBA, SAPAD protected wetlands, provincial CBAs, NFEPA) will be rasterised to the working grid (if necessary). To avoid double-counting, overlapping sites will be resolved using a cell-wise maximum of source-specific class values after normalisation (e.g., Ramsar and KBA polygons will retain the higher ecological class if co-incident; sites with multiple designations will inherit the highest class).

A Set 2 composite (environmental & ecological significance) will then be created by combining the normalised GDE surface and the Ecologically Significant Sites raster at equal weight, with a cell-wise maximum operator to preserve high-priority cells from either theme. Consistent with Part 3 buffering logic, suitable clusters (classes ≥ 4) will receive a localised eco-hydrological buffer reflecting short-range groundwater–ecosystem connectivity (e.g., hundreds of metres to ~2–3 km, adjusted by ecosystem type—smaller for springs/seeps and peatlands; larger for riparian corridors where groundwater sustains baseflow). The default buffer will be calibrated during sensitivity testing and refined where karst systems or mapped spring sheds indicate larger influence zones.

The buffered Set 2 composite will be overlaid on GRUs from Part 2; any GRU intersected by a buffered cell will inherit the highest intersecting class as its preliminary Strategic Significance Score (environmental/ecological). This score will then be rolled up with Set 1 (governance/policy and demand-side themes) according to the Part 3 framework, ensuring that GRUs advanced to Part 4 reflect both hydrogeological favourability (Parts 1–2) and strong environmental/ecological justification (see **Section 3.4.3** Part 3 description and **Figure 3-6** Part 3 Conceptual Diagram).

3.4.4. Part 4 – Additional Considerations & Adjustment

Part 4 provides a final refinement to the candidate SWSA-gw GRUs identified in Part 3 (**Section 3.4.2.1**), incorporating contextual pressures that may influence strategic prioritisation. This step ensures that GRUs experiencing elevated levels of groundwater stress, quality concern, or future development pressure are not excluded due to slightly lower base scores. It serves as a corrective mechanism to account for external factors not captured in earlier steps. Importantly, this part of the workflow also allows for the inclusion of additional datasets—beyond those considered in the current methodology—to be integrated in future iterations. Three additional datasets are introduced for this adjustment:

1. Current Status Quo includes indicators of existing pressures on groundwater systems, specifically the presence of stressed or over-allocated aquifers and known pollution hotspots.
2. Groundwater Quality reflects areas where natural water quality may limit usability, or where water is not fit for intended use without treatment.
3. Future Development Options identifies GRUs with strong potential for artificial recharge, or where groundwater may serve as a mitigation measure for climate change impacts.

Each dataset is normalised to the common five-class ordinal scale (Class 1 = Low to Class 5 = High), consistent with the standard applied throughout the Refined Methodology. Once normalised, each raster is reclassified into a binary mask: Cells scoring 4 or 5 are flagged as suitable and assigned an adjustment value of +1; Cells scoring 3 or below are flagged as not suitable and assigned a value of 0.

These three binary masks (which may include additional indicators in future iterations of the methodology) are combined to form a single Adjustment Grid, with values ranging from 0 to +1. This grid is overlaid onto the GRU layer from Part 3 (**Section 3.4.2.1**), and for each GRU, the maximum adjustment value present within its spatial extent is added to its existing Strategic Significance Score.

This approach allows for previously borderline GRUs to be elevated if they are subject to high contextual pressures, thereby expanding the shortlist to include both high-need and high-risk areas. Following this adjustment, a final round of topological cleaning is conducted to ensure spatial coherence and eliminate minor artefacts.

The combined outputs of Parts 3 and 4 yield the final national shortlist of SWSA-gw GRUs, each carrying a refined Strategic Significance Score. This list reflects a fully integrated assessment of:

1. Intrinsic groundwater availability (Part 1)
2. Hydrostratigraphic coherence (Part 2)
3. Socio-economic and ecological value (Part 3)
4. Contextual pressures and management relevance (Part 4)

Together, these components provide a robust, multi-dimensional foundation for scenario testing, sensitivity analysis, and evidence-based groundwater investment planning.

