GROUNDWATER RESOURCE DIRECTED MEASURES

TECHNICAL REPORT

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ABBREVIATIONS

BFI	Baseflow Index
BHN	Basic Human Needs
CMA	Catchment Management Agency
CRD	Cumulative Rainfall Departure
DSS	Decision Support System
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EARTH	Extended Model for Aquifer Recharge and Soil Moisture Transport through the Saturated Hardrock
EC	Electrical Conductivity
EIS	Ecological Importance and Sensitivity
EMC	Ecological Management Category
ER	Ecological Reserve
EWR	Ecological Water Requirements
EWR_MLF	Ecological Water Requirements for Maintenance Low Flows
GGP	Gross Geographic Product
GRDM	Groundwater Resource Directed Measures
GRIP	Groundwater Resource Information Project
ICM	Integrated Catchment Management
IFR	Instream Flow Requirements
IGS	Institute for Groundwater Studies
IUA	Integrated Unit of Analysis
IWRM	Integrated Water Resource Management
K	Hydraulic Conductivity
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MLF	Maintenance Low Flows
NAPLs	Nonaqueous Phase Liquids

NEMA	National Environmental Management Act
NGA	National Groundwater Archive
NGDB	National Groundwater Data Base
NWA	National Water Act (Act 36 of 1998)
NWRS	National Water Resource Strategy
PES	Present Ecological State
PESC	Present Ecological State Category
RDM	Resource Directed Measures
RQOs	Resource Quality Objectives
RU	Resource Unit
S	Storativity
SA	South Africa
SAM	Strategic Adaptive Management
SANBI	South African National Biodiversity Institute
SDC	Source Directed Controls
T	Transmissivity
UA	Unit of Analysis
USGS	United States Geological Survey
WARMS	Water Use Authorisation and Registration Management System
WMA	Water Management Area
WMS	Water Management System
WR2005	Water Resources of South Africa 2005
WR2012	Water Resources of South Africa 2012
WRC	Water Research Commission

UNITS OF MEASUREMENT

a	annum
cm	centimetre
d	day
i	gradient
km^2	square kilometre
ℓ	litre
m	metre
mg/L	milligram per Litre
m^2	square metre
m^3	cubic metre
mamsl	metres above mean sea level
mbgl	metres below ground level
mbsl	metres below sea level
mm	millimetre
mS	milliSiemens
q	flux
s	second

DEFINITIONS

Abstraction: The act of removing water from a groundwater resource.

Allocable Groundwater: The volume of groundwater available to allocate or distribute.

Alluvial Aquifer: An aquifer comprising unconsolidated material deposited by water, typically occurring adjacent to rivers and in buried paleochannels.

Anisotropy: Having some physical property that varies with direction.

Aquatic Ecosystems: Defined as the abiotic (physical and chemical) and biotic components, habitats and ecological processes contained within rivers and their riparian zones and reservoirs, lakes, wetlands, and their fringing vegetation.

Aquiclude: A geologic formation, group of formations, or part of formation through which virtually no water moves.

Aquifer: Aquifer means a geological formation which has structures or textures that hold water or permit appreciable water movement through them.

Aquifer System: A heterogeneous body of intercalated permeable and less permeable material that acts as a water-yielding hydraulic unit of regional extent.

Aquifer Testing: Aquifer testing involves the withdrawal of measured quantities of water from or the addition of water to, a borehole(s); and the measurement of resulting changes in head in the aquifer both during and after the period of abstraction or addition.

Aquitard: A saturated low permeability unit that can restrict the movement of groundwater. It may be able to store groundwater.

Artesian Aquifer: Artesian is a term originally applied to boreholes in Artois in France from which a constant supply of water was obtained because groundwater spontaneously discharged from them. It is suspected that the term was then applied to confined aquifers into which several artesian boreholes had been sunk. The term artesian aquifer is probably a misnomer, and the term confined aquifer should rather be used.

Artesian Borehole: Boreholes that penetrate confined aquifers in which the piezometric surface is above ground level, so that the boreholes spontaneously discharge water without being pumped.

Assurance of Supply: The reliability at which a specific quantity of water can be provided.

Attenuation: The breakdown or dilution of contaminated water as it passes through the earth's material.

Available Drawdown: Available drawdown in a borehole is the difference between the static water level or piezometric surface and the main water strike (in fractured aquifers) and the pump depth (in porous aquifers).

Available Yield: The amount of water that can be expected to be 'available' for use during any one year, at a specific assurance of supply, either from dams, rivers, or groundwater during any one year.

Bank Storage: Bank storage is water absorbed and stored by the soil pores of the bed and banks of a river, lake or reservoir during higher stage periods and returned, fully or partially to the water body as the water stage falls.

Baseflow: Sustained low flow in a river during dry or fair-weather conditions, but not necessarily all contributed by groundwater; includes contributions from interflow and groundwater discharge.

Baseflow Index (BFI): The ratio of annual baseflow in a river to the total annual run-off.

Basic Human Need (BHN): The least amount of water required to satisfy basic water requirements; this is currently set at 25 ℓ/person/d.

Basic Water Supply: The prescribed minimum standard of water supply services necessary for the reliable supply of a sufficient quantity and quality of water to households, including informal households, to support life and personal hygiene.

Blow Yield: The volume of water per unit of time blown from the borehole during drilling.

Borehole: Includes a well, excavation, or any other artificially constructed or improved underground cavity which can be used for the purpose of intercepting, collecting, or storing water in or removing water from an aquifer; observing and collecting data and information on water in an aquifer; or recharging an aquifer.

Borehole Log: A record of the geological and hydrogeological conditions encountered in the drilling of a borehole and the construction thereof.

Borehole Testing: The process whereby a borehole is subjected to pumping under controlled test conditions in order to determine the performance characteristics of a borehole.

Borehole Yield: The volume of water that can be abstracted from a borehole.

Catchment: Catchment in relation to watercourse or watercourses or part of a watercourse means the area from which any rainfall will drain into the watercourses, or part of a watercourse, through surface flow to a common point or points.

Classification: The classification system prescribed under the National Water Act (1998) provides guidelines on how to set appropriate levels of protection for water resources.

Conceptual Model: A conceptual model includes designing and constructing equivalent but simplified conditions for the real-world problem.

Cone of Depression: The depression of hydraulic head around a pumping borehole caused by the withdrawal of water.

Confined Aquifer: A formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations; confined groundwater is generally subject to pressure greater than atmospheric.

Confining Layer: A layer of low permeability material overlying an aquifer, which restricts the vertical movement of water.

Conjunctive Use: Combined use of surface water and groundwater.

Contamination: The introduction of any substance into groundwater systems by the action of man.

Desired Ecological Status: The future desired status of groundwater within the resource unit as used in setting the groundwater component of the ecological Reserve.

Detached Stream: See disconnected stream.

Discharge Area: That portion of catchment in which the net flow of subsurface water is directed toward the water table.

Discharge Rate: The volume of water per unit of time abstracted from an aquifer system.

Disconnected Stream: A stream detached from and not in hydrological contact with the groundwater system below.

Dissolved solids: Minerals and organic matter dissolved in water.

Drawdown: The distance between the static water level and the surface of the cone of depression.

Dug Well: A shallow large diameter man-made pit or hole from which groundwater can be abstracted.

Dyke: A tabular or sheet-like body of igneous rock that cuts through and across the layering of adjacent rocks.

Ecological category: The assigned ecological condition by the Minister to a water resource that reflects the ecological condition of that water resource in terms of the deviation of its biophysical components from a predevelopment condition.

Ecologically Sustainable Base Configuration Scenario: The lowest acceptable level of protection required for the sustainable use of the entire integrated unit of analysis.

Ecological Water Requirements: The quantity and quantity of water of that resource that is required to maintain the said water resource in its assigned ecological category.

Ecology: The study of the interrelationships between organisms and their environment.

Ecoregions: Regions within which there is a relative similarity in the mosaic of ecosystems and ecosystem components (biotic and abiotic, aquatic, and terrestrial).

Ecosystem: An organic community of plants, animals and bacteria and the physical and chemical environment they inhabit.

Ecosystem Goods, Services and Attributes: The goods, services, and attributes that ecological systems provide that are critical to the functioning of the earth's life-support system, and which contribute both directly and indirectly to human welfare, and therefore have economic value.

Effluent Stream: A stream fed directly by groundwater; the surrounding water table or piezometric surface is above the stream surface; opposite of influent stream.

Electrical Conductivity (EC): Electrical conductivity is a measure of how well a material accommodates the transport of electric charge. The more salts dissolved in the water, the higher the EC value. It is used to estimate the amount of total dissolved salts, or the total amount of dissolved ions in the water.

Ephemeral Rivers: These rivers are generally storm-event driven and flow occurs less than 20% of the time; these rivers have a limited (if any) baseflow component with no groundwater discharge.

Estuary: A partially or fully enclosed body of water, which is open to the sea permanently or periodically, and within which the sea water can be diluted, to an extent that is measurable, with fresh water drained from the land.

Evapotranspiration: The loss of water from a land area through transpiration of plants and evaporation from the soil and surface water bodies.

Exploitation Potential: The volume of harvest potential that can practically be exploited due to borehole yield constraints.

Fault: A zone of displacement in rock formations resulting from forces of tension or compression in the earth's crust.

Feasibility Study: The detailed analysis of a possible solution(s) described in the pre-feasibility study to a water resource related problem to determine if it is feasible.

Fissures: An extensive crack, break, or fracture in rocks.

Fitness for use: Refers to water whose quality meets the requirements for a particular use.

Flow Regime: A hydrological profile of a water resource.

Fluvial: Of, or pertaining to, rivers; produced by river action.

Formation: A body of rock identified by lithic characteristics and stratigraphic position.

Fracture: Any break in a rock including cracks, joints, and faults.

Fracture Flow: Water movement that occurs predominantly in fractures and fissures.

Fracture Zone: A zone of fissures, fractures, cracks, joints, and faults within rocks.

Fractured Aquifer: An aquifer that owes its water-bearing properties to fracturing.

Freshwater: Water that contains less than 1 000 mg/l salts.

Gaining Stream: Synonymous with effluent stream.

Geohydrology: The study of the properties, circulation, and distribution of groundwater.

Groundwater: Water found in the subsurface in the saturated zone below the water table.

Groundwater Allocation: That volume of groundwater that can be allocated for use after consideration of the Reserve and Resource Quality Objectives.

Groundwater Divide: The boundary between two groundwater basins which is represented by a high point in the water table or piezometric surface.

Groundwater Monitoring: The regular or routine sampling, analysis, and evaluation of one or more elements of the groundwater resource for a specific objective(s).

Groundwater Resource: All groundwater available for beneficial use, including man, aquatic ecosystems, and greater environment.

Gross Geographic Product (GGP): Amounts to the total income or payment received by the production factors – land, labour, capital, and entrepreneurship – for their participation in the production within that area.

Habitat: The environment or place where a plant or animal is most likely to occur naturally.

Hard-rock: Igneous, metamorphic, and sedimentary rocks that lack adequate primary interstices to function as a primary aquifer.

Harvest Potential: The harvest potential is the maximum amount of groundwater that can be abstracted per square kilometre per annum in South Africa without depleting the aquifers.

Head: See hydraulic head.

Heterogeneous: Of dissimilar nature. Different in structure or composition throughout.

Homogeneous: Of the same or similar nature. Uniform in structure or composition throughout.

Hydraulic Conductivity: Measure of the ease with which water will pass through the earth's material; defined as the rate of flow through a cross-section of one square metre under a unit hydraulic gradient at right angles to the direction of flow (m/d).

Hydraulic Gradient: The rate of change in the total hydraulic head per unit distance of flow in each direction.

Hydraulic Head: Hydraulic head is the height above a datum plane such as sea level of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system.

Hydrogeology: In South Africa the terms *geohydrology* and *hydrogeology* are used interchangeably. In theory hydrogeology is the study of geology from the perspective of its role and influence in hydrology, while geohydrology is the study of hydrology from the perspective of the influence on geology.

Hydrograph: A graph which displays specific hydrological measurements over time, including water levels and discharges.

Hydrological Cycle: The continuous circulation of water between oceans, the atmosphere and land. The sun is the energy source that raises water by evapotranspiration from the oceans and land into the atmosphere, while the forces of gravity influence the movement of both surface and subsurface water.

Hydrological Year: A continuous 12-month period from 1 October to 30 September.

Hydrology: The study of the properties, circulation, and distribution of water.

Hydrophytes: Plants that take their nutrients directly from water, typically found in water or wet habitats.

Hyporheic Zone: The saturated and biologically active zone in the permeable substrate beneath and adjacent to a riverbed.

Infiltration: The downward movement of water from the atmosphere into the ground.

Influent Stream: An influent stream is positioned above the water table and discharges into the underlying groundwater system.

Interacting Stream: See Intermittent Stream.

Integrated Unit of Analysis: A water resource catchment that incorporates a socio-economic zone but is defined by a watershed.

Interflow: The rapid flow of water along essentially unsaturated flow paths, water that infiltrates the subsurface and moves both vertically and laterally before discharging into other water bodies.

Intergranular Aquifer: A term used in the South African map series referring to aquifers in which groundwater flows in openings and void space between grains or weathered rock.

Intermittent Stream: Rivers and streams whose interaction with groundwater depends on the fluctuating position of the water table, ranging from effluent streams in the wet season to influent streams in the dry season.

Isotropy: The condition of having properties that are uniform in all directions.

Karst Aquifer: Limestone and dolomite areas that possess a topography peculiar to and dependent upon underground solution and the diversion of surface waters to underground routes.

Latrine: A pit used for the disposal of human excreta, particularly prevalent in rural areas.

Leachate: Any liquid, including any suspended components in the liquid that has percolated through or drained from human-emplaced materials.

Lithology: Lithology refers to the physical characteristics of rock.

Losing Stream: See Influent Stream.

Major Aquifer System: Highly permeable formations, usually with a known or probable presence of significant fracturing. They may be highly productive and able to support large abstractions for public supply and other purposes. Water quality is generally very good (less than 150 mS/m).

Mine: A mine can be defined as an excavation in the earth, from which substances such as ores and minerals are extracted.

Minor Aquifer System: These can be fractured or potentially fractured rocks which do not have a high primary permeability, or other formations of variable permeability. Aquifer extent may be limited and water quality variable.

Monitoring Borehole: A borehole used to measure groundwater trends.

Multiphase Flow: Two or more distinct phases of a compound or its breakdown products flowing through the subsurface at the same time.

Nonaqueous Phase Liquids (NAPLs): Organic compounds that do not dissolve readily in water.

Observation Borehole: A borehole used to measure the response of the groundwater system to an aquifer test.

Paleochannel: A paleochannel is an old or ancient channel.

Perched Aquifer: Aquifers that contain perched groundwater, i.e., bodies of groundwater separated from an underlying body of groundwater by an unsaturated zone.

Perennial Stream: Streams where surface flow persists throughout the year.

Permeability: The ease with which a fluid can pass through a porous medium and is defined as the volume of fluid discharged from a unit area of an aquifer under unit hydraulic gradient in unit time (expressed as $m^3/m^2/d$ or m/d); it is an intrinsic property of the porous medium and is dependent of the properties of the saturating fluid.

Phreatophytes: Plants that habitually obtain water from below the water table or from the capillary fringe directly above the water table.

Piezometer: A non-pumping borehole, generally of small diameter, for measuring the elevation of a water table or collecting water samples.

Piezometric Surface: An imaginary or hypothetical surface of the piezometric pressure or hydraulic head throughout all or part of a confined or semi-confined aquifer; analogous to the water table of an unconfined aquifer.

Pollution: Pollution means the direct or indirect alteration of the physical, chemical, or biological properties of a water resource so as to make it –

a) less fit for any beneficial purpose for which it may reasonably be expected to be use;

b) harmful or potentially harmful –

    to the welfare, health of safety of human beings;

    to any aquatic or non-aquatic organisms;

    to the resource quality; or to property.

Poor Aquifer System: These are formations with negligible permeability that are generally regarded as not containing groundwater in exploitable quantities. Water quality may also be such that it renders the aquifer as unusable. However, groundwater flow through such rocks, although imperceptible, does take place, and needs to be considered when assessing the risk associated with persistent pollutants.

Porosity: Porosity is the ratio of the volume of void space to the total volume of the rock or earth material.

Porous Media: A geological formation with voids or pore spaces within the porous texture that can hold water or permit water movement.

Potable Water: Water that is safe and palatable for human use.

Pre-Development Condition: The condition of that resource prior to significant alteration to its biophysical components by human impact.

Pre-feasibility Study: A Pre-feasibility study focuses on the additional work that has been identified in the Reconnaissance study to better define the options available for solving a water resource problem.

Preferential Flow: The preferential movement of water through more permeable zones in the subsurface.

Primary Aquifer: An aquifer in which groundwater moves through the original interstices of the geological formation.

Quaternary Catchment: A fourth order catchment in a hierarchal classification system in which a primary catchment is the major unit.

Recharge: The addition of water to the saturated zone, either by the downward percolation of precipitation or surface water and/or the lateral migration of groundwater from adjacent aquifers.

Recharge Area: An area over which recharge occurs.

Reconnaissance Study: A desktop study of options available on a catchment scale to solve a water resource related problem.

Remediation: Reduce the concentrations of contaminants in groundwater to some acceptable level.

Remote Stream: See Disconnected Stream.

Reserve: Reserve means the quantity and quality of water required –

a) to satisfy basic human needs by securing a basic water supply, as prescribed under the Water Services Act, 1997 (Act No 108 of 1997), for people who are now or who will, in the reasonably near future, be –

   relying upon;

   taking water from; or

   being supplied from,

   the relevant water resource; and

b) to protect aquatic ecosystems in order to secure ecologically sustainable development and use the relevant water resource.

Resource: A resource is a substance or item available for use. A natural resource is a resource that man can use but cannot manufacture or create.

Resource Directed Measures (RDM): A term used but not defined by the National Water Act. The objective of Resource Directed Measures is to facilitate the proactive protection (for use) of the country's water resources, in line with sustainability principles. The National Water Act (NWA) recognises the need to develop and use the country's water resources to grow. However, the Act also recognises that our water resources should not be used to the detriment of future users. RDM hence strives to ensure that the water resources are afforded a level of protection that will assure a sustainable level of development for the future. To this end, RDM comprises three main interrelated components, namely:

- Classification
- Reserve
- Resource Quality Objectives.

Resource Quality: The quality of all the aspects of a water resource including –

- the quantity, pattern, timing, water level and assurance of instream flow;
- the water quality, including the physical, chemical and biological characteristics of the water;
- the character and condition of the instream and riparian habitat; and
- the characteristics, condition and distribution of the aquatic biota.

Resource Quality Objectives (RQOs): A term used but not defined by the National Water Act. Resource Quality Objectives are used to put a Classification and Reserve into practice by specifying conditions that will ensure that the Class is not compromised, and the Reserve can be met. Resource quality may relate to critical flows, groundwater levels and quality that must be maintained.

The objectives are to articulate goals that result from the catchment visioning process but must be based on DWAF policy statements and methodologies and aligned with the National Water Resource Strategy.

Rest Water Level: The groundwater level in a borehole not influenced by abstraction or artificial recharge.

Riparian Habitat: Area of land directly adjacent to a stream or river, influenced by stream-induced or related processes.

River: A physical channel in which runoff will flow from higher to lower ground, and to the sea.

River System: A network of rivers ranging from streams to major rivers and, in some cases, including rivers draining naturally into separate catchments that have been interconnected by man-made transfer schemes.

Rock: Any mass of mineral matter, whether consolidated or not, which forms part of the earth's crust.

Runoff: All surface and subsurface flow from a catchment, but in practice refers to the flow in a river, i.e., excludes groundwater not discharged into a river.

Safe Yield: Safe yield is defined as the maximum rate of withdrawal that can be sustained by an aquifer without causing an unacceptable decline in the hydraulic head or deterioration in water quality in the aquifer.

Saline Intrusion: The replacement of fresh groundwater by saline water in an aquifer, usually as a result of groundwater abstraction.

Sanitation: The prescribed minimum standard of services necessary for the safe, hygienic, and adequate collection, removal, disposal or purification of human excreta, domestic wastewater and sewage from households, including informal households, to support life and personal hygiene.

Saturated Zone: The subsurface zone below the water table where interstices are filled with water under pressure greater than that of the atmosphere.

Seasonal Stream: These streams are driven by seasonal rainfall patterns and flow occurs between 20% and 80% of the time. These streams have a limited baseflow component with little or no groundwater discharge.

Secondary Aquifer: An aquifer in which groundwater moves through secondary openings and interstices, which developed after the rocks were formed.

Semi-confined Aquifer: An aquifer that is partly confined by layers of lower permeability material through which recharge and discharge may occur.

Significant Water Resource: A term used but not defined by the National Water Act. It relates to the size of the water resource rather than its importance. A resource is deemed to be significant if it is large enough to warrant its own Reserve determination.

Sill: Sheet-like body of igneous rock which conforms to bedding or other structural planes.

Sinkhole: Sinkholes are subsidence or collapse features that form at points of local instability and are usually associated with dolomite or karstic landscapes.

Situation Assessment: An assessment describing the status quo of groundwater-related issues within a study area.

Soil: The usually thin upper surface layer of the earth's crust comprising living organisms, organic matter, decomposed rock or unconsolidated sediments, water, and gases with properties attributable to the interaction of its parent material, time, climate, fauna, and flora.

Sole Source Aquifer: An aquifer that is needed to supply 50% or more of the domestic water for a given area, and for which there are no reasonably available alternative water sources should the aquifer be impacted upon or depleted.

Special Aquifer System: An aquifer designated as such by the Minister of Water Affairs, after due process.

Specific Yield (Sy): The ratio of the volume of water that drains by gravity to that of the total volume of the saturated porous medium.

Spring: A point where subsurface water emerges at surface, usually as a result of topographical, lithological or structural controls.

Storage Coefficient (S): The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Stream: A small narrow river; often used interchangeably with river.

Subsurface Water: All water occurring beneath the earth's surface, including soil moisture, that in the vadose zone and groundwater.

Surface Water: Bodies of water, snow, or ice on or above the surface of the earth (such as lakes, streams, ponds, wetlands, etc.).

Sustainable Development: Use, development, and protection of natural resources in a way and at a rate that allows for social, economic, and cultural needs of people and communities to be met without compromising the ability to meet the needs of future generations.

Transmissivity (T): The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It is expressed as the product of the average hydraulic conductivity and thickness of the saturated portion of an aquifer.

Unconfined Aquifer: An aquifer where the water table is the upper boundary and with no confining layer between the water table and the ground surface. The water table is free to fluctuate up and down.

Unsaturated Zone: That part of the geological stratum above the water table where interstices and voids contain a combination of air and water, synonymous with zone of aeration or vadose zone.

Velocity: Two types of groundwater velocities are of interest to geohydrologists:

- *Darcy flux*: The Darcy flux (or velocity) is the hydraulic conductivity (K) times the gradient of the water/piezometric level (i.e., $q=Ki$).
- *Seepage velocity*: The seepage velocity is defined as the Darcy flux divided by the effective porosity. This is also referred to as the average linear velocity.

Vulnerability: The vulnerability of groundwater to contaminants generated by human activities considering the inherent geological, hydrological, hydrogeological characteristics of an aquifer.

Water Course: A river or spring; a natural channel in which water flows regularly or intermittently; a wetland, lake, or dam into which, or from which, water flows; any collection of water that the Minister of Water and Environmental Affairs may, by notice in the Government Gazette, declare to be a water course (National Water Act, Act 36 of 1998).

Water Management Area (WMA): An area established as a management unit in the National Water Resource Strategy within which a Catchment Management Agency will conduct the protection, use, development, conservation, management, and control of water resources in South Africa.

Water Resource: Includes a water course, surface water, estuary, or aquifer.

Watershed: Means a line of separation between water resources.

Water table: The upper surface of the saturated zone of an unconfined aquifer at which pore pressure is equal to that of the atmosphere.

Wellfield: A group or cluster of boreholes in an area used collectively to supply sufficient groundwater to a user or users.

Wetland: Land, which is transitionary between terrestrial and aquatic systems, where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil.

Xerophytes: Plants that have adapted to dry or arid conditions.

Yield: The quantity of water removed from a water resource, e.g., yield of a borehole.

EXECUTIVE SUMMARY

In 2007, a research study to develop the methods to assess the groundwater component of the Resource Directed Measures [RDM] was initiated. This study was funded by the DWS, implemented by the Water Research Commission (WRC) and undertaken by a Professional Service Provider (PSP). As methods of this study were applied and tested, gaps were identified, for example, the issue of scale i.e. regional scale versus local scale. Subsequently in 2011, a new project was conducted to build on the existing information, address the gaps identified in the methods and include new methods which could be applied to assess groundwater resource directed measures [GRDM]. The outcomes of the project were a revised methodology as well as updated GRDM software. This study was completed in 2013.

There has been a gradual improvement in methodologies for groundwater modelling and groundwater protection thereof. With the continuous use of the 2013 GRDM methodology and software version, some serious issues with the methodology have come up and gaps identified. Furthermore, the software presented serious short-comings in application by the users. These issues include, but not limited to; addressing the issue of quaternary catchments delineation whilst groundwater is not bounded by them; groundwater contribution to baseflow (or ecological water requirements – EWR); capability to update data used as new data becomes available; formatting of the quality component of groundwater Reserve; accommodating groundwater-surface water interaction in the assessment of the resource; and linking of GRDM to the existing databases of the DWS where possible. In addition to that, various review exercises by experts in the groundwater field, in studies commissioned by the WRC, have highlighted issues with the current GRDM methodology which need to be addressed in order to protect the groundwater resource effectively.

All these have necessitated the updating of the current GRDM methodology, which entails the enhancement of the software for its functionality and that it becomes user friendly. The DWS officials are the target users for the system when determining groundwater resource classes and the Reserve, and setting the resource quality objectives [RQOs]. With challenges relating to staff turnover in the DWS and required training to DWS officials on the use of the GRDM methodology and software, it was deemed necessary that a formal training programme be developed as part of this project and awareness created among the water resource managers among others.

The main aim of the GRDM Project to be concluded in the year 2024 was to improve GRDM methodology and its associated software to standardize the approach used in all GRDM studies and to improve knowledge and practical skills necessary for protection of groundwater resources in the country. For the main objective of the project to be achieved, the following specific objectives were established for the project; 1) To update the GRDM methodology for classification, Reserve determination, and setting of RQOs for groundwater resources, 2) To improve the GRDM software with user-friendly features and its functionality, 3) To provide theoretical training on the GRDM methodology, practical training on field data collection, and practical demonstration on the application of the GRDM software.

The initial phases of the project included identifying knowledge gaps from literature, and having workshops with users of the methodology and software to gather information about their experiences with the methodology and software. Workshop attendees included a wide variety of participants. Students, lecturers, DWS officials from around the country, consultants and other organizations that depend on the information and data produced by the GRDM method and software. Seven issues were identified as knowledge gaps during the analyses including aspects of the methodology and software. The need to incorporate the updated GRDM methodology, the need to capture recharge values per aquifer delineation, the need to make the software more user-friendly (easy to enter user data as it comes), the need for specifics about the river where the baseflow comes from, the need to provide a comprehensive analysis of water quality, the need to show icons for groundwater contribution to baseflow, the need to simplify the 15 steps for desktop delineation work. Two additional workshops were held for the duration of the project, one to share progress with attendees and to get input regarding the method development, and the other to provide training on the methodology, data collection and software.

The updated methodology outlines a few key parameters and the approach used to determine key values that contribute to the reserve and RQOs, these include recharge, groundwater dependent population, the contribution of groundwater to baseflow. These parameters are integral to the figures that are calculated for the reserve of a particular area. Considering the determination of RQOs for a particular area for water quality parameters, a new method called the CDC method or concentration duration curve method was used. Recharge methods used or prescribed to users of the methodology include only those methods for the saturated zone, as potential recharge can lead to overestimation of recharge and hence over estimation of the reserve. These include the Chloride Mass Balance (CMB), the Rainfall Infiltration Breakthrough (RIB) method, the EARTH model, The water-table fluctuation (WTF) method and the cumulative rainfall departure method (CRD). The groundwater use term in the reserve determination previously related to the total population of an area, this has been narrowed down to reflect only actual groundwater dependent population. Which is a more accurate value to use to reflect groundwater use in a particular area. Baseflow is made up of water from various sources hence it is not a good measure of the role of groundwater in reserve determination. Baseflow was previously overestimated in some areas, the use of baseflow separation to determine the GW contribution to baseflow as a percentage of the total baseflow was the approach used in the updated methodology. Other significant changes to the methodology include the first step of the classification process, delineating the unit of analysis. Previously this was viewed as a quaternary catchment. This is however not always relevant when dealing with groundwater systems. The UAs are decided based on geohydrological, hydrological and ecological criteria, considering the significance of groundwater. The major adaptation for RQO determination is that a list of parameters including major ions and some compounds with health related impacts be included. Parameters related to specific land use practices in areas should also be used. Additionally, the use of water quality guidelines is discouraged especially for the natural environment, as highly mineralized areas are not likely to adhere to water quality guidelines, but are in a natural state. Hence the concentration duration curves are recommended where data is available.

The GRDM software was adapted to deal with most of the parameters highlighted by the gap analysis. A long list of software specific adaptations were recorded from interactions with workshop attendees and literature. The software was updated bearing in mind the user inputs. Beta testing took place with a postgraduate group of students at NWU. This highlighted a few aspects of the software that needed some work. This facilitated further improvement of the software's user friendliness. Training of DWS national office officials and some regional officials took place at a workshop at the University of the Western Cape to address any additional issues with the software. The training provided included methodological changes, field data collection and software training. A website housing the software is available, along with training videos and help files to guide users during the use of the software.

The methodology and software have been tested and compared for different catchments as part of testing of reliability of the method and software.

Applying the methodology and software to two catchments showed that the use of groundwater dependent population, groundwater contribution to baseflow and appropriate recharge methods greatly improved the reserve values determined. The updated version of the software and methodology makes use of a double layer model. This enables the consideration of confined and unconfined portions of aquifers. This allows for two values of reserve to be determined for the same surface area. This addresses the issue of people having water available while the unconfined aquifer has been fully or over allocated.

Shortcomings of the software and method identified related to data accessibility and availability. Default values are used where up to date data is not available, these normally relate to historical data such as that used for GRAII.

Recommendations of the work are as follows:

- To facilitate more accurate aquifer delineation countrywide, updated geological information is required. E.g. aquifer thickness, structural features, aquifer types.
- To improve the accuracy of determining the quantity and quality reserve of a particular area, National databases (e.g. GRAII used data from 2012) need to be updated as part of a separate/new project
- To accurately assign a class, set RQOs and to determine the reserve, monitoring data and data from other sources need to be made available. GRDM software makes use of national databases as much as possible.
- To ensure that proper training of users and potential users of the software takes place countrywide. This was highlighted during workshops as a need.

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1. INTRODUCTION

1.1 Background

Sustainability, equity, and efficiency are identified as central guiding principles in the protection, use, development, conservation, management, and control of water resources. Chapter 3 of the National Water Act (Act 36 of 1998) (NWA) focuses on the protection of South Africa's water resources. Resource Directed Measures (RDM) are the three (classification of water resources, quantification of the Reserve, determination of the Resource Quality Objectives) measures used for the purpose of water resources protection in the country. When these measures are directed specifically to groundwater resource protection, they are referred to as Groundwater Resource Directed Measures (GRDM).

To be able to implement the NWA for water resources protection, required tools and expertise must be available to facilitate the practise. In response to this need, The Department of Water and Sanitation (DWS) established the Framework Programme for Education and Training in Water (FET-Water). Through the FET-Water, the DWAF documented methods to undertake the groundwater component of RDM determinations in Volume 6 of the September 1999 version of RDM for water resource protection. Since then, several research projects and Reserve determination studies have been undertaken. In the year 2007, a research study to develop methods and a software to assess the groundwater component of the RDM was initiated. Johan Wentzel, Roger Parsons, and Ingrid Dennis formed part of the team that compiled the 2007 GRDM manual, with the GRDM software which had been initially developed by Prof Gerrit van Tonder.

The application of the GRDM 2007 methodology in practise provided insight on the shortcomings of the methodology which required redress and improvement. This resulted in the undertaking of a new project in 2011 which was conducted to build on the existing information, address the gaps identified in the methods and include new methods which could be applied to assess GRDM. The outcomes of the project which was completed in 2013 were a revised methodology as well as updated GRDM software.

Due to the developing nature of the field of groundwater resources protection and management some serious issues and gaps were noted in the application of the 2013 GRDM methodology and software version. Furthermore, over the last decade or two, new knowledge has become available regarding groundwater systems that may not have been accounted for in the 2013 GRDM methodology.

The identified challenges related to the application of the 2013 GRDM methodology necessitated updating of the GRDM methodology and its associated software. As a result, financial support was made by the DWS, and the Water Research Commission (WRC) was made available for the improvement of the 2013 GRDM methodology. The University of the Western cape (UWC) was appointed to undertake the project titled "Groundwater Resource Directed Measures Methodology Update, Software Enhancements, and Training".

1.2 The Current GRDM Project [2024]

The main objective of the GRDM Project to be concluded in the year 2024 is to improve GRDM methodology and its associated software to standardise the approach used in all GRDM studies and to improve knowledge and practical skills necessary for protection of groundwater resources in the country. For the main objective of the project to be achieved, the following specific objectives were established for the project; 1) To update the GRDM methodology for classification, Reserve determination, and setting of RQOs for groundwater resources, 2) To improve the GRDM software with user-friendly features and its functionality, 3) To provide theoretical training on the GRDM methodology, practical training on field data collection, and practical demonstration on the application of the GRDM software. The trainings that are provided by the Research Team would improve computation/analysis of data for protection of groundwater resources and for the uptake of the improved knowledge and practical skills.

1.3 Key Focus Areas of the GRDM Project

The current GRDM project build on the existing GRDM methodology and the software. The project focuses only on the aspects that that have been identified as needing improvements. Therefore, areas that needed improvement on the GRDM methodology had to be identified, and this was ensured by sourcing information from the Terms of Reference (ToR) for the project from the DWS, review of relevant literature, and conducting wide/ public stakeholder workshops. The identified key focus areas that required improvement were grouped into six (6) key focus areas which are i) key parameters, ii) water resource classification, iii) Reserve determination, iv) determination of RQOs, v) the GRDM software, vi) GRDM implementation.