Spatial and MCDA Principles Embedded in Part 4

- Part 4 completes the MCDA cycle by introducing forward-looking and context-sensitive indicators that account for external stressors or policy priorities. It reflects several core spatial MCDA principles:
- Contextual layering: The inclusion of Current Status Quo, Groundwater Quality, and Future Development Options introduces additional themes not considered in core delineation, aligning with adaptive MCDA principles.
- Threshold-based scoring: Conversion of input rasters into binary masks (+1 or 0) applies a rule-based MCDA approach, using transparent thresholds to flag areas of concern.
- Controlled additive scoring: Adjustments are added to base GRU scores but capped at Class 5, reflecting a bounded additive model used in risk-based MCDA to identify high-priority areas without over-amplification.
- Zonal overlay and attribute transfer: Raster values from the Adjustment Grid are intersected with GRUs, and the maximum value is transferred to each unit—mirroring zonal aggregation techniques used in spatial MCDA.
- Integrated prioritisation logic: The final output combines both intrinsic and contextual criteria, resulting in a holistic MCDA framework suitable for policy guidance and groundwater resource planning.

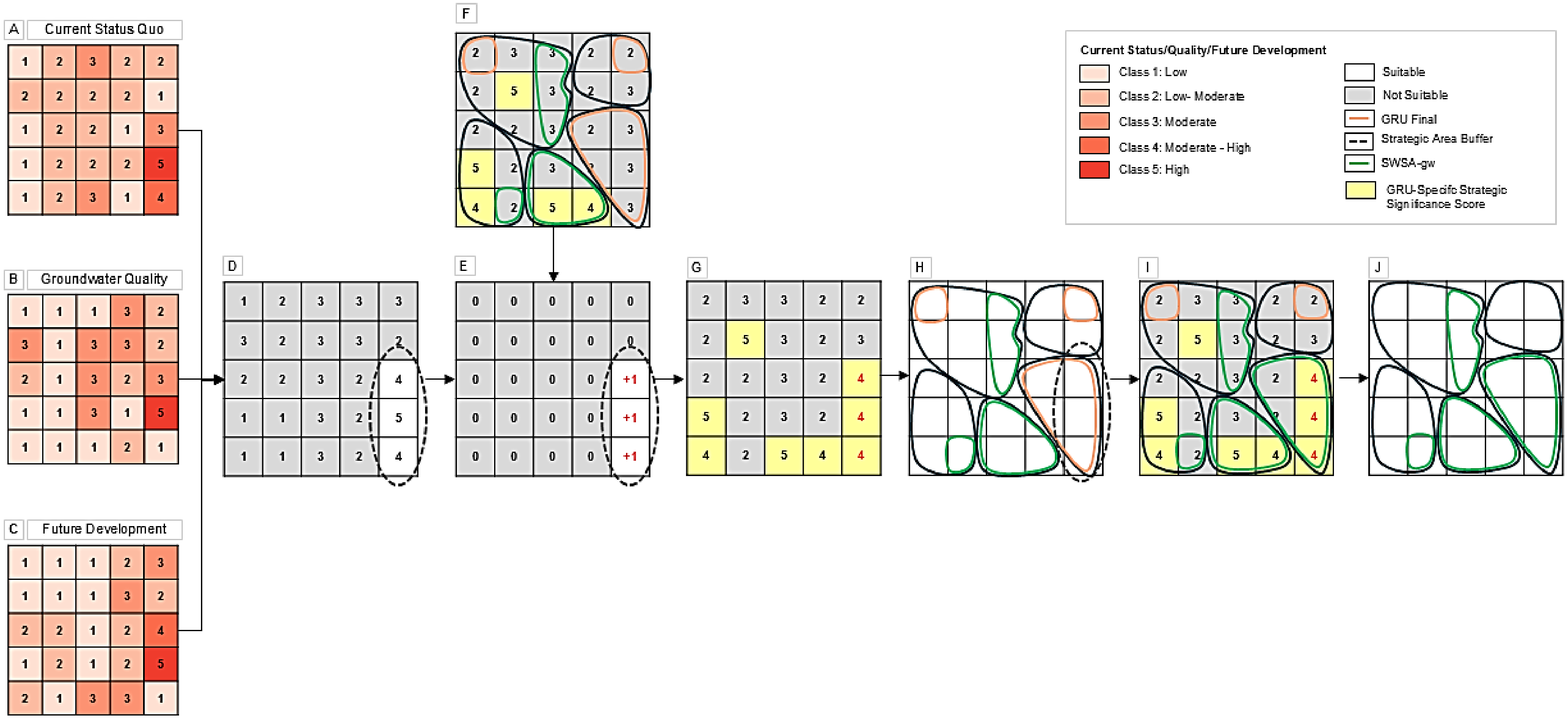


Figure 3-7 **Conceptual flow diagram of Part 4: Contextual Adjustment and Final Prioritisation. Panels A (Current Status Quo), B (Groundwater Quality) and C (Future Development) are the three contextual rasters, each on the five-class scale (Class 1 = Low, Class 5 = High). Cells scoring ≥ 4 are flagged suitable in the aggregated layer D; those ≤ 3 remain (not suitable). Suitable cells are converted to a +1 adjustment mask (E, red values). The mask is added to the baseline Strategic Significance surface from Part 3 (F, yellow = Class 4–5) to create the Adjusted Significance grid in G. GRU boundaries are overlaid (H), and any unit intersecting a +1 cell inherits the higher class (I). GRUs with final scores ≤ 3 are removed, leaving the national shortlist of priority SWSA-gw units in J. Green outlines show the existing SWSA-gw footprint; orange outlines indicate GRUs retained from earlier steps; white/grey shading denotes suitability at each stage.**

3.4.4.1. Current Status Quo

Datasets and Resolution

The Current Status Quo component for the Refined Methodology will draw on the national datasets and interpretive rules already established in the 2025 Status Quo Report (DWS, 2025) review for the existing SWSA-gw (2018), ensuring methodological continuity. Two indicators are carried forward: (i) Stressed / Over-allocated Aquifers, which compares lawful groundwater use to long-term recharge, and (ii) Pollution (Contamination Pressure), which synthesises monitoring exceedances, trends, and land-use hazard intensity. The datasets underpinning these indicators have national coverage but differ in spatial granularity (from borehole/point and 1 km rasters to GRU or quaternary catchment units). For this study, all inputs will be spatially harmonised and reported at the GRU scale to match Parts 2-4 of the workflow.

- **Stressed / Over-allocated Aquifers**

  Stress status in the Status Quo was derived from a reconciliation of WARMS licensed/registered groundwater abstractions against GRA II long-term natural recharge (1 km grid, aggregated to reporting units). Abstraction volumes were compiled by use sector and spatially normalised to the assessment unit, while recharge provided the baseline renewable input under undeveloped conditions.

  The primary indicator was Abstraction:Recharge (%), classified into a five-class scheme (e.g., A < 10%, through to E / F ~ 80–100%) to reflect increasing proximity to allocation limits. Where available, NGA (National Groundwater Archive) water-level trends were used to corroborate stress interpretations (e.g., persistent declines as supportive evidence of high stress). The approach yielded a transparent, nationally comparable stress picture while recognising uncertainties related to legal vs actual abstraction, temporal permit status, and spatial precision of WARMS records.

  To align the approach and preserve methodological continuity, the stress metric will be re-cast on a demand basis that explicitly (a) considers the groundwater component of the Reserve (i.e., Ecological Water Requirements), and (b) treats vegetation-induced recharge reduction from plantations/invasive alien plants (IAPs) as an equivalent “pseudo-demand” term (calculated after e.g., Van Wilgen et al. (2008)).

- **Pollution (Contamination Pressure)**

  The Status Quo synthesised groundwater quality monitoring (WMS/WMS-GW: pH, EC, major ions such as NO_3, SO_4, F, etc.) with land-use hazard proxies to map contamination pressure. Monitoring data were screened for exceedances of drinking-water/reference thresholds and analysed for temporal trends, then summarised to assessment units as an exceedance ratio and trend flag.