1.4 Purpose of the Close-Out Report

The close-out report on the updated methodology and software for GRDM serves to highlight several aspects of the project as outline below but not limited to these aspects only:

First, the close-out report provided a short summary with an executive summary of the research project from inception to completion. Secondly, the report showcased the creation of new knowledge alongside the competency development via capacity building of university students. These students were involved in various practical technical tasks including their Ph.D. and MSc theses tasks. Thirdly, the dissemination and application of the generated knowledge were carried out via various training sessions and workshops online and in-person meetings. Fourthly, innovations and new research areas that came out from the research project were demonstrated and recommendations were made to carry those aspects further the current project. Finally, the progress made and reports and deliverables were provided in detail and as snapshots as well.

2. INFORMATION GAPS: KEY ISSUES NEEDING UPDATES

2.1 Literature Review

The gap analyses took on a phased approach, with initial gap analyses being based on published reports and literature and the second phase involving stakeholders, which included participants from academia, consulting, and government. Many of these stakeholders were either users of the software or receivers of the results of the outputs of the software. When consulting the literature and stakeholder gap analyses, it was evident that there was some overlap, and there were definite gaps highlighted that linked to the methodology, software, implementation, or both.

Methodological updating was a recommendation from both stakeholder and literature gap analyses. It is a requirement of the software update. The main aspects that were highlighted regarding the methodology were aspects that directly impacted the reserve determination. Parameters that are discussed in the literature include recharge, baseflow, and groundwater quality. Methods for estimating groundwater recharge and their accuracy and appropriateness for different environments were highlighted as one of the critical aspects that require updating. The issues related to recharge link to how the recharge is estimated (based on average annual rainfall), the level of uncertainty of determined values, and how one would determine or account for recharge in an area that has experienced prolonged drought or where there is more than one aquifer system. Issues of scale in the methodology were highlighted by both literature references and stakeholders. The unit of study used by DWS is quaternary catchments, while aquifer boundaries do not coincide with these surface water river basins/catchments. The methodology and hence the software have difficulty in addressing the issue of scale and groundwater properties or parameters that might differ when considering a shallow, versus a deeper aquifer system. The difference between local versus regional recharge or potential versus actual recharge is lost due to the issues of scale. Consideration of groundwater-specific guidelines was suggested, as developed guidelines may be based on surface water and drinking water/health, while certain groundwater environments may in their natural state not be suitable for drinking, but may not be contaminated per se.

Data availability, data types, measurement frequency, and distribution were also raised by stakeholders participating in the workshop and was a point that was considered during the literature GAP analysis. There is no certainty that this can be addressed as data sets used during the methodology and software depend on the level of national datasets that are available, it may require a shift in the extent to which data is collected and redefining what data is collected.

Recharge methods, this was a contentious issue during the workshop. The accepted way of calculating recharge using annual and average values and water balance methods. This is challenged by climatic changes and the fact that rainfall primarily occurs in a short period while the calculations use the entire year. Also depending on the environment and the amount of rainfall, rainfall does not always equal the occurrence of recharge, hence the use of threshold values for different types of environments in the software. This contributes to the value eventually determined as the reserve. So, refining the recharge method would refine the determination of the reserve and the baseflow contribution to rivers.

With regards to the software update, several issues were raised by stakeholders regarding the software. Literature gap analysis unearthed issues with user-friendliness and functionality relating to baseflow and water quality. Stakeholders were concerned about different versions of the software being available and the ease of use of older versions seemed to be preferred, while this was resulting in erroneous figures for the reserve. It was concluded that the latest version of the software compared to earlier versions was deemed more suitable, however, the updates from the methodological updates would need to be included (recharge, baseflow, and water quality related). The latest version of the software had limited training, and it can be said that it has not been properly evaluated by users. Users of the older versions of the software were doing so as they were well-trained and comfortable with the older versions.

Both literature gap analysis and workshop gap analyses revealed that a large and focused training component is required once the software update is completed. Reasons from the literature and stakeholders include, ensuring capacity within the governmental departments; Ensuring proper rollout and acceptance of the software; To ensuring that all users have a good understanding, and that help is available. Users and potential users of the software gave a detailed account of what would constitute an effective training program and continued learning about the software. It was in line with what came from the literature. Requirement of a user guide with step-by-step operational manual. Users specified that quarterly training or refreshers be offered. Another aspect of training included the availability of short video clips of about 2 minutes demonstrating every step of working with the software. The setting up of a community of practice where users can share concerns with the software was also suggested, as well as regular discussions as required.

2.2 Stakeholder Engagement

Through sharing knowledge, skills, and experiences as they interact throughout the activities of the GRDM project, stakeholders [developers, users, and researchers] have been working on addressing prevailing challenges, practicing problem-solving techniques, and internalizing protocol set for future references regarding the technicalities about the GRDM methodology and software. We agreed to design a training manual to cover the following themes/topics: 1: Step-by-step user guide; 2: Troubleshooting guide with tutoring service; 3: Computational guide with tutoring service; 4: Quarterly meetings with actual users, potential users, and developers; 5: A team of Community of Expert Practitioners with support service to be addressing the Question-and-Answer aspects. The suggested course topics and descriptors are covered in the training manual in chapter 8 of this report. Details of training materials on GRDM are available on request.

2.3 Department of Water and Sanitation Engagement

The research team has been engaging the DWS staff members from the Department of Water and Sanitation both at the regional office in Bellville and at the head office in Pretoria. These engagements were on data collection including the context, objectives, and expected outcomes for the update of the existing GRDM methodology and software among others. Being the final users of the updated methodology and software, such engagements provided a relevant reflective analysis and ensured that the final product should be relevant to day-to-day use within the Department of Water and Sanitation and institutions of higher learning.

2.4 Software Gaps

A gap analysis, whether it pertains to software applications or departmental objectives is about taking a realistic snapshot of where something is at the current moment and comparing it against where it should be. The difference, or gap, that resides in the middle helps you to understand what needs to happen in order to move from one point to the next. Various workshops where existing users of the GRDM system were engaged were held for the purpose of the gap analysis. The feedback from users were used to compile a list of issues they experience with the existing software generation and this was used to create an action list for targeting specific functionality that needs to be addressed. These are discussed below.

After consultation with the existing and future users through workshop platforms, the identified issues and requests were categorised into four classes as shown in **Error! Reference source not found.**.

Table 1– Classification of identified issues

Category	Description
1. Software Enhancement	Enhancement of existing functionality or bug fix required in G2.
2. New Functionality	New functionality required i.e. new methods or change in existing methodology required.
3. Out of Scope	These requests are considered out of scope of this project, but will added to recommendations.
4. Existing Functionality	This is functionality that already exists in G2 and users might not have been aware of it – relates to training of software. Alternatively the issue is already addressed in one of the other categories.

Error! Reference source not found. to **Error! Reference source not found.** provides a summary of the identified list together with the comments from the software development team. All category 4 items were illustrated to the project team that they do in fact exist in the G2.

Table 2– Software functionality to enhance

No	Software Issue Identified	Comments
1	In the current software version, the database requires Microsoft Access Drivers that cannot coexist with newer Office versions such as 365. Thus, the need to migrate to a new database.	Migrating to SqlLite.
2	In the updated version, the interface needs to change to "green" to distinguish it from the Aquiworx blue personality. This is ensuring that users see the change get used to the new change.	Green personality will be assigned to G3.
3	Sometimes the software does not display all the boreholes on the map when imported with the spreadsheet e.g., if you import 8 boreholes only 6 are displayed.	Would be helpful to get dataset that does this. A borehole name are not allowed to have a space in it, maybe it might be such an issue? Testing will be done with provided data.
4	The software should allow for export of the final map.	Image format already supported, will look into PDF format.
5	The software must be stable before release; the PSP shall therefore provide 12 months GRDM software maintenance and technical support services, after the completion of the GRDM software enhancements aspects of the project.	Beta testing will be conducted making use of provided case study. The same case study will form the basis for training workshops and help material.
6	Update GRDM GUI making use of FNC Components.	Proposed by the developer as G2 made use of DevExpresss components and no existing license exists. The developer has a FNC license and these components are web ready as well.
7	The WR2005 data should be replaced by the WR2012 data as this is the most recent dataset.	This requires 450 rainfall text files to be processed and 1946 flow files. Might be worth while writing a program or script to do the processing as it will take quite a bit of time doing it by hand.
8	Update census data.	Research team to provide dataset per quaternary for database update.
9	Update of existing use data (WARMS).	Research team to provide dataset per quaternary for database update.
10	The total Reserve calculation must be re-visited. The calculation should be BHN + GWbf or BHN + EWRgw. Currently the equation appears to add BHN + Baseflow.	The GWbf can be obtained from Herold's method. The EWRgw are not readily available for each quat, but it can be included so that the user specify this.

Table 3– New functionality required

No	Software Issue Identified	Comments
11	Quaternary catchment delineation which is more related to surface water than groundwater which behaves differently. It is recommended to consider aquifer delineation or rather groundwater resource units.	Since the G2 already account for custom delineation of groundwater units, maybe the underlying water balance model requires a new approach. Research team to document new methodology for implementation.
12	The need new methods for groundwater contribution to baseflow.	Currently software supports Herold's method and a mass-balance approach. Research team to document new methodology for implementation.
13	The inclusion of help files or frequently asked questions or prompts during the process that give users tips and pointers or advice regarding tabs they have selected.	Video help tutorials will be created and a FAQ Blog/User Group will be established.
14	The need to provide a comprehensive analysis of water quality.	Research team to document new methodology for implementation.
15	Revisit the formats of various outputs of the software in order to align them with the formats used by the DWS team to report on groundwater Reserve, e.g., Reserve template Tables, maps and their Legends to follow the DWS specifications.	Research team to document new methodology for implementation.
16	Default Chem values using Vegter Maps	Research team to provide dataset per quaternary for implementation.

Table 4– Out of scope requests

No	Software Issue Identified	Comments
17	The need to add an overlaying quaternary map on the map of aquifer types.	The system GIS already makes provision for this and the user can import the groundwater occurrence map. No aquifer map exists for South Africa and it does not fall within the scope of this project to create such a map.
18	Explore the possibility of linking GRDM to the existing and relevant DWS databases as this will ensure use of up-to-date data as it is updated in a given database.	Various databases exist that provide valuable information to the GRDM, these include, WR2012, GRAII, NGA, GRIP, WARMS, DWS Hydrological Services and DWS Resource Quality Services. None of them provide a public interface through which programmatic queries could be directed to obtain the data. An interim solution to have programmatic queries be executed on some of these databases is web scraping, but it should be noted that if any format change takes place on the targeted platform, the web scarping will fail and will have to be adapted. The optimal solution is that each database provide an API to access the required data via the internet.
19	The software should be continuously updateable as new data and information become available. For instance, as new Recharge values become available with various research studies, so these must be editable to replace the old ones from e.g., GRA II.	This only requires the database to be updated. As the current database is local users will only see the updated values if they download an update of the software. An online database is a possibility, but falls outside the scope of this project.
20	Quality characterization plots must be expanded and not only limited to Piper and Radar charts.	This is not considered as part of the scope of the project unless it is explicitly required by the updated methodology.

Table 5– Functionality already existing

No	Software Issue Identified	Comments
21	The Quaternary shape file containing the base data needs to be updated as it mainly contains the Groundwater Resource Assessment II (GRAII) data.	The GRAII data has not been updated since the release of the project, so there is no new data in GRAII. If a newer dataset can be provided, the shapefile can be updated.
22	Quaternary catchment delineation which is more related to surface water than groundwater which behaves differently. It is recommended to consider aquifer delineation or rather groundwater resource units.	Already supported in G2.
23	The need to capture recharge values per aquifer delineation.	Already supported in G2.
24	The need for specifics about the river where the baseflow comes from.	Current values are representative of quat and obtained from WR2012.
25	Automation of the addition of shapefiles.	Import function does exist and can be automated. The GRDM cannot distribute DWS product without permission. Users must contact data owners and get permission for use.
26	The need to simplify the current 15 steps process for desktop study for delineation.	Current delineation process is not 15 steps. All GRDM steps work in the context of the object tree and therefore steps cannot be reduced.
27	Estimation of groundwater contribution to baseflow. Currently, it seems only the baseflow is considered.	See point 12.
28	The software does not indicate the river from which the baseflow was estimated and its geographical location. It further does not show the name and location of the flow station.	See point 7.
29	The software needs to enable the user to add a hydrological station and upload its data such that this can be included in baseflow separation.	Already supported in G2.
30	Recharge values need to be presented as volumes instead of percentages.	Already supported in G2.
31	It is not readily clear how the issue of groundwater-surface water interaction is handled in the software. This needs to be elucidated.	See point 12.
32	Groundwater quality component methodology needs to be re-conceptualised. This involves coming up with the appropriate way of assessing and presenting quality considering the difficulty of presenting it at a catchment scale. For instance, if there are two boreholes in one catchment, and one has good quality water whilst the other has bad quality water, the Reserve class for the catchment would follow that of bad quality, which might not be applicable to the user who is located in the vicinity of a good quality water borehole.	Please provide methodology to implement. See Point 14.
33	There is a scaling up of the groundwater quality Reserve by 10% provided it is not more than the basic human needs quality Reserve but there is no scientific basis or a definition for such allowance. Additionally, there is setting of the 5th and 95th percentiles that are used for the groundwater quality, however, it is not defined as to when these percentiles are applicable.	See point 14.
34	Layers are not readily available or are hidden, and shapefiles have to be uploaded manually.	See point 25.
35	The software uses WR90 for estimation of baseflow using the Herold method. It is recommended that it uses WR2012, possibly where resource data and information has been enhanced.	See point 7.

36	A toolbox approach should be followed where a software user is able to interrogate the output parameters for a given area, and not use a rigid algorithm.	The toolbox approach is already supported in G2, not sure what is meant with the comment on "a rigid algorithm" as all calculations are indeed based on rigid algorithms.
37	If the output result does not make sense, the user should be able to work through it and come up with a scientifically acceptable result.	Is this a software or user issue? This comment is disregarded.
38	The software must be user-friendly, and it must be able to give a model report in a pre-determined template format.	Please specify which parts are not user-friendly and how this can be improved. See Point 15.

3. GRDM METHODOLOGY UPDATES

3.1 Key Parameters for GRDM Studies

In Chapter 2, a gap analysis has been provided highlighting parameters that required updating in terms of practical measurements for Reserve and RQOs determination. In this section, a demonstration is provided on how to execute such parameters in different aquifer settings.

3.1.1 Recharge parameter:

Groundwater recharge can be determined by an array of methods, depending on the hydrogeological settings. Local or regional or actual or potential recharge mechanisms need to be considered when estimating groundwater recharge. Such mechanisms guide the selection of the methods to be used and guide interpretations of results obtained from estimations. Table 6 provides the available methods for estimating groundwater recharge. Estimated values from groundwater recharge assessments need to be relevant to inform action about groundwater resources i.e., groundwater planning, allocation, monitoring, and protection among others.

Table 6. Methods for estimating local, regional, potential, and actual groundwater recharge

Zone	Approach	Method	Limitation
Surface water	Physical	Baseflow	Emphermal rivers
		CWB	Inaccurate flow measurements
		WB	Emphermal rivers
Unsaturated	Physical	Lysimeter	Surface runoff
		UFM	Poor known relationship between hydraulic conductivity moisture
		ZFP	Subsurface heterogeneity; periods of high infiltration
	Tracer	CMB	Long term atmospheric deposition unknown
		Historical	Poorly known porosity; present ^3H levels almost undetectable
Saturated - Unsaturated	Physical	CRD	Deep (multi-layer) aquifer; sensitive to specific yield (Sy)
		EARTH	Poorly known Sy
		WTF	inflow/outflow and Sy usually unknown
	Tracer	CMB	Long-term atmospheric deposition unknown
Saturated	Physical	GM	Time-consuming; poorly known transmissivity; sensitive to boundary conditions
		SVF	Flow-through region; multi-layered aquifers
		EV-SF	Confined aquifer

	Tracer	GD	^{14}C, $^{3}H/^{3}He$, CFC: poorly known porosity / correction for dead carbon contribution

HS: Hydrograph Separation – Baseflow	CWB: Channel Water Budget
EARTH: Extended model for Aquifer Recharge and Moisture Transport through Unsaturated Hardrock	WTF: Water Table Fluctuation
WM: Watershed Modelling	CMB: Chloride Mass Balance
UFM: Unsaturated Flow Modelling	ZFP: Zero Flux Plane
SVF: Saturated Volume Fluctuation	GM: Groundwater modelling
EV-SF: Equal Volume - Spring Flow	GD: Groundwater Dating
CRD: Cumulative Rainfall Departure	

Equations for calculating various parameters

1. The water-table fluctuation (WTF) method provides an estimate of groundwater recharge by analysis of water-level fluctuations in observation wells. The water-table fluctuation (WTF) method provides an estimate of groundwater recharge by analysis of water-level fluctuations in observation wells. The method assumes that a rise in water-table elevation measured in shallow wells is caused by the addition of recharge across the water table.

Recharge by the WTF method is estimated as:

$$R(t_j) = Sy * DH(t_j) \qquad (1)$$

Where, R (t_j) (cm) is recharge occurring between times t_0 and t_j, Sy is specific yield (dimensionless), and DH (t_j) is the peak water level rise attributed to the recharge period (cm).

2. Chloride Mass Balance method (CMB): Chloride is regarded as a suitable environmental tracer since it is highly soluble, conservative, and not substantially absorbed by vegetation. The chloride mass-balance method is convenient and inexpensive because of its simple data requirements. The CMB method hinges on the principle that a portion of the chloride in rainfall and from dry atmospheric deposition infiltrates the zone of saturation. The assumptions necessary for successful application of the chloride mass-balance method are:

i. The absence of additional chloride sources such as dissolution of minerals, use of road salts and any potential source of pollution like wastewater.

ii. Chloride is of a conservative nature in the system meaning that the ion neither leaches from, nor is absorbed by, aquifer sediments and does not participate in any particular chemical reaction.

iii. The depth of the groundwater table should be deep enough to prevent groundwater evaporation.

iv. Surface runoff should be minimal.