  To represent source pressure, National Land Cover (NLC, 2022, 73-class) was used to quantify and weight high-risk land uses (e.g., mining/quarries, dense urban–industrial fabric, intensive agriculture); mining exposure was cross-checked with national mining/AMD context layers. The combined evidence was classified into a five-class ordinal field from “natural / compliant” through to “widespread pollution” balancing measured condition with proximal hazard intensity. Limitations noted in the Status Quo—such as uneven monitoring density, station representativeness, and the proxy nature of land-use hazards—were managed through conservative classing and consistency checks.

Processing and Integration into Part 4

The stressed and over-allocated aquifer index will be recalculated using the most recent WARMS abstraction dataset (**Section 3.4.3.1**) in combination with the recharge layer developed in Part 1 (**Section 3.4.1.1**). WARMS records will be spatially intersected with GRU boundaries, with inactive, expired, or duplicate authorisations removed to improve reliability.

Abstraction volumes will be aggregated per GRU and expressed as a proportion of mean annual recharge to generate an Abstraction-to-Recharge ratio. This ratio will be classified into the five-class ordinal scale, ranging from Class 1 (low utilisation) to Class 5 (over-allocation).

Pollution pressure will be assessed using a combined approach. Observed exceedances of water-quality standards will be calculated from DWS WMS and NGA records, determining the proportion of sampling points within each GRU that exceed national thresholds for key parameters such as nitrate, electrical conductivity, and selected trace metals. This will be complemented by a potential hazard footprint derived from the National Land-Cover dataset, in which high-risk land-use classes are reclassified into a hazard score and summarised per GRU. Both observed and hazard-based measures will be normalised to the five-class scale and merged using a cell-wise maximum to ensure that either measured exceedance or significant hazard coverage can elevate a GRU's pollution class.

For integration into the Four-Part MCDA workflow, the Current Status Quo raster, incorporating both groundwater stress and pollution indicators, is normalised to the standard five-class ordinal scale (Class 1 = Low to Class 5 = High). This raster is then reclassified into a binary mask, with Classes 4–5 flagged as suitable and assigned an adjustment value of +1, and Classes 1–3 assigned 0. This binary mask is combined with the corresponding masks for the other Part 4 indicators (Groundwater Quality and Future Development) to form a single Adjustment Grid with values ranging from 0 to +1.

The Adjustment Grid is overlaid on the GRUs from Part 3 (**Section 3.4.3**), and for each GRU, the maximum adjustment value present within its extent is added to its existing Strategic Significance Score. This process ensures that GRUs experiencing significant stress or pollution are elevated in priority where their baseline hydrogeological or socio-economic score was marginal, aligning with the integrated, non-compensatory MCDA approach described for Part 4 (see **Section 3.4.4** Part 4 description and **Figure 3-7** Part 4 Conceptual Diagram).

3.4.4.2. Groundwater Quality

Datasets and Resolution

This component assesses the natural chemical quality of groundwater resources and their suitability for different end uses. It combines broad national salinity classifications (as a proxy) with finer-scale hydrogeological mapping and point chemistry data to identify areas where natural water quality may limit usability or require treatment. The assessment differentiates between the intrinsic quality of groundwater and its "fitness for use" against recognised potable and sectoral standards. This separation allows for both a hydrogeological perspective and a user-focused interpretation that supports practical water management decisions.

- **Groundwater Quality**

  Groundwater quality will be characterised using the Department of Water and Sanitation's national groundwater quality map (August 2012), which provides broad salinity classes at a minimum cartographic scale of 1:500 000. The classification reflects total dissolved solids/electrical conductivity regimes, expressed as qualitative salinity categories ranging from slightly salty to extremely salty and bitter.

  This national product will be supplemented by the DWS Hydrogeological Map Series (typically compiled at 1:500 000 scale, with some inputs from 1:250 000 geological mapping), which offers finer-resolution polygons by aquifer unit and, in some cases, highlights specific geogenic concerns such as fluoride or nitrate exceedances.

  Where available, point chemistry data from the National Groundwater Archive/Database (NGA/NGDB) and regional monitoring networks will be consulted for validation or local refinement of mapped classes. Limitations include the generalised nature of the 2012 layer, thematic rather than measured boundaries in the hydrogeological sheets, and sparse or temporally inconsistent NGA/NGDB records.

- **Fit for Use**

  Fitness for use will be evaluated by interpreting the mapped groundwater quality classes against current SANS 241:2015 drinking water quality standards and the DWAF (1996) South African Water Quality Guidelines for sectoral applications (e.g., irrigation, livestock watering, aquatic ecosystem health). This step will determine where groundwater meets potable standards, requires minor treatment, or is inherently unsuitable for certain uses.

  Salinity categories will be cross-walked to TDS/EC thresholds, and point chemistry data will be assessed against both potable and sector-specific criteria to flag exceedances. Limitations are that the baseline maps are salinity-focused, with less explicit coverage of chemical constituents influencing fit-for-use (e.g., trace metals, microbiological contamination), and that available monitoring data is unevenly distributed.

Processing and Integration into Part 4

The national salinity/taste polygons from DWS (2012) will form the baseline quality surface and will be spatially refined by incorporating the higher-resolution hydrogeological sheet overlays. Legends from both sources will be harmonised into the project's five-class ordinal scale (Class 1 = low concern/fresh to Class 5 = high concern/very saline or otherwise poor). NGA/NGDB point chemistry will be used to validate or adjust polygon classes, applying SANS 241:2015 exceedances or compliance to elevate or moderate classifications, respectively. The harmonised layer will be rasterised to the project grid.

For Fit for Use, potable and sectoral suitability will be derived by classifying each raster cell according to SANS 241 and DWAF (1996) threshold "classes". Where monitoring data indicates consistent exceedance for key parameters (e.g., TDS, nitrate, fluoride), the cell's fit-for-use category will be downgraded. The resulting suitability raster will be aligned to the 1–5 ordinal scale.

Both quality and fit-for-use rasters will then be reclassified into binary masks following the workflow rules: Classes 4–5 will be flagged as suitable for adjustment and assigned +1, Classes 1–3 will be assigned 0. These binary masks will be combined into the Groundwater Quality Adjustment Grid. This grid will be overlaid on the GRUs carried forward from Part 3, with the maximum adjustment value in each GRU footprint added to its Strategic Significance Score, capped at Class 5. This ensures that GRUs located in areas of significant natural quality concern or poor fit-for-use are elevated in the final prioritisation without overriding the hydrogeological, socio-economic, or ecological signals established in earlier parts of the MCDA (see **Section 3.4.4** Part 4 description and **Figure 3-7** Part 4 Conceptual Diagram).

3.4.4.3. Future Development Options

Datasets and Resolution

This component considers where groundwater development could be strategically expanded in future—either by Managed/Artificial Aquifer Recharge (MAR) or by deploying groundwater explicitly as a climate-change mitigation measure to buffer surface-water shortfalls. The intent is to identify GRUs where favourable hydrogeological conditions coincide with either (a) proven MAR opportunity or (b) high climate-related water-supply risk that groundwater could reasonably offset. As with other Part 4 elements, inputs were normalised to the common five-class ordinal scale to support consistent scoring and masking.

- **Potential for Artificial Recharge**

  Evidence for MAR opportunity drew primarily from the Artificial Recharge Strategy (DWAF, 2007) and the follow-on Potential Artificial Recharge Areas in South Africa assessment (DWA, 2009). These studies delineated MAR-favourable zones by intersecting mapped aquifer polygons with hydrogeological parameters—saturated thickness, specific yield (unconfined) or storativity (confined)—and screening for permeability/yield thresholds, depth-to-water considerations, and practical source-water availability (e.g., surplus surface flows, treated effluent, seasonal dam releases).

Resulting "storage" and "favourability" layers were compiled nationally and commonly summarised at Water Management Area (WMA) and sub-WMA scales; geometry originated from national hydrogeological mapping (typically 1:500 000, with local 1:250 000 refinement), and parameter values were supported by NGDB/NGA borehole records and literature for analogous aquifer types. These products provided a policy-tested baseline of MAR opportunity, albeit at coarser resolution than the 1 km project grid.