Chloride Mass Balance method: Calculation

$$R = P * \frac{Cl_p^-}{Cl_{gw}^-} \quad (2)$$

Where, R is recharge (mm/year); P is rainfall (mm/year); Cl_P^- is weighted average chloride concentration in rainfall (mg/L); and Cl_{gw}^- is average chloride concentration in groundwater (mg/L).

3. The RIB model simulates groundwater levels, and it accounts for the manner in which recharge occurs. The RIB model uses the relationship between water level fluctuation and the departure of rainfall from the mean rainfall of a preceding time. The water level fluctuations from the monitoring borehole should be representative of the study area; the term groundwater abstraction (Qp), flow (Qout) and volume changes (Qoth) could be ignored if the impact of pumping and/or outflow on WTF is not evident; the specific yield should be representative of the aquifer system; it is usually applicable where transmissivity is relatively small, and where the water level responds clearly to rainfall and where suitable time series of rainfall and groundwater level are available.

Rainfall infiltration breakthrough (RIB)

$$RIB(i)_m^n = r\{\sum_{i=m}^{n} Pi - (2 - \frac{1}{Pav(n-m)} \sum_{i=m}^{n} Pi) \sum_{i=m}^{n} Pt\} \quad (3)$$

(i=1, 2, 3…I) (n=i, i−1, i−2 …N) (m=i, i−1, i−2 … M) m<n<I

Where: RIB(i) is the cumulative recharge from rainfall event of m to n; I is the total length of rainfall series, while parameters m and n, introduced as memory markers, represent the start and end of a time series length, during which period rainfall events contribute to the breakthrough RIB(i); r is a fraction of cumulative rainfall departure; Pi is the rainfall amount at ith time scale (daily, monthly or annually); Pav is the mean precipitation of the whole time series; Pt is a threshold value representing the boundary conditions (Pt ranges from 0 to Pav).

4. Cumulative rainfall departure (CRD) method: CRD is a method that uses the relationship between groundwater levels and the rainfall pattern to estimate recharge. The cumulative rainfall departure (CRD) method depends on the water balance principle. It is assumed that CRD is the driving force behind a monthly water level change if the other stresses are relatively constant. The groundwater level will rise if the cumulative departure is positive, and it will decline if the cumulative departure is negative.

Cumulative Rainfall Departure (CRD) method

$$ {}_{i}^{1}CRD_i = \sum_{n=1}^{i} R_n - \left(2 - \frac{1}{R_{av}\, i} \sum_{n=1}^{i} R_n\right) \sum_{n=1}^{i} R_t \quad (4)$$

$$(i = 1,2,3, \ldots N)$$

Where, R_t, a threshold value representing aquifer boundary conditions, is determined during the simulation process. It may range from 0 to Rav with 0 indicating an aquifer being closed and Rav implying that the aquifer system is open, perhaps being regulated by spring flow.

5. EARTH (Extended model for Aquifer Recharge and soil moisture Transport through the unsaturated Hardrock) is a lumped parametric model that simulates water levels by coupling climatic data, soil moisture and groundwater levels to estimate groundwater recharge.

The general equation for estimating recharge with the EARTH model can be written as follows:

$$S\frac{dh}{dt} = R - \frac{h}{DR} \quad (5)$$

Where R is recharge (m^3/month), S is specific yield and dh/dt is change in water level head during the month, DR is the drainage resistance (site specific parameter), h is the groundwater level.

6. Saturated Volume Fluctuation (SVF) method is a lumped parametric method that considers the change in storage against recharge and abstraction. Water levels from observation boreholes are combined to establish the saturated volume status for the entire aquifer.

Saturated Volume Fluctuation (SVF) method

$$R + I - O - Q = S\Delta V \qquad (6)$$

Where R is Recharge (m^3/month), I = inflow into the aquifer (m^3/month), O = outflow from aquifer (m3/month), Q denotes withdrawal from the aquifer (m^3/month), S is Specific yield and ΔV change in saturated volume (m^3/month).

3.1.2 Groundwater-dependent population for basic human needs

The Water Services Act (Act No. 108 of 1997) currently sets the basic human needs (BHN) threshold at 25 l/p/d. By multiplying the population of a resource unit by 25 l/d, it is simple to get the BHN component of the Reserve. This volume needs to be increased by the proportion of people who rely on groundwater for their water supply in order to be accurate. This correction is rarely required, though, as the BHN component is typically quite minor (in comparison to recharge).

There must be a clear citation for the population numbers utilized in this calculation.

Those who currently depend on a water resource or who will in the reasonably near future are referred to as being in the Reserve. Although there is no explanation of what is meant by "the reasonably near future," it is presumed that this refers to a time frame of about five years. The most recent census data will do for estimating this component of the Reserve because they are rarely updated more regularly than this and because the basic human needs component is typically extremely minimal.

Methods for calculating groundwater-dependent population

Basic Human Needs (BHN) (25 l/p/d is accounted for in determining the Reserve; this volume is the minimum and may be gradually increased as necessary, this method is an oversimplification. The assumption that everyone uses groundwater leads to the over-allocation of the resource. Alternatively, a more accurate method is using the groundwater-dependent population. The data for this method is acquired from the NGA, WARMS, and Stats SA. For this, the abstraction data from the WARMS database can used to determine the allocation of water per GRU. The Stats SA data can be used to retrieve the number of individuals depending on groundwater per quaternary catchment. To get this information, one needs to be part of the water user association or forum where groundwater user meeting quarterly on groundwater use related discussions.

3.1.3 Groundwater contribution to baseflow

Baseflow is made up of water from various sources hence it is not a good measure of the role of groundwater in reserve determination. There is a need to calculate the amount of groundwater only in the calculation of groundwater reserve. Measures focused on groundwater must consider the quantification of groundwater outflow mechanisms. Measuring the contribution of groundwater to surface water requires accurate methodology. There are various methods for calculating the contribution of groundwater to surface water. These consist of:

- Direct seepage measurements using seepage meters
- Hydraulic tests using mini piezometers
- Chemical analysis
- Trace tests
- Hydrograph separation

Equations and parameters

Digital filters

The Nathan and McMahon (1991) filter is given by;

$$Q_s(t) = \beta Q_s(t-1) + \frac{(1+\beta)}{2}\{Q(t) - Q(t-1)\} \quad (7)$$

$$\boldsymbol{Q_b(t) = Q(t) - Q_s(t)} \quad \textbf{(8)}$$

where $Q_s(t)$ = surface runoff at time t, $Q_b(t)$ = baseflow, $Q(t)$= total flow, β = parameter, t = time interval which is daily interval.

The Eckhardt (2005) digital filter is given by;

$$Q_b(t) = \frac{(1-BFI_{max})\alpha Q_b(t-1) + (1-\alpha)BFI_{max}}{1-\alpha BFI_{max}} Q(t) \quad (9)$$

where $BFImax$ = maximum value of the base flow index, and α is the recession constant.

The Lynne & Hollick (1979) algorithm is given by;

$$qf(i) = \alpha\, qf(i-1) + ((q(i) - q(i-1)))\ (1+\alpha)/2 \quad (10)$$

Chapman (1991) algorithm is given by;

$$qf\,(i) = \frac{3\alpha-1}{3-\alpha}\, qf\,(i-1) + \frac{2}{3-\alpha}\,(q\,(i) - \alpha\, q\,(i-1)) \qquad (11)$$

In both equations q (i) refers to the original streamflow for the ith sampling instant, qf (i) is the filtered quick flow for the ith sampling instant, q (i-1) is the original stream flow for the previous sampling instant to i, qf (i-1) is the filtered quick flow for the previous sampling instant to i and α is the filter parameter. According to Welderufael & Woyessa, (2009), the most appropriate alpha and beta parameters to be used in the filtering algorithm were 0.925 and 0.5.

Given that separation algorithms only provided the component of river flow derived directly from direct runoff (rainfall), calculating the difference between the filtered river flow and the total recorded river flow using the proposed filter parameter (0.925) was required to calculate the baseflow contribution. The fraction of total flow obtained from the baseflow (BFI) was calculated after determining the baseflow component. The baseflow and baseflow index were calculated using the following equations using the filtered quick flow value qf (i -1)

$$\text{Baseflow: } qb\,(i) = q\,(i) - qf\,(i) \qquad (12)$$

$$\text{Baseflow index (BFI \%)} = qb\,(i) / qf\,(i) \qquad (13)$$

Mass balance equation using EC

The baseflow separation method assumes that baseflow equates to groundwater contribution, which is not always the case. In conjunction with this method, a mass balance method using EC concentrations by Yang et al. (2014) was used to estimate groundwater contribution to baseflow. The used EC concentrations in groundwater and surface water were measured in the field using the multi-parameter probe (YSI). The mass balance equation is as follows.

$$Q1 = Qin\,(Cin - Cg)/(C1 - Cg) \;/\; Qin = Q1\,(C1 - Cg)/(Cin - Cg) \qquad (14)$$

$$Qg1 = Q1 - Qin \qquad (15)$$

Where the Qg1 and Q1 are the groundwater discharge in the first segment and the discharge at the end of the first segment in m^3 /s; Qin is the inflow from the upstream in m^3/s; Cg and C1 are the tracer values of the groundwater discharge and total discharge at the end of the first segment in µS/cm

3.1.4 Probability Concentration for RQOs

Methods

The quality component of the reserve can be determined using two methods i.e., concentration duration curves and baseline analysis or background condition. The CDC method is used to establish the percentage of time a concentration level of a particular water quality parameter is met and sustained in a particular area. The curves are generated using the recorded historic groundwater quality data, which is ranked in an ascending order for the total of *n* values in Microsoft Excel. However, ranking recorded historic data generated CDCs for pH in a descending order for the total of *n* values for lower limits, and in an ascending order for the total of *n* values for upper limits. The concentration value for each of the water quality parameters was given a rank (M) starting with 1 for the lowest value of concentration. Exception for pH, where value was given a rank (M) starting with 1 for the lowest value for upper limits and starting with 1 for the highest value for lower limits. The CDC is plotted with calculated *P* values on the *X*-axis (% equaled or exceeded) and corresponding concentration values on the *Y*-axis (mg L^{-1}), and mSm^{-1} in case of electrical conductivity.

Equations

The equal or exceedance probability for each concentration of water quality parameter considered was determined using the formula:

$$P = (\frac{M}{n+1}) \times 100 \quad (16)$$

where *P* = the probability that a concentration will be equalled or exceeded (% of time); M = assigned a rank number; *n* = the total number of data set recorded on each water quality parameter for a period of record.

Parameters

The water quality parameter for the CDC method is dependent on the user's objective but these are some of the common parameters used (Ca, Mg, Na, NO3, Cl, SO4, F, EC)

3.2 Groundwater Resource Classification

Step 1: Delineate the units of assessment (UA) and describe the status quo of the water resource(s)

The key outcome of this step is a map demarcating UAs, each of which is to be classified, a Reserve assessment undertaken and Resource Quality Objectives (RQOs) set. In most instances, it is assumed that the UA is the quaternary catchment[1]; however, this might not always be the case. The UAs are decided based on geohydrological, hydrological and ecological criteria, considering the significance of groundwater. Other aspects such as physical and management criteria must also be considered. Figure 1 demonstrates the delineation of units of assessment.

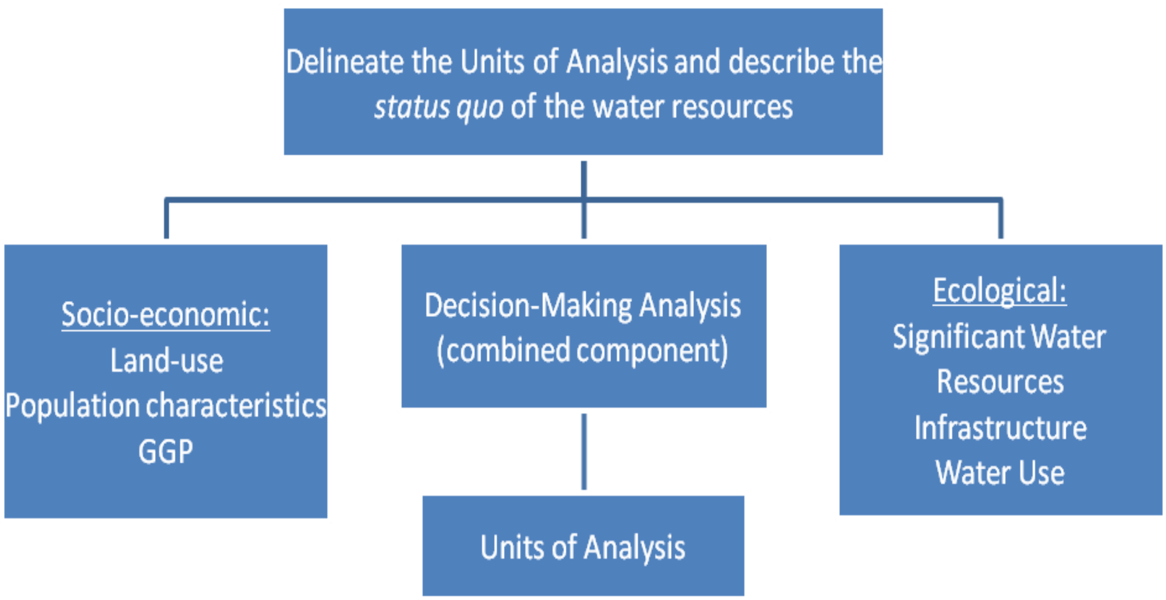

Figure 1: Delineation of UAs

The catchment should be described in as much detail as possible with appropriate maps included to assist the specialists in collecting data (relevant to the catchment area) on their specialist fields and to identify the main areas of impact in the catchment. This would then also assist the GIS specialist in determining the UAs.

Units of assessment can be delineated using aquifer extent maps which are overlayed with quaternary or quinary catchment boundary maps. This enables more accurate estimation of recharge figures per unit of assessment. Unit of assessment should be based on the delineated aquifer or aquifer scale. Recharge, Abstraction, groundwater dependence, RQOs should be monitored on aquifer scale rather than quaternary scale.

Step 2: Link socio-economic and ecological value and condition of the water resource(s)

The project team can then select areas for more detailed studies. Groundwater nodes need to be established with the objective of predicting probable surface water – groundwater areas of interaction, specifically, of groundwater supplying water to rivers, springs, wetlands and other terrestrial ecosystems. To this end, a multi-tiered approach to establishing the location and number of nodes in a target catchment is recommended. The nodes may capture the following:

- Lithological boundaries at aquifers and aquitards.
- Groundwater contribution to base flow.
- Groundwater contribution to wetlands.
- Geological faults.
- Groundwater levels.
- Springs.

Stakeholders should be the primary drivers of the GRDM process, and they should be included in the assessments to ensure all their concerns and issues are addressed. Socio-economic2 issues must be considered. These include factors such as land-use, population statistics and gross geographical product (GGP).

Step 3: Quantify the ecological water requirements and changes in non-water quality ecosystems goods, services and attributes

This step is where the ecological requirements, basic human needs etc. are calculated. Typical calculations include:

- Recharge estimation
- Groundwater surface water interaction
- Groundwater use
- Groundwater quality estimations
- Aquifer vulnerability
- *Groundwater dependent ecosystems*
- *Ecological Water requirements for maintenance Low Flows (EWRMLF)*

Step 4: Assess system and set baseline class (or configuration)

The concept of a baseline configuration in groundwater is not easy to quantify. However, the objective of Step 3 of the classification procedure is to set the water quantity (use) and quality base configuration in terms of long-term sustainability.

Indexes or indicators are selected to describe the baseline class and are used in scenarios to describe change. They should cover the main physical and chemical aspects of the system, including issues raised by stakeholders. Potential indicators are suggested in this section.

Defining the point at which a resource is no longer being used in a sustainable manner is generally very difficult. The level of sustainability probably fluctuates through time and impacts from over-use could manifest themselves sometime after the impact was caused. The change from sustainable use to over-use is gradational, and not necessarily marked by some distinct change. Indicators of quantitative unsustainable groundwater use include:

- Land subsidence or sinkhole formation.
- Long-term declining water levels on a regional level.

- Long-term declining water quality levels.

Step 5: Scenario development within the IWRM process

The objective of Step 5 of the classification procedure is to evaluate scenarios within the IWRM process so that a subset of catchment configuration scenarios can be put forward for stakeholder evaluation in Step 5. The current Classification (status quo and management) of the Resource should be presented to stakeholders and they must be informed of the implications thereof. Different management scenarios can include changes in land use and climate change impacts. It is for them to decide, taking the social and economic considerations into account, whether they would like to change the Management Class.

Important note: With regard to groundwater quality management, the NWA states that the classification system for water resources may establish procedures which are designed to satisfy the ***water quality requirements*** *of water users as far as is reasonably possible,* ***without*** *significantly altering the* ***natural water quality*** *characteristics of the resource. The NWA classification system does not explicitly refer to groundwater. The water quality includes, in this regard, all aspects of a water resource, i.e. beyond quantitative and ecological aspects, also the* ***water quality, including the physical, chemical and biological characteristics*** *of the water.*

Step 6: Assess scenarios with stakeholders

This phase will normally be part of the bigger assessment where groundwater has been integrated into the other components of the Reserve. The procedure as spelt out by Dollar *et al*. (2006) should be followed.

Step 7: Gazette class configuration

This phase will normally be part of the bigger assessment where groundwater has been integrated into the other components. The procedure as spelt out by Dollar et al. (2006) should be followed.

3.3 Reserve Determination

3.3.1 Quantity Component

The reserve, according to the National Water Act (NWA 36 of 1998), is an unallocated part of water that is not in competition with other users. It refers to the quantity and quality of water necessary to meet basic human needs by securing a basic water supply as required by the Water Services Act (Act 108 of 1997), for people who currently rely on, take from, or are supplied by the relevant water resources or who will do so in the near future. It also refers to the need to protect aquatic ecosystems in order to ensure the development and use of the relevant water resources in an ecologically sustainable manner (known as the ecological reserve).

The ecological reserve must be determined using approved procedures. In order for all of the ecosystems in the water resource to maintain or reach the chosen level of health and, as a result, be classified as an ecosystem, the methodologies call for quantifying the flow, habitat, and water quality requirements of each ecosystem. According to Palmer et al. (2000), the NWA is one of the most comprehensive and progressive water laws in the world and is supported on two pillars. In accordance with Local Agenda 21 and the Republic of South Africa's constitution, one of sustainability and one of equity. The main goal of the NWA is to ensure that the nation's water resource is protected, used, developed, conserved, managed, and controlled in ways that consider meeting the basic human needs of the present and future generation, promoting social and economic development, managing floods and droughts, and complying with international obligations, among other things. The twin pillars that support the right in law to the use of water for human and environmental needs are the twin pillars (DWAF, 2003a). The reserve must be measured using recognized techniques.

The minister must establish the reserve in accordance with Section 16 of the NWA following the classification of the water resources. A sufficient allowance must be provided for each reserve component when determining the reserve in line with section 13 of the NWA.

The process of determining groundwater reserve is broken down into eight related parts.

Step 1: Start evaluating the natural water requirements and fundamental human demands.

Step 2: Pick study locations, define resource units, and identify eco-regions.

Step 3: Determine each study site's reference condition.

Step 4: Analyse the ecological condition and fundamental human requirements of each chosen study site.

Step 5: Determine operational possibilities and their effects on the socio-economic and ecological systems.

Step 6: Review the scenarios with the relevant parties.

Step 7: Create a suitable monitoring program.

Step 8: Gazette and put the reserve into effect.

Approach

Reserve quantification is the measurement of the amount of groundwater that can be removed from a groundwater unit without negatively influencing the groundwater system. The fraction of the groundwater resource known as the groundwater reserve contributes to ecological water needs while still providing for fundamental human needs. To calculate the groundwater component of the reserve, the amount of groundwater needed to meet ecological water needs and basic human needs must be calculated. The following ecological needs for water:

- groundwater's contribution to river baseflow [groundwater discharges into rivers or flux measurement in rivers]
- groundwater's contribution to wetlands [groundwater discharges into wetlands or flow measurement into wetlands]
- Groundwater's contribution to springs (quantification of spring flows) and other groundwater-dependent ecosystems (GDEs).

Quantifying the contribution of groundwater to surface water is necessary. Due to a number of considerations, including geographical and seasonal volatility in groundwater allocation to users without significantly harming the reserve, it is currently difficult to determine or quantify the contribution of groundwater to baseflow. Information about groundwater's contribution to baseflow is included in Section 1 of this study. Groundwater quantification statistics are available, according to maps of South Africa's aquifer categorization areas produced by the CSIR in 2013. There are sizable aquifer regions with very productive aquifer systems and high-quality water. There are weak aquifer regions with low to negligible yielding aquifers of moderate to poor water quality, and minor aquifer regions with moderate-yielding aquifers of variable water quality. In order to access the database and do additional groundwater resource quantifications as well as evaluate the quality of the groundwater reserve, this categorization is required.

In determining the reserve, recharge methods should consider the type of aquifer system/s in the delineated unit of assessment, basic human needs (BHN) quantity needs to reflect only the groundwater dependent population and baseflow should be expressed as groundwater contribution to baseflow, see calculations in chapter 8.

3.3.2 Quality Component

Approaches

Groundwater quality can be evaluated spatially and temporally in South Africa, and this evaluation can be used to gain access to the database that created the maps using the Cape Mapper database from the department of Agriculture. The CSIR created maps in 2012 and 2013 that displayed the propensity or possibility for pollution to arrive at locations in the groundwater system following introduction at a place above the highest aquifer system. The least vulnerable areas, including moderately vulnerable areas that are exposed to some pollutants but only when continually discharged or leached, were identified, and mapped. These areas are only long-term vulnerable to conservative contaminants. There is information and a database on the most vulnerable aquifer regions, which are susceptible to all contaminants apart from those that are strongly absorbed or easily changed in scenarios with multiple pollutants.

Murry et al. (2012) and DWA (2013) used the database to create a spatial assessment in the form of a susceptibility matrix map that included both the aquifer's vulnerability and its relative importance in terms of its classification. The map showed the qualitative measures of the relative ease with which a groundwater system can be potentially contaminated by anthropogenic activities. Dennis et al (2012) from WRC project No.1763/1/11 evaluated the quality of South Africa's groundwater for a variety of applications in addition to the susceptibility matrix map. For instance, sections of groundwater that tasted slightly salty, noticeably salty, markedly salty, excessively salty, or bitter were evaluated and plotted. In other words, a database on the quality of groundwater reserves exists and must be accessed for fresh research or new interpretations of the quality of groundwater reserves. It is crucial to note that the CSIR (2013) generated maps of South Africa's aquifer systems, classifying them as having good water quality, variable water quality, and moderate to low water quality. For additional evaluations on the quality of groundwater reserves and related assessments, this categorization serves as the gateway to the database that generated the initial assessment.

The quality component of the reserve considers guideline values for parameters as a default where no long-term data is available for a unit of assessment, while summary statistics and concentration duration curves are used to assess the quality component of the reserve where long term data is available.

3.4 Reserve Determination for Groundwater Resources

3.4.1 Quantity Component

The reserve, according to the National Water Act (NWA 36 of 1998), is an unallocated part of water that is not in competition with other users. It refers to the quantity and quality of water necessary to meet basic human needs by securing a basic water supply as required by the Water Services Act (Act 108 of 1997), for people who currently rely on, take from, or are supplied by the relevant water resources or who will do so soon. It also refers to the need to protect aquatic ecosystems to ensure the development and use of the relevant water resources in an ecologically sustainable manner (known as the ecological reserve).

The ecological reserve must be determined using approved procedures. For all the ecosystems in the water resource to maintain or reach the chosen level of health and, as a result, be classified as an ecosystem, the methodologies call for quantifying the flow, habitat, and water quality requirements of each ecosystem. According to Palmer et al. (2000), the NWA is one of the most comprehensive and progressive water laws in the world and is supported on two pillars. In accordance with Local Agenda 21 and the Republic of South Africa's constitution, one of sustainability and one of equity. The main goal of the NWA is to ensure that the nation's water resource is protected, used, developed, conserved, managed, and controlled in ways that consider meeting the basic human needs of the present and future generation, promoting social and economic development, managing floods and droughts, and complying with international obligations, among other things. The twin pillars that support the right in law to the use of water for human and environmental needs are the twin pillars (DWAF, 2003a). The reserve must be measured using recognized techniques.

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In determining the reserve, recharge methods should consider the type of aquifer system/s in the delineated unit of assessment, basic human needs (BHN) quantity needs to reflect only the groundwater-dependent population, and baseflow should be expressed as groundwater contribution to baseflow, see calculations in chapter 3.

3.4.2 Quality Component

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Murry et al. (2012) and DWA (2013) used the database to create a spatial assessment in the form of a susceptibility matrix map that included both the aquifer's vulnerability and its relative importance in terms of its classification. The map showed the qualitative measures of the relative ease with which a groundwater system can be potentially contaminated by anthropogenic activities. Dennis et al (2012) from WRC project No.1763/1/11 evaluated the quality of South Africa's groundwater for a variety of applications in addition to the susceptibility matrix map. For instance, sections of groundwater that tasted slightly salty, noticeably salty, markedly salty, excessively salty, or bitter were evaluated and plotted. In other words, a database on the quality of groundwater reserves exists and must be accessed for fresh research or new interpretations of the quality of groundwater reserves. It is crucial to note that the CSIR (2013) generated maps of South Africa's aquifer systems, classifying them as having good water quality, variable water quality, and moderate to low water quality. For additional evaluations on the quality of groundwater reserves and related assessments, this categorization serves as the gateway to the database that generated the initial assessment.

The quality component of the reserve considers guideline values for parameters as a default where no long-term data is available for a unit of assessment, while summary statistics and concentration duration curves are used to assess the quality component of the reserve where long-term data is available.

3.5 Determination of RQOs for Groundwater Resources

The interplay of groundwater with different water bodies and systems creates the requirement for groundwater resource quality targets linked to water quantity. According to Dennis (2007) and Wentzel, RQOs have established criteria for groundwater interactions with rivers, wetlands, estuaries, springs, protected areas, strategic use areas, and international duties. Rivers may be riparian vegetated or nourished by groundwater. Rivers, whether they are perennial or not and have pools, are frequently nourished by groundwater, thus they must be safeguarded. This is accomplished by computing the volume of groundwater entering the river (i.e., groundwater contribution to baseflow). The needed flow regime can be maintained by maintaining the RQO as a groundwater level or gradient for a predetermined distance from the river. The method used to determine whether these rivers or pools are fuelled by groundwater is not further described. However, a flow diagram was created to consider the setting of RQOs for rivers during the 2013 upgrade to the technique and software. There are three important things to think about. They consist of the following: Is riparian vegetation present? The river is seasonal or not. Are there pools, too? RQOs can be set in accordance with Dennis and Wentzel's specifications based on the answers to these questions. According to Vivier et al. (2009), the GRDM method is used with a precautionary approach; if a specific water body is not explicitly known to be fed by groundwater, it is believed to be such and is included in the reserve. Similar to this, it is necessary to calculate the amount of groundwater entering the water body in order to determine RQOs for wetlands and estuaries. The RQO can then be established as a groundwater level or gradient that must be maintained for a predetermined distance from the wetland or estuary. Here, the wetland or estuary's dependence on groundwater is the only option for the approach that is considered. This suggests that prior understanding of the system dynamics is required of the individual using the methodology. For users of the approach to assess this as a prerequisite to setting RQOs, the current methodology expands on the requirements to ascertain whether interaction is taking place with respect to water level data or flow gradients. The quantification, however, is still lacking.

RQOs pertaining to the use of groundwater for essential human needs, strategic purposes, and in accordance with international responsibilities must also be safeguarded. The software program and approach only use yes/no decision trees. No RQO setting is required in this regard if a place lacks these necessities for fundamental human needs and others. It is necessary to compute the recommended abstraction rates in the boreholes or flow over international boundaries and to define protection zones. The RQO can then be specified as a groundwater level or gradient that must be maintained for a specific distance or as a guarantee of supply (sustainability) of the groundwater resource.

It is necessary to calculate the quantity of groundwater entering these regions when assigning RQOs to protected areas like national parks and world heritage sites. The RQO can then be established as a groundwater level or gradient that must be maintained for a predetermined distance away from the protected area. This suggests that for a user of the methodology to make an informed decision, all relevant data regarding the quantities and aquifer parameters should be available. Over the past ten years, the number of sinkholes and subsidence zones in South Africa has increased because of water abstraction from Karst aquifers. As a result, it was decided to establish RQOs for these aquifer systems. According to Dennis and Wentzel (2007), the RQO in karst aquifers is defined as a groundwater level variation within a certain range, namely, it may not fluctuate by more than 2 m over time. RQO setting is a very site- or region- or area-specific component of the

GRDM. It emphasizes how crucial it is to have solid data that can be trusted, as well as a reasonable grasp of the hydrogeological and hydrological system that is being assessed. Thus, the data sources for the new technique are crucial. While WR2005 offers datasets up to 2004, WR90 covers time periods from 1920 to 1989. For the sake of making management and monitoring choices, especially when RQOs are considered, more recent data or established databases must be employed. Baseflow and the contribution of groundwater to baseflow need to be explained to practitioners, and they need to be measured and interpreted using practical skills.

Mass balance equation using EC

The baseflow separation method assumes that baseflow equates to groundwater contribution, which is not always the case. In conjunction with this method, a mass balance method using EC concentrations by Yang et al. (2014) was used to estimate groundwater contribution to baseflow. The used EC concentrations in groundwater and surface water were measured in the field using the multi-parameter probe (YSI). The mass balance equation is as follows.

$$Q1 = Qin\ (Cin - Cg)/(C1 - Cg)\ /\quad Qin = Q1\ (C1 - Cg)/(Cin - Cg) \tag{17}$$

$$Qg1 = Q1 - Qin \tag{18}$$

Where the Qg1 and Q1 are the groundwater discharge in the first segment and the discharge at the end of the first segment in m3 /s; Qin is the inflow from the upstream in m3/s; Cg and C1 are the tracer values of the groundwater discharge and total discharge at the end of the first segment in µS/cm.

Quality Aspect

The South African National Standard for drinking water (SANS 241:2015) and other South African Water Quality Guidelines (SAWQG) for various water users are available and extensively used in the county to ensure that their requirements in terms of water quality are met. Importantly, when setting RQOs, a balance must be sought between the need to protect and sustain water on the one hand, and the need to develop and use them on the other. But due to lack of a prescribed procedure for setting numerical limits for quality component of groundwater RQOs practitioners often rely on the water quality guidelines, subsequently using their limits as numerical limits for groundwater RQOs. Numerical limits prescribed in the water quality guidelines are the same nationally, and do not reflect on the spatial variability of catchments, they are a requirement for a specific water use such as domestic, industrial, aquatic ecosystem, and they are not a requirement for the environment which is the focus for resource protection.

Although groundwater contamination may result from anthropogenic sources, however, natural geogenic sources through hydro-geochemical processes may be responsible for controlling groundwater quality in various aquifers (Lalumbe et al., 2022). Therefore, it is critical that when RQOs for groundwater quality are set, reference or background/prevailing conditions within a particular area under investigation are taken into consideration. RQOs cannot be set at a level more stringent than background conditions of a particular groundwater resource, otherwise, such RQO would be impractical to implement. To redress the challenge, a methodology that applies a technique of Concentration Duration Curves (CDCs) construction for groundwater quality parameters is presented.

CDC a is a graphical illustration of the percentage of time (duration) a concentration level of a particular groundwater quality parameter is met and sustained in the study area, and such illustration uses time-series data from a catchment, which is analysed based on temporal variation (Nzama et al., 2021). CDC for each water quality parameter is generated using the recorded historic groundwater quality data, and the equal or below or no exceedance probability for each concentration of water quality parameter considered is determined using the formula in Eq. (19)

$$P = \left(\frac{\mathrm{M}}{n+1}\right) \times 100 \tag{19}$$

where P = the probability that a concentration will be equalled or exceeded (% of time); M = assigned a rank number; n = the total number of data set recorded on each water quality parameter for a record period of interest.

The CDC is constructed by plotting the calculated P values on the X-axis (% equalled or exceeded) and corresponding concentration values on the Y-axis (mg/L), and mS/m in case of electrical conductivity.

Two disadvantages associated with the use of this methodology are evident:

- The method requires extensive data to establish trends which is not always available in some catchments.

- The method is labour intensive as the CDCs must be determined for each water quality parameter, but this can be minimized through prioritization of water quality parameters.

Some of the advantages associated with the use of this methodology are as follows:

- The method relies on the use of data collected from the catchment instead of relying on limits from the water quality guidelines. This implies that the method considers prevailing environmental conditions which differ from one catchment to another (spatial variability consideration).
- It gives stakeholders powers to decide on the level of protection (numerical limits) which conforms with requirements for RDM processes. Numerical limits are derived from the data and not extracted from the water quality guidelines.
- It further enables stakeholders such as local communities, NGOs, private sector to play a significant role in groundwater resources protection in terms of data provision, thus improving groundwater governance and decentralized decision making (polycentric governance).

The outcomes of the graphical illustration of the percentage of time (duration) a concentration level of a particular groundwater quality parameter, allows for the establishment of numerical limits which is linked to step 5 of the RQOs determination procedure. When setting numerical limits from the constructed CDC, it is critical to note that the lower the concentration level set, the lower the percentage of time (duration) a concentration level of a particular groundwater quality parameter is met, and vice versa. The established numerical limits from the CDCs are then presented to the stakeholders with full explanation of their implications for stakeholders to agree on the final outcomes (limits), and this activity is linked to step 6 of RQOs determination process. Table 7 presents the water quality parameters considered using the CDC method.

Table 7: Water quality parameters and their associated human health impacts as per WRC (1998)

Parameters	**Consideration as per Implications**
pH	The parameter is considered as a general indicator of water quality in domestic water use.
Electrical Conductivity as EC	The parameter is considered as a general indicator of water quality in domestic water use.
Calcium as Ca	The parameter may commonly be present at concentration of aesthetic or economic concern in domestic water use.
Magnesium as Mg	The parameter may commonly be present at concentration of aesthetic or economic concern in domestic water use.
Sodium as Na	The parameter may commonly be present at concentration of aesthetic or economic concern in domestic water use.
Chloride as Cl	The parameter is commonly present at a concentration which may lead to health problems in domestic water use.
Sulphate as SO4	The parameter is commonly present at a concentration which may lead to health problems in domestic water use
Nitrate as NOx-N	The parameter is commonly present at a concentration which may lead to health problems in domestic water use.
Fluoride as F	The parameter is commonly present at a concentration which may lead to health problems in domestic water use

When groundwater is mainly used for drinking purposes in the study area, it is important to take note of the individual water quality parameter impacts on human health (Table 2) as provided in the South African water quality guideline (WRC,1998). The guideline considers electrical conductivity and pH as general indicators of water quality for domestic water use. Therefore, these parameters are deemed to require less stringent conditions for compliance, and thus can be assigned *less stringent target level* of management corresponding to a 95% compliance over a period of interest. Calcium, magnesium, and sodium may commonly be present at concentrations of aesthetic or economic concern in domestic water use. Thus, these parameters can be assigned *stringent target levels* of management corresponding to at least 85% compliance over a period of interest. Furthermore, the guidelines consider chloride, sulphate, nitrate, and fluoride as parameters that are commonly present at concentrations that may lead to health problems in domestic water use. Therefore, these water quality parameters can be assigned *higher stringent target levels* of management requiring at least 75% compliance over a period of interest. In cases where dominant groundwater use is for industrial or agriculture, stakeholders can decide and agree on the numerical limit taking into consideration the need to support agricultural and industrial activities for socio-economic sustainability.

4. PILOTING OF THE UPDATED GRDM METHODOLOGY

4.1 Selection of Case Study Catchments

The purpose of this project is in threefold; first to update the current GRDM methodology to enable operation of groundwater resource classification in line with the overall water resource classification processes; groundwater reserve determination; and setting of groundwater resource quality objectives (RQOs); secondly, to update the current GRDM software with the aim of making the software more user-friendly, in terms of improve functionality and simplicity and thirdly, to provide training to institutions of higher learning and community of practitioners [users] such as officers from the department of water and sanitation among others. It was understood that this project demonstrated the collecting, analysis and computation of relevant parameters for determining resource quality objectives or reserve for the water resources. Existing data were sourced for various analyses and primary data were used for validation of the results.

This section of the report outlined a case study area selection criterion developed for selecting of sites for testing of the methodology and software. The main aspects of the study area selection that were highlighted included site representability, data availability, issues of scale, aquifer delineation, human impacts, and historical and current data collection. In summary, the key aspects that were deemed important for the site selection criteria included.

- The presence of surface water bodies in the form of a river, lake, vlei, or wetland to evaluate surface water groundwater interactions
- The scale of the area to include recharge and discharge areas to evaluate recharge processes, discharge processes, and volumes
- The presence of monitoring infrastructure, e.g. boreholes, flow gauges, rain gauges, plant water use equipment and so forth
- The availability of historical data as a baseline in terms of setting RQOs
- Pristine areas, as well as areas which are either impacted or have land-use activities which pose a potential threat in terms of impacting water quality
- Rainfall data (long term if available) may link to aspects of changing climatic conditions in an area, and impact groundwater recharge and surface water flows and, in turn, the interaction between these resources

- An existing relationship with stakeholders in the study area includes farmers, municipalities, and local authorities.

Two case studies were identified based on the outlined criteria. These sites complied with the outlined criteria in most respects. The study sites were described with respect to their locality, geology, hydrogeology, drainage patterns, groundwater flow and recharge as far as possible. In addition, the study sites were described in terms of application of the methodology and the parameters required for the respective steps of classification, reserve and setting of RQOs.

4.2 Data Collection in the G10A (Upper Berg Catchment)

To delineate groundwater resource units, the geology and borehole layers of the Upper Berg catchment and the quaternary catchments data were required. These were acquired from the DWS and Cape Farm Mapper (CFM). A review of groundwater recharge values in the upper Berg was performed, and two results studies in the G10A quaternary catchment were considered, as indicated in table 8.

Table 8: Recharge values in the upper Berg River catchment

Recharge (% of MAP)	Source
22.4%	DWA (2007)
24.66%	Mutoti, (2015)
28.8%	Albhaisi et al. (2013)

To quantify groundwater contribution to baseflow from 2016 to current, streamflow data have been collected from Berg gauging stations G1H077 and G1H076. Lynne and Hollick and Chapman filtering baseflow separation methods were used to quantify groundwater contribution to baseflow. For the mass balance equation, the EC values were measured using a YSI multi-parameter probe in the river and groundwater within the catchment. The EWR-MLF Values and the groundwater-dependent population and general population in the study area were requested from WARMS.

Data Quality Assurance/Control for Upper Berg River Catchment

After data was generated for the various, it had to be sorted (cleaned). This process included checking for blanks, removing duplicates, and backing up data. The multi-parameter probe was calibrated while measuring water quality field parameters.

Prior to data analysis, the accuracy of the hydrochemical analysis of major ions was tested using the cation-anion balance (CAB). Given that all portable waters, in theory, are electrically neutral, the sum of cations and anions in a sample is expected to balance or equalize. The reliability of the water quality results was first checked by testing the error margin of major ion analysis. This was done by conducting a Charge Balance Error (CBE) using the formula:

$$CBE\ (\%) = \frac{(\Sigma meq\ cations - \Sigma meq\ anions)}{(\Sigma meq\ cations + \Sigma meq\ anions)}\ x\ 100 \quad (1)$$

An ionic balance error of less than 5% is usually acceptable to be used for scientific investigations whereas errors from 5 – 10 % should be used with caution. In this analysis, the error was relaxed to a maximum of 10% to reduce the risk of discarding too many data if a <5% error rule was applied. Out of the 43 samples collected in the G10A, 12 samples had a CBE greater than 10% and were eventually not considered in the analysis, thus, 31 samples were adopted.

Data Analysis for Upper Berg Catchment area

The Berg River catchment is the largest in the Western Cape province of South Africa. The Berg catchment covers a surface area of 9 000 km^2 and is divided into 12 quaternary catchments each of which has a different size, starting with G10A near the Berg River's source and terminating with G10M at the Atlantic Ocean as shown in figure 2. The largest of them are the Quaternary catchments G10L and G10M, situated in the western drier portions of the Berg catchment covering a surface area of 1750 km^2 and 2000 km^2 respectively. G10A and G10B are the smallest quaternary catchment in this area and occupy 172km^2 and 125 km^2 respectively (Ratcliffe, 2007). There are two aquifer systems in the Upper Berg catchment but even though the area covered by the catchment is known, the area each system covers is not known.

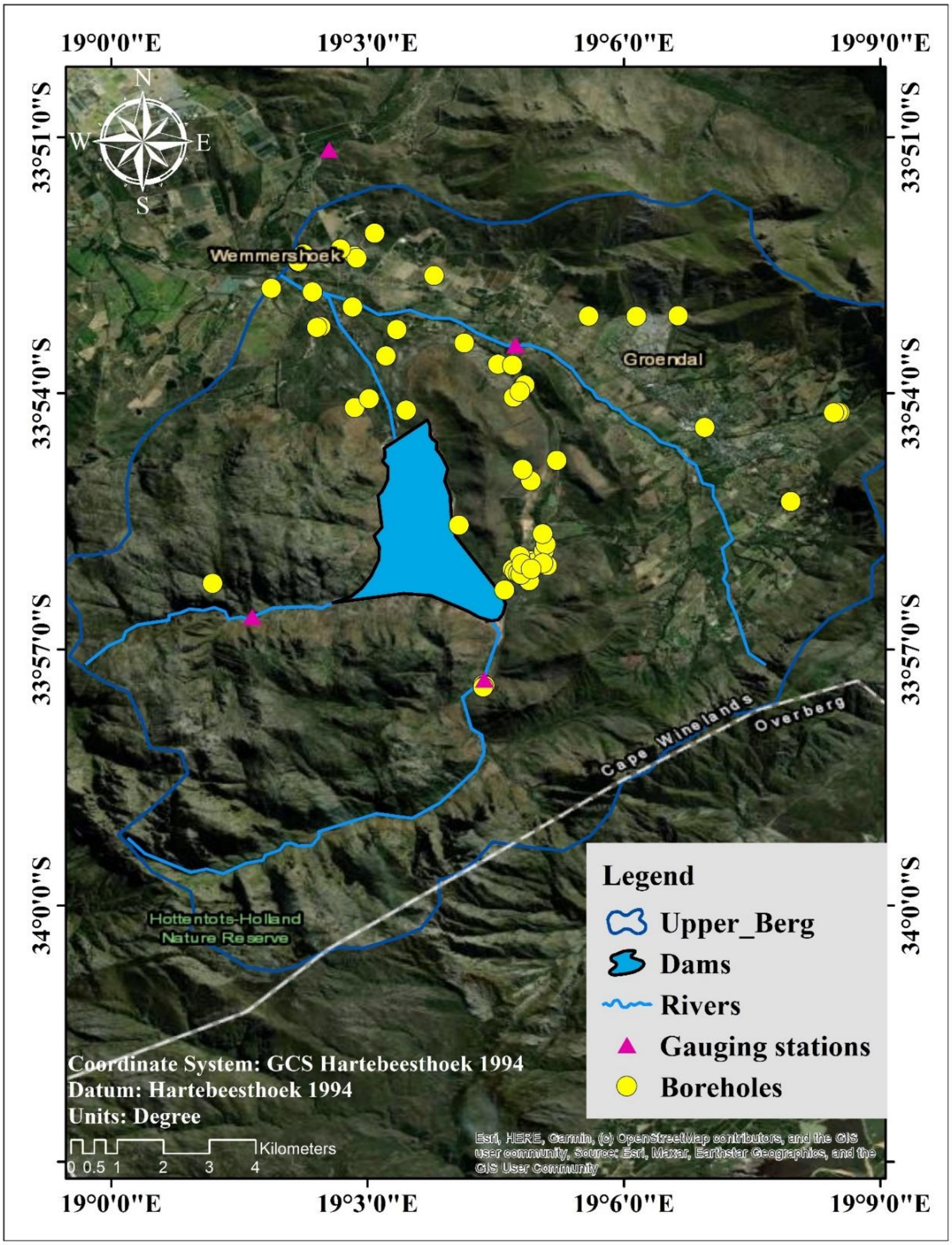


Figure 2: Stream gauging stations and boreholes around the Upper Berg River catchment

Delineating the aquifer specific GRUs necessary for this study begins with the delineation of aquifer extents, which is based on geological and hydrogeological maps (1:50 000 to 1:250 000), soil, strategic groundwater resources, aquifer types and yields (See Figure 4 to 10). The Malmesbury and Klipheuwel Groups, which are mostly composed of usually argillaceous greywackes and shales, underlie most of the Berg basin. In the Upper Berg (G10A), the Franshoek Formation of (Malmesbury Group) overlies the Swartland Subgroup, and this formation is composed of feldspathic conglomerate and quartzite, grit, slate, and phyllite. Berg River Formation, Kliplaat and Mooressburg Formations are structurally and tectonically complex in relation to other terranes of Malmesbury Group.

The Cape Granite Suite, which is primarily occur as plutons and batholith such as Darling pluton and Stellenbosch batholith, intruded these basement rocks in the catchment (see Figure 4). Sandstones that make up the TMG were deposited after the Cape Granite Suite intrusion as a result of extensive uplift and erosion. In particular, the Peninsula and Skurweberg formations, which are composed of quartzites that are resistant to erosion, form the area's escarpments (Table Mountain, the Hottentot Mountains, etc.). Deep fractured rock aquifers are formed by these formations (specifically the Peninsula and Nardouw Subgroub (Goudini, Skurweberg, and Rietvlei formations) which have yields ranging from 0.1 to > 5L/s.

Sediment deposition was caused by further erosion of these formations, especially the softer Malmesbury Group, which creates eroded valleys, in the western and coastal half of the catchment. These major primary sedimentary / intergranular aquifers, including the Cape Flats Aquifer (CFA), the Atlantis/ Silwerstroom aquifers, and the West Coast aquifers, are made up of sand deposits, which are part of the Bredasdorp Group, Sandveld Group, and Quaternary period deposits such as Elandsfontein and Langebaan Road aquifers.

Figure 3: Showing the extent of the Berg Management Area

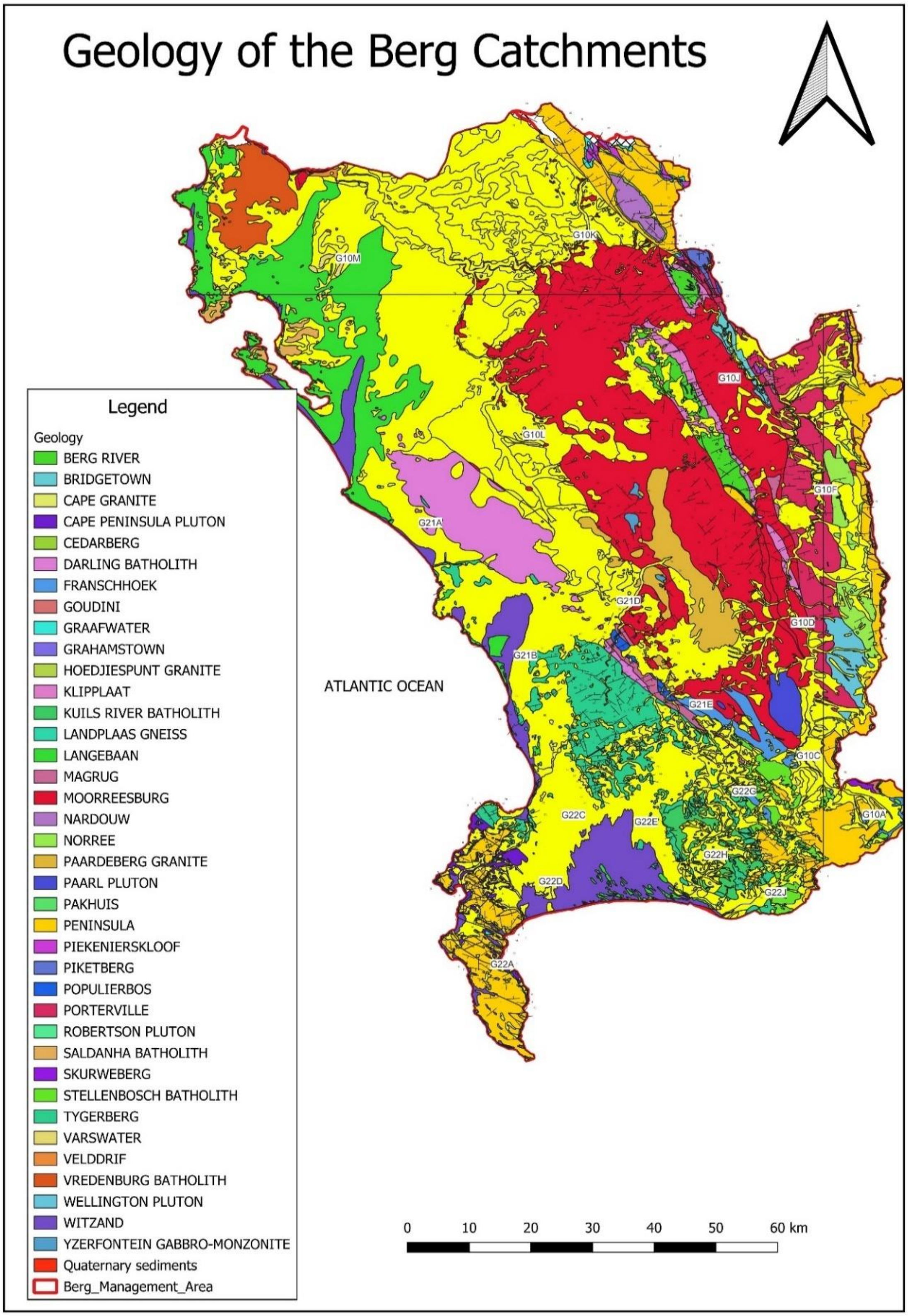


Figure 4: Geological map of the Berg Management Area

The data about aquifer types and yields from Cape Farm Maper was used to show the distribution extent in the Berg Management Area as shown in (Figure 5) below. The Berg Management Area is dominated by the fractured aquifer which yields (1 to 2 l/s) indicated by blue colour in the map. Both primary and secondary aquifers are present in the Berg management Area. The high yielding fractured aquifers occurs along the boundary of the Berg Management Area (part of G10A, C, D, F, K and G22J). These fractured aquifers are associated with sandstone and arenite sandstones of the Table Mountain Group. The primary aquifers (unconfined aquifers) with high yields occur along the coast which form part of the Langebaan and Witzand Formations. These high yielding aquifers occur in G21B and G22D catchments.

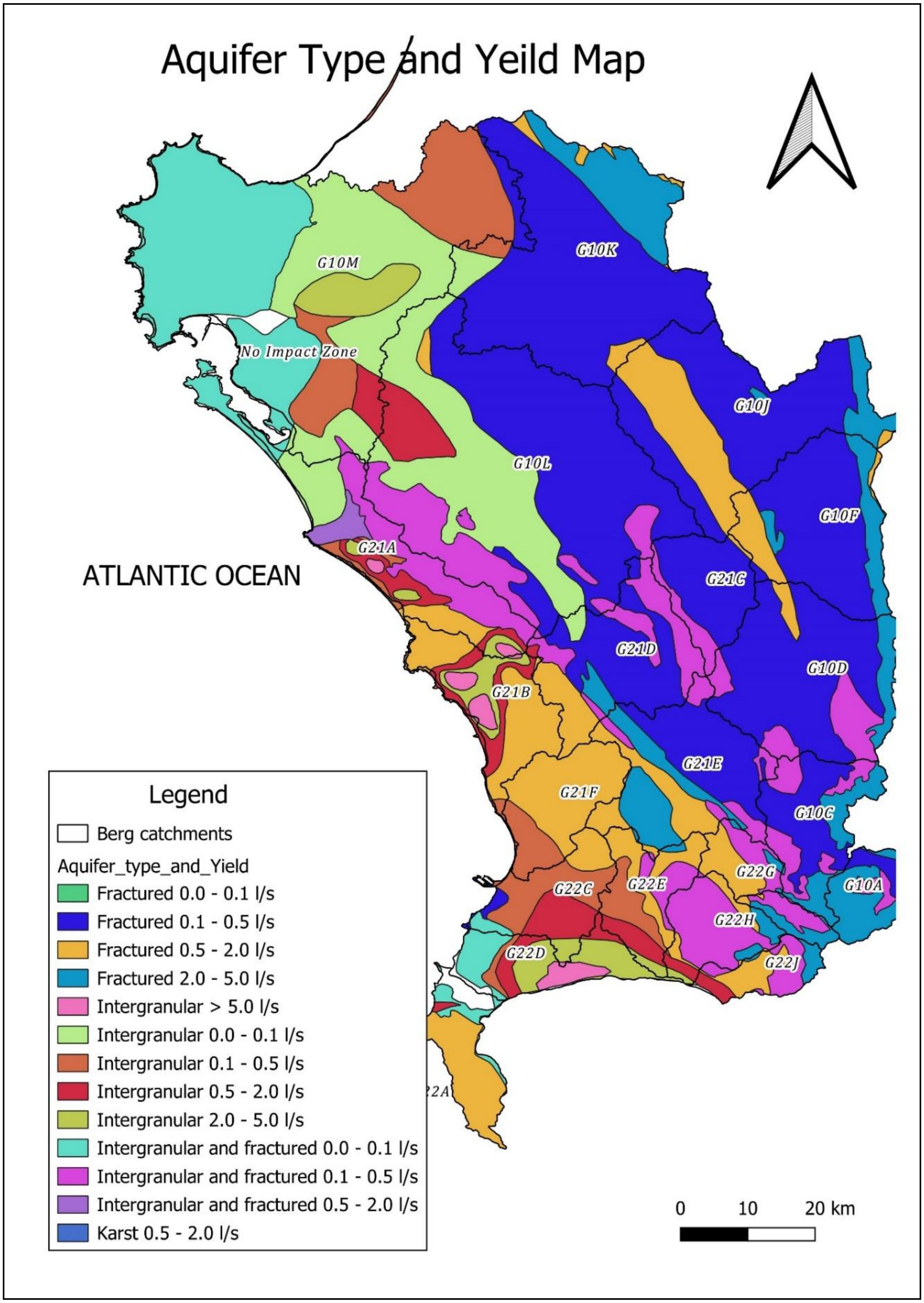


Figure 5: Aquifer type and aquifer yield map

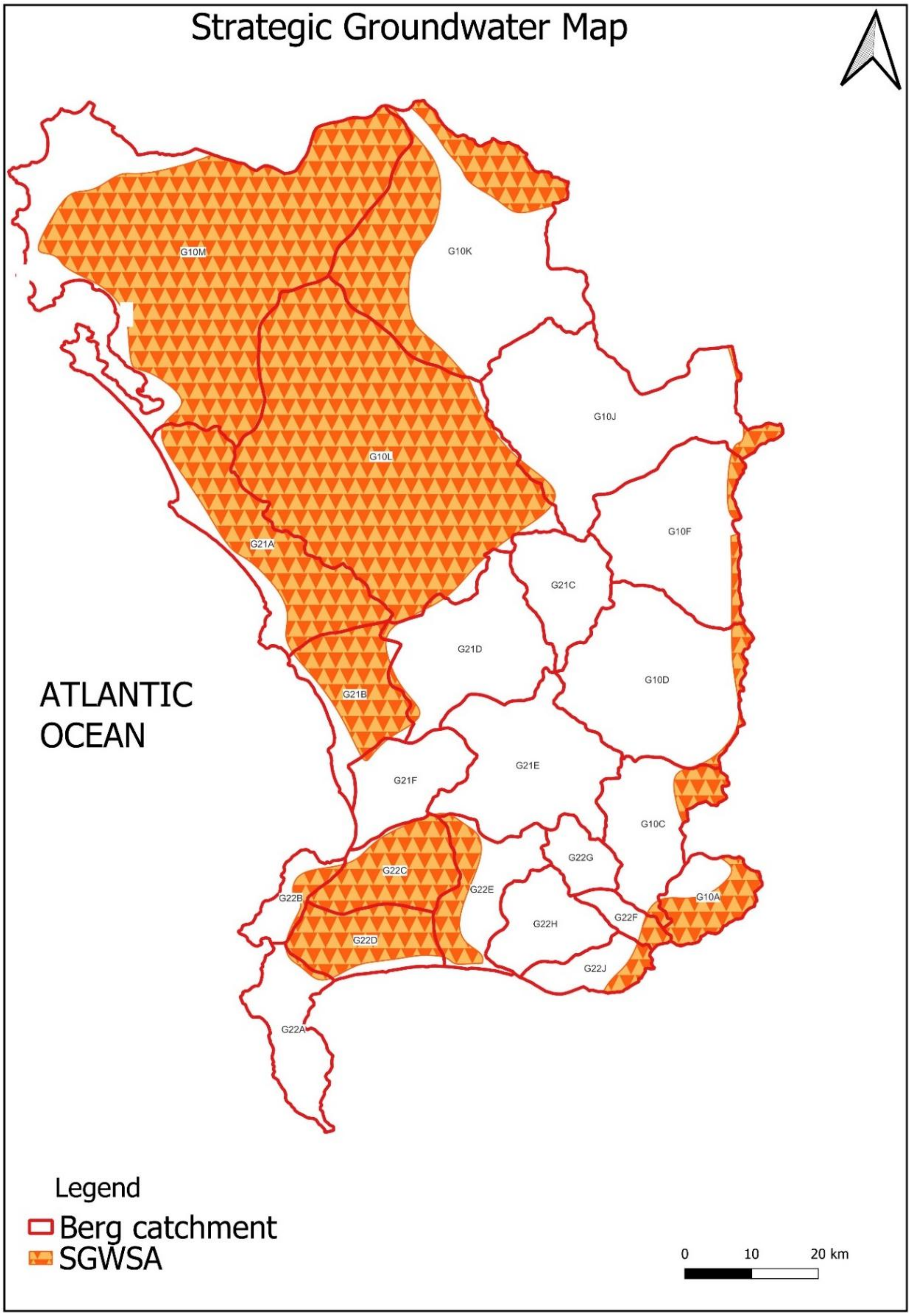


Figure 6: Showing the strategic groundwater in the Berg Management Area

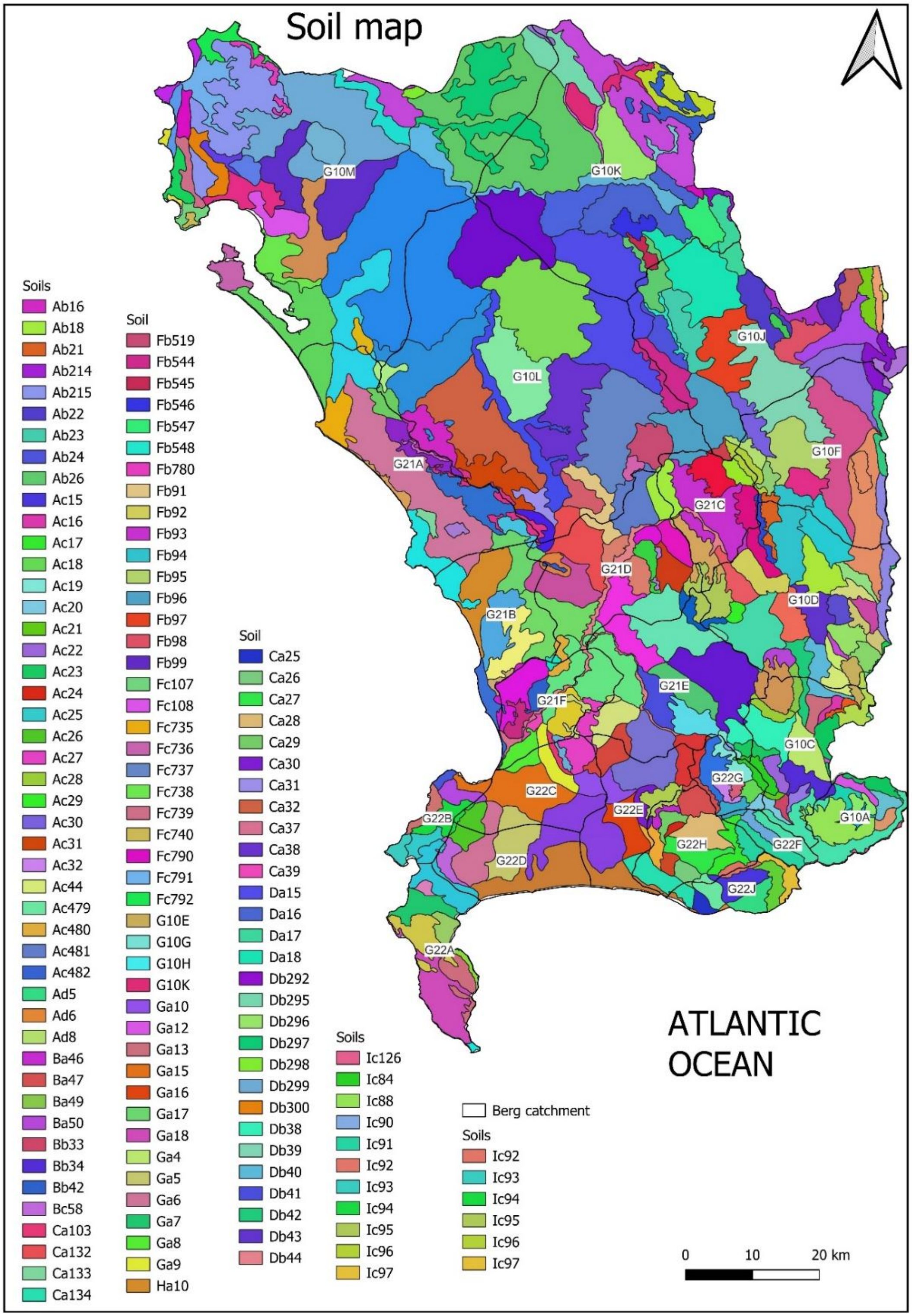


Figure 7: Soil distribution a map in Berg Management Area

4.2.1 Upper Berg Catchment (G10A)

The main aim of the delineation of aquifer system in the G10A catchment was based on the geology polygons (Worcester and Cape Town Geology shapefiles which is owned by Council for Geoscience) and geological logs (obtained from the National Groundwater Archive) to describe lithology and subsurface geology. The locality map of the upper Berg catchment is shown in the Figure below. Due to the large number of boreholes in the Upper Berg – 12 boreholes were selected to describe and classify the aquifer system (BG00032, BG00039, BG00040, BG00041, BG00042, BG00043, BG00045, BG00046, BG00048, 3319CC00017 and 3319CC00019). The selected were used to categorize the catchment and understand which boreholes are tapping on unconfined or confined. Moreover, delineation was aimed in determining the total thickness and the area of each aquifer system (confined or unconfined

The unconfined aquifers in the G10A catchment occur along the rivers (Franchoek and Berg River) and are more prone to pollution and easily contaminated. The delineation of unconfined aquifer system showed that the thickness is undulating depending on underlying rocks and their thickness varies within the catchment. The thickness of these unconfined aquifers (colluvium, sand (alluvium) and gravel) ranges from 1 meter to 38 meters. The average thickness of the unconfined aquifers in the G10A catchment is 21.1 m. The area of each aquifer system is given by the following equation:

$$Area_{unconfined} = Area_{G10A} - Area_{confined}$$

The confined aquifer system in the G10A catchment is dominated by TMG rocks. The data obtained from the geologic logs indicates that the sandstone or fractured aquifers are thinning or pinching out towards the upper part of the catchment. This is due to the presence of granites intrusions that are more dominant toward the upper part of the catchment (after the Berg Dam towards the source of the river). The thickness of the sandstone varies, and many boreholes in G10A were drilled to the sandstone. For example, BG00039 intersects sandstone 2 meters below the ground. The confined aquifers in G10A have an average thickness of 31 meters.

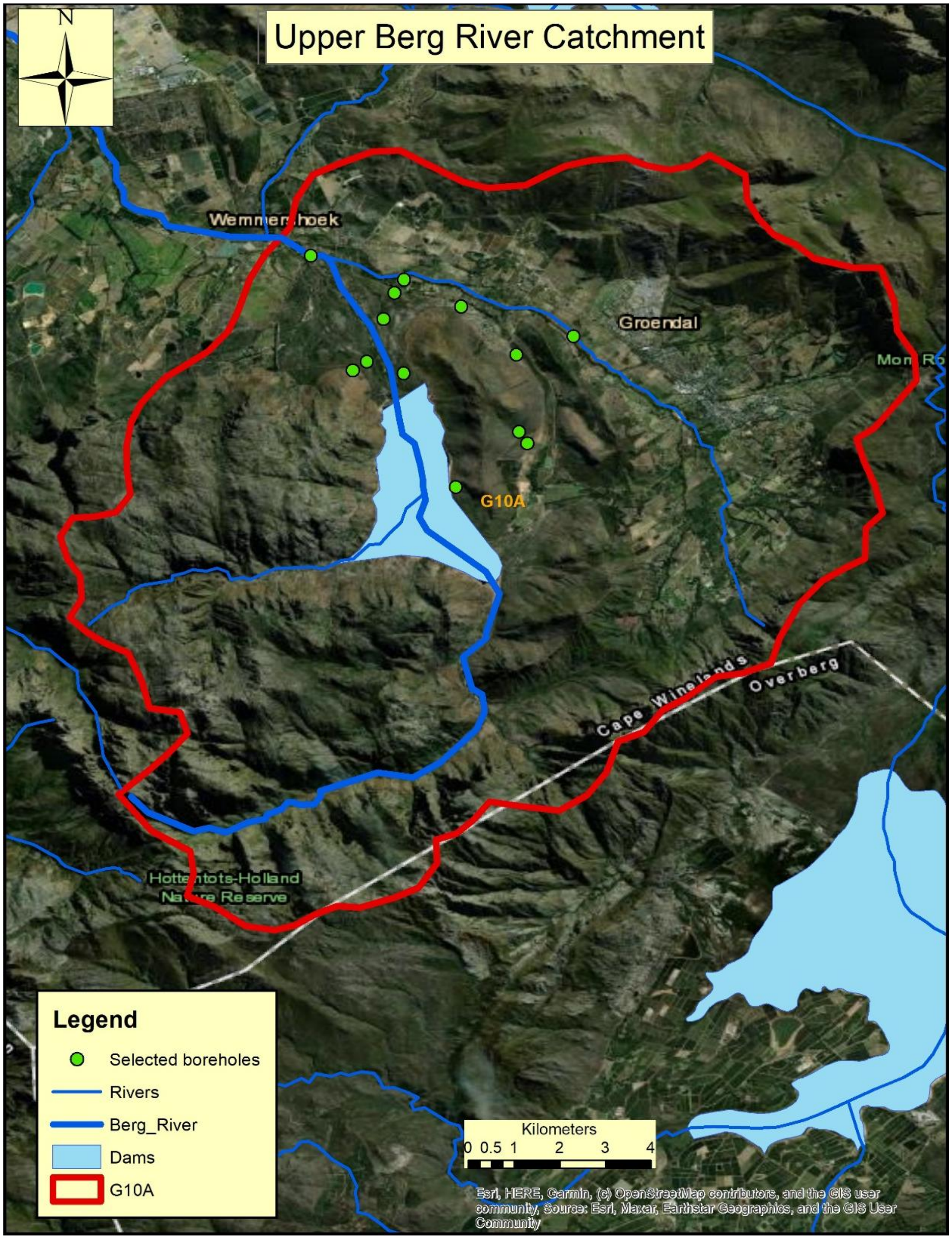


Figure 8: Locality map of the Upper Berg Catchment

The G10A boundary was overlaid in the delineated aquifer systems. The classification of the aquifer system into unconfined and confined was done in line with the software that now allow the dual model (double layer model).

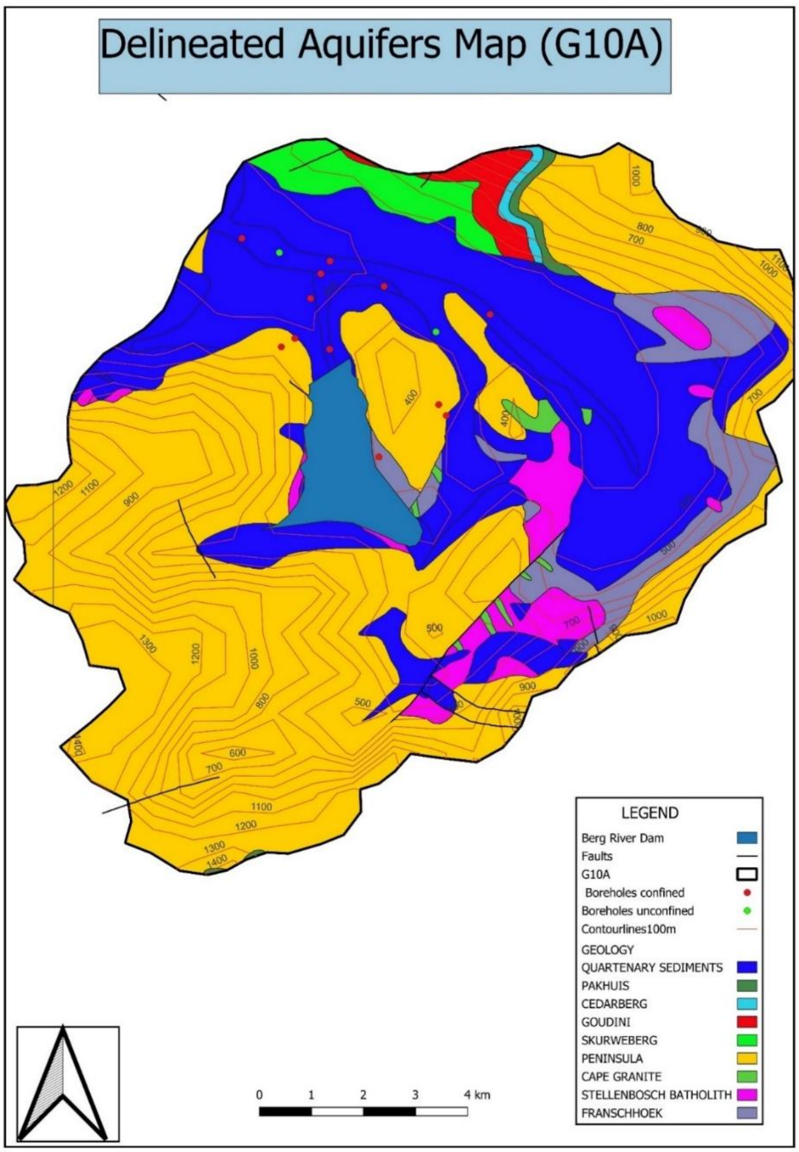


Figure 9: Delineated aquifers in Berg River Catchment (G10A)

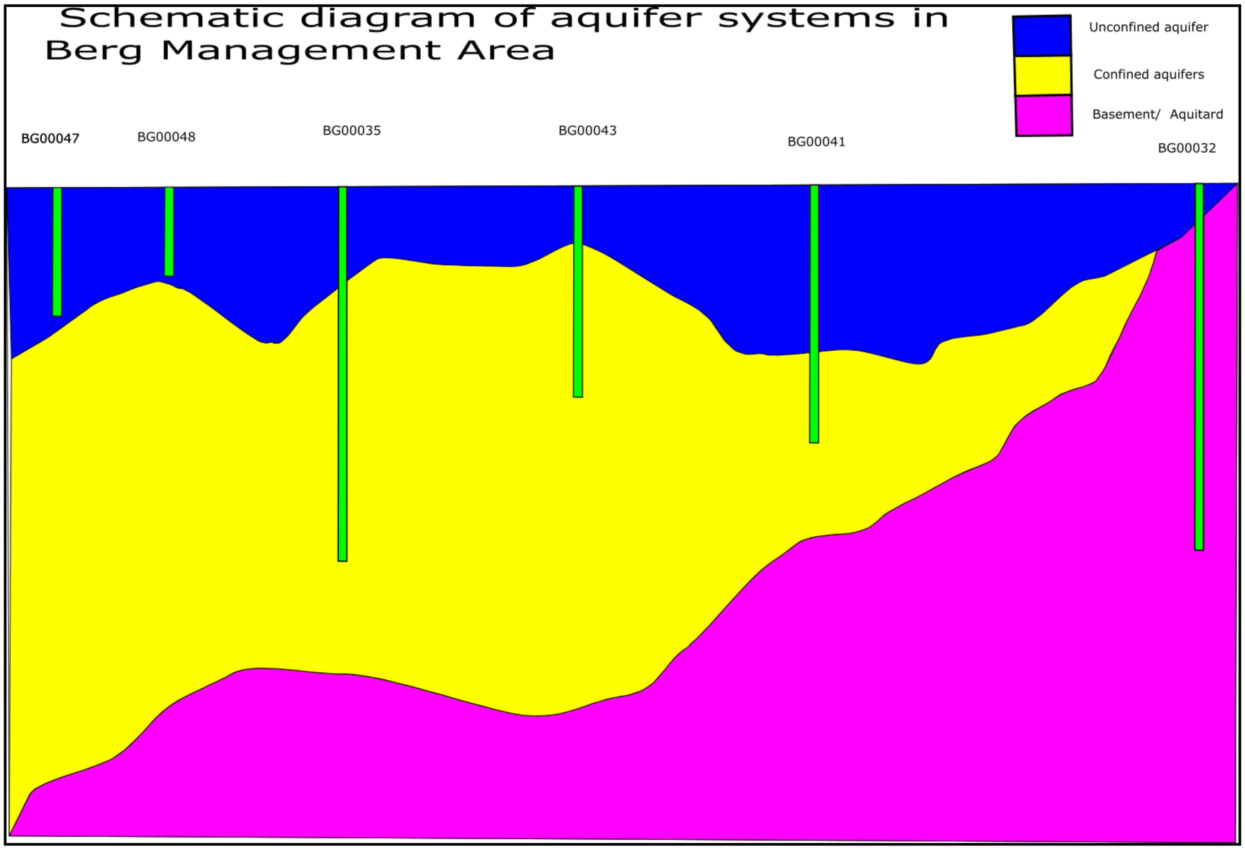


Figure 10: Showing the aquifer system of the Upper Berg River catchment

Groundwater Use

For the Upper Berg catchment, groundwater use per delineated aquifer system data was not available hence groundwater use in the catchment was used (current approach used). We are however moving away from the usage of this current method of using the catchment, so where data is available, it is recommended to use groundwater from the delineated aquifer systems specifically and not the catchment in general. Groundwater use in the catchment is presented in the table below. The average groundwater use in the Upper Berg catchment of 3908318 m^3/a which is a total of all activities utilizing groundwater in the catchment, see table 9.

Table 9:Groundwater use in the Upper Berg catchment

Sector	**Water use (m^3/a)**
Agriculture (irrigation)	3 135 346
Agriculture (Aquaculture)	220 000
Industry (Urban)	208 989
Industry (non-urban)	323 811
Water supply service	4 050
Schedule 1	16 122

Groundwater Recharge

Groundwater recharge per delineated aquifer in the Upper Berg catchment data was not available hence the current method of using catchment groundwater recharge was applied. Where groundwater recharge per aquifer systems in the study area data is available or can be estimated, the usage of this is recommended as the new approach. The mean groundwater recharge values calculated in the Upper Berg catchment using the chloride mass balance, rainwater infiltration breakthrough, and water table fluctuation methods were 27.6 %, 23.67 %, and 22.7 % of the total precipitation received in the catchment, respectively (Mutoti, 2015). Using the average of these groundwater recharge percentages of 24.66 % and mean annual precipitation (MAP) in the catchment of 1603mm/a, the Berg catchment experiences groundwater recharge of 395.3 mm/a. Based on the area of the G10A catchment, groundwater recharge as a volume is estimated to be 68 335 000 m^3/a.

Aquifer Stress Index for groundwater use

The Aquifer Stress Index (SI) for an assessment area is defined as follows:

$$SI_{Upper\ Berg}\ (\%) = \frac{gwUse}{Recharge}\ x\ 100$$

$$SI\ (Upper\ Berg) = \frac{3908318\ m^3/a}{68335000\ m^3/a}\ x\ 100$$

$$= 5{,}72\%$$

Based on a guide for determining stress levels in a groundwater unit (Table 9), the Berg catchment with a stress index (SI) of 5,72 % falls under class I where groundwater is minimally used and therefore not stressed. This implies that there is enough groundwater to be allocated to users as the used volumes are less than the water coming into the catchment.

Environmental Stress Index

The Upper Berg catchment is divided into two sections which are the section before the dam (natural flows) and the section after the dam (modified flow). Two aquifer systems were observed in the Upper Berg catchment (Unconfined and Confined aquifers). Groundwater contribution to baseflow data from the unconfined aquifer system was unavailable, therefore the environmental stress index was estimated only for confined aquifer systems in the area. Groundwater contribution to baseflow was estimated from the confined aquifer system from both sections. The estimated groundwater contribution to baseflow from the confined aquifer system before and after the dam was 0.051942 m^3/s and 0.399244 m^3/s respectively. The addition of these two groundwater contributions to baseflow estimates produced the total groundwater contribution to baseflow from the confined aquifer system of the Upper Berg catchment which was 0.451186 m^3/s. The total groundwater contribution to baseflow for the year 2022 was converted from m^3/s to m^3/a which was 14228601.7 m^3/a (14.229 Mm^3/a). The Ecological Water Requirements for Maintenance Low Flows for 2022 was 2.556 Mm^3/a (WARMS).

$$Environmental\ SI_{confined\ aquifer\ system\ (Upper\ Berg)}$$

$$= \frac{EWR - MLF}{Groundwater\ contribution\ to\ Baseflow} \times\ 100$$

$$= \frac{2.556\ Mm3/a}{14.229\ Mm3/a} \times\ 100$$

$$=\ 18.03\%$$

This index indicates that groundwater from the confined aquifer system of the Upper Berg catchment sustains the ecosystem in the area. The index however shows that the ecosystem does not only depend on groundwater contributions from the confined aquifer system even in the dry season meaning that except from groundwater contribution, but the ecosystem could also be receiving water from unconfined aquifer systems, river flow, among others. Figures 11 and 12 shows the distribution of boreholes in the Berg river catchment.

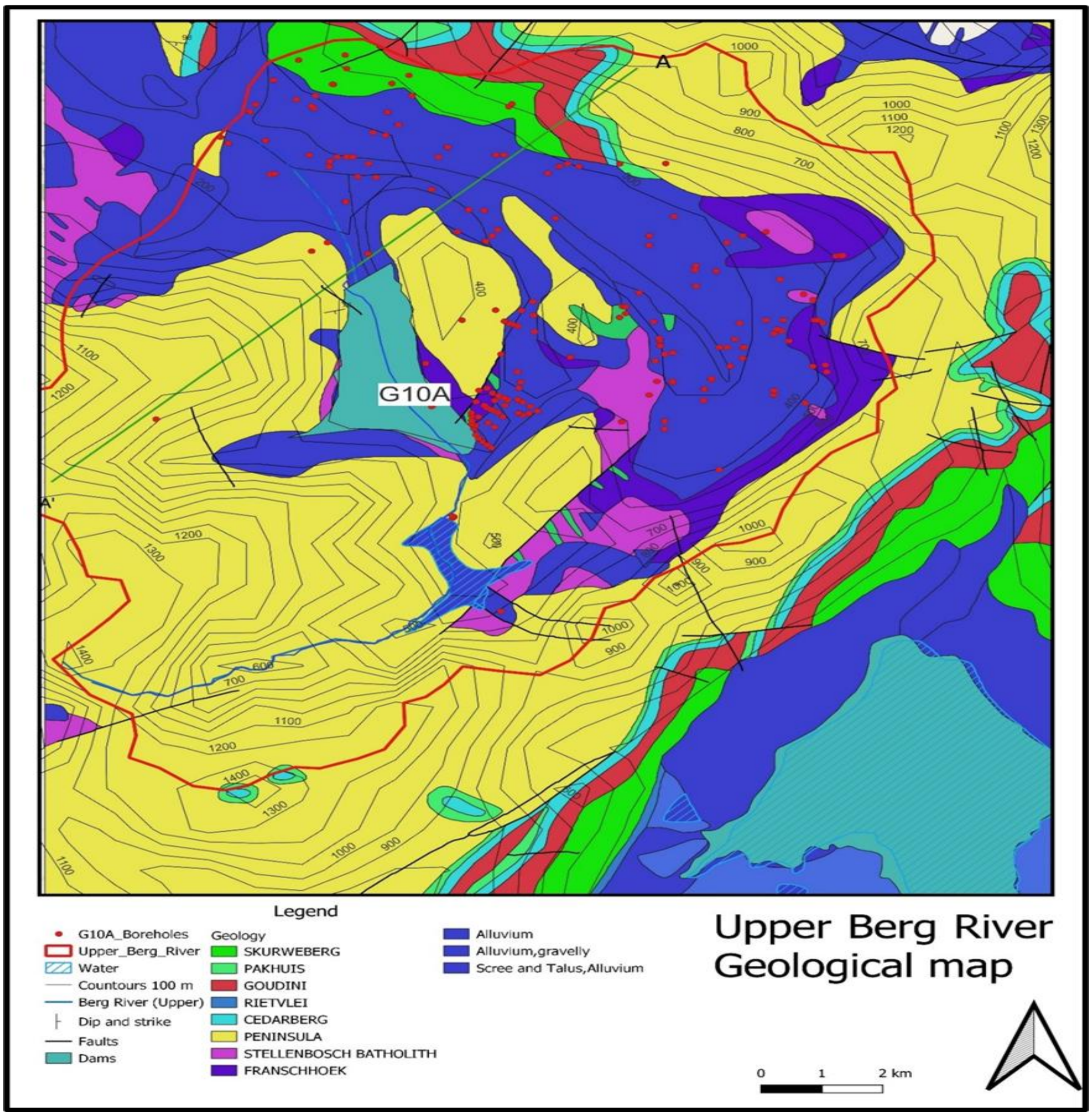


Figure 11:Boreholes in the Upper Berg Catchment

The Map above shows boreholes in the Upper Berg Catchment that are drilled in unconsolidated geological materials [unconfined aquifer system) and those boreholes that drilled in consolidated geological materials [Confined Aquifer System]. Such information on the map provided key insight on the existence of unconfined and confined aquifer systems in the catchment. This report recommends delineating aquifers in all quaternary catchments for aquifer-focussed analyses.

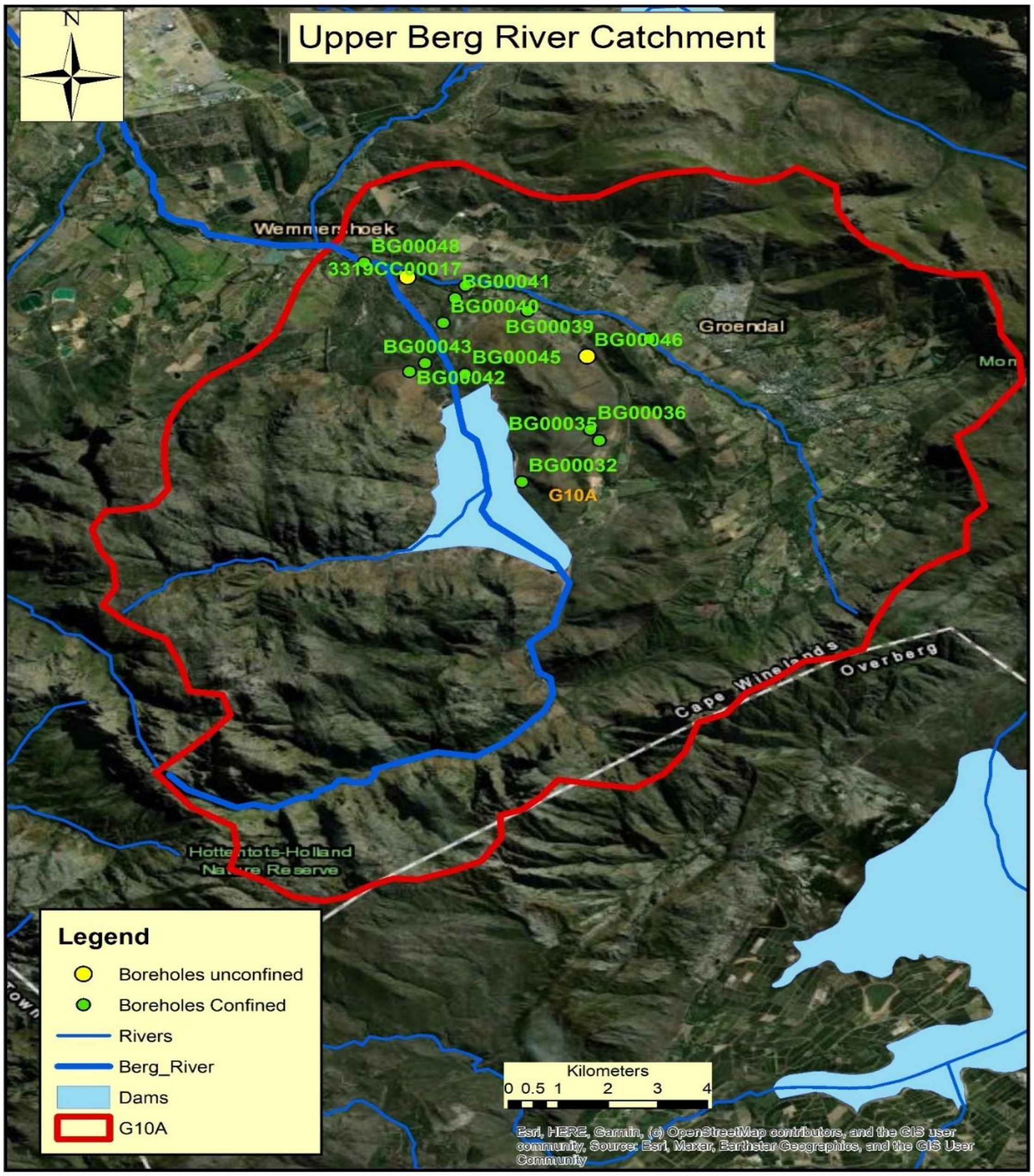


Figure 12: Boreholes in the Upper Berg Catchment

The Map above shows selected boreholes in the Upper