- **Groundwater as a Mitigation Measure for Climate-Change Impacts**

  The CSIR Green Book provided settlement-scale indicators of climate-related water-supply risk and drought exposure suitable for identifying where groundwater could mitigate climate stress. Relevant layers included settlement-based Water Supply Risk (composite hazard–exposure–vulnerability metric) and Drought Hazard/Pressure indicators, together with the Settlement Footprint geometry and associated present/forecast populations for magnitude estimates. It is acknowledged that certain DART input data and climate models are outdated, and it is recommended updating the analysis in future iterations; however, resolving this uncertainty is beyond the scope of the present study

  These layers were published as national coverages, attributed at settlement polygon resolution, with underlying climate exposure derived from downscaled projections for mid-century horizons. While not intrinsically groundwater-specific, the indicators captured where surface-water vulnerability and service risk were elevated, providing a logical demand-side signal for potential substitution or conjunctive use by groundwater—especially when overlaid with hydrogeologically favourable GRUs from Parts 1 and 2. Known limitations included baseline timing (ca. 2016–2019), modelled risk (rather than metered service reliability), and potential under-representation of recent scheme upgrades; these were addressed through the integration logic rather than by re-modelling.

Processing and Integration into Part 4

For MAR potential, MAR-favourable polygons from DWAF (2007) and DWA (2009) will be digitised/validated where necessary, harmonised to the project scale, and rasterised to the 1 km working grid. Where both studies provide overlapping attributes (e.g., storage volume proxies, favourability ranks), values will be reconciled to a single ordinal favourability surface. This surface will then be cross-checked against Part 1 indicators (notably Storage Capacity and Recharge) to down-weight areas where mapped MAR favourability conflicts with thin saturated thickness, very low storage, or negligible recharge potential. After harmonisation, the MAR favourability raster will be normalised to the five-class scheme (Class 1 = very low, Class 5 = very high).

For groundwater as a climate-mitigation measure, settlement-level Water Supply Risk and Drought Hazard/Pressure will be translated into a continuous demand-side signal by assigning scores to settlement polygons and transferring those scores to the grid (e.g., area-weighted rasterization or kernel influence to capture near-settlement demand). This demand signal will then be constrained by hydrogeological potential using Part 1 composites: cells will retain their climate-demand score only where Set A (Recharge & Baseflow) and Set B (Storage Capacity & Potential Yield) meet minimum availability thresholds (e.g., Classes ≥ 3) to ensure the mitigation signal only persists where aquifers are plausibly able to supply. The resulting mitigation raster will be normalised to the five-class scheme.

Following the Part 4 workflow, each of the two rasters (MAR potential; groundwater-as-mitigation) will be reclassified to a binary mask: Classes 4–5 will be flagged as suitable and assigned +1, and Classes 1–3 assigned 0. These masks will be combined (logical OR) to form the Future Development Options Adjustment Grid with values in {0, +1}. The adjustment grid will be overlaid on the GRUs carried forward from Part 3; for each GRU, the maximum adjustment value present within its footprint will be added to its existing Strategic Significance Score. This ensures that GRUs situated in areas of strong MAR opportunity or high climate-driven supply risk (where groundwater could act as a mitigation measure) are elevated into the final shortlist even if their base scores were marginal, without over-amplifying beyond the national classification cap (see **Section 3.4.4** Part 4 description and **Figure 3-7** Part 4 Conceptual Diagram).

4. CONCLUSION

This report presents the first generation of a refined methodology for identifying and delineating Strategic Groundwater Source Areas (SWSA-gw) in South Africa. The approach builds on the 2018 national assessment by Le Maitre et al. (2018), retaining its conceptual focus on identifying groundwater areas of disproportionate national importance but replacing the coarse 1 km × 1 km grid and proxy-heavy evaluation with a hydrogeologically grounded, aquifer-specific framework. This refinement directly addresses key gaps identified in the Status Quo Report (Deliverable 3.1) and aligns with the strategic and legal drivers outlined in **Section 2**, including the proposed National Water Amendment Bill (2023), which for the first time formally recognises water source areas—both land and aquifers—as assets requiring legal protection.

The methodology is structured around two core, interlinked components:

- **Enhanced Spatial Framework (Section 3.3.1)**

  Replacing the uniform national grid with aquifer-specific Groundwater Resource Units (GRUs) derived from the CGS 1:250 000 geological series and the DWS 1:1 000 000 hydrogeological series. This ensures that subsequent evaluation is aligned with real aquifer boundaries and hydrogeological behaviour.

- **Enhanced Evaluation Framework (Section 3.3.2)**

  Expanding and restructuring the criteria set to include not only recharge and use (as in 2018) but also baseflow, storage capacity, potential yield, socio-economic and ecological indicators, and contextual factors such as groundwater quality and vulnerability. The framework is transparent, modular, and designed for Multi-Criteria Decision Analysis (MCDA), allowing for parameter weighting, scoring, and aggregation to be clearly documented and repeatable.

Together, these components underpin the Four-Part Workflow (**Section 3.4**):

1. **Groundwater Availability** – This stage evaluates the physical capacity of aquifers to sustain supply over time by combining four key parameters: recharge, baseflow, storage capacity, and potential yield. Recharge and baseflow layers are developed using a downscaled Mean Annual Precipitation (MAP) surface and refined recharge-to-MAP ratios, while storage and potential yield are derived from national geological and hydrogeological datasets. Each parameter is reclassified to a common scale and integrated into composite indices that identify zones with consistently high groundwater potential.
2. **Aquifer-Specific GRU Delineation** – High-availability zones are intersected with mapped aquifer boundaries to produce Groundwater Resource Units (GRUs), ensuring that subsequent evaluation aligns with actual hydrogeological systems. GRUs are retained only if they meet defined availability thresholds, and their aggregated scores from Part 1 are carried forward. This step is critical in shifting from a generic grid-based approach to an aquifer-specific framework that supports practical management and protection planning.
3. **Strategic Significance** – Each GRU is evaluated using socio-economic and ecological indicators that reflect its importance at a national scale. Socio-economic indicators include groundwater dependence for domestic supply, economic activity, and governance context, while ecological indicators consider groundwater-dependent ecosystems and designated recharge protection areas. Using a Multi-Criteria Decision Analysis (MCDA), these indicators are standardised, weighted, and combined to generate a Strategic Significance Score for each GRU.
4. **Additional Considerations & Contextual Adjustment** – The preliminary rankings from Part 3 are refined by incorporating additional datasets that influence viability and resilience, including groundwater quality, aquifer vulnerability, and future development opportunities. These factors allow for the adjustment of scores, and the outcome is a final, prioritised shortlist of GRUs that meet both hydrological and strategic criteria while remaining viable in terms of quality, vulnerability, and resilience.

By building on the previous methodological framework, this refinement keeps the principle of identifying nationally significant groundwater areas but strengthens it in three critical ways:

1. Aligning analysis with aquifer systems rather than arbitrary grids.
2. Broadening and balancing the criteria set to capture both hydrological potential and strategic importance.
3. Embedding flexibility for iterative improvement as new datasets, tools, and policies become available.

As set out in **Section 2.2.4**, this work also adopts the following proposed definition of SWSA-gw for South Africa, consistent with the intent of the 2023 Amendment Bill:

SWSA-gw are aquifers (geological bodies capable of holding and transmitting water) that can naturally supply disproportionately large volumes of groundwater per unit area and are considered of national strategic significance for water security, socio-economic development and sustainability.

The outputs presented here are first-generation results. While the structure and evaluation logic have been established and tested, the upcoming Delineation of Refined SWSA-gw (Deliverable 3.3) will be the critical stage for:

- Sensitivity testing of thresholds, classification schemes, and weights,
- Refinement of parameters, data sources and decision rules based on updated datasets and local validation, and
- Calibration against observed aquifer behaviour and management needs.

While the methodology generates aquifer-specific outputs, these should be regarded as indicative at a national scale. Their application in local or site-specific decision-making requires further validation with local/regional and higher-resolution datasets, local expertise, and ground-truthing to ensure robustness.

The methodology has been deliberately designed to be modular, ensuring that updates can be incorporated without disrupting the core workflow.

Following delineation, the refined outputs will inform the Protection and Management Framework (Deliverable 3.4) and be integrated into the national SWSA-gw database and final national products (Phase 4). By combining a strengthened spatial framework, a broader and more rigorous evaluation process, and a clear definition of SWSA-gw within a legally recognised framework, this methodology provides a defensible foundation for the long-term protection and management of South Africa's most strategically important groundwater resources.

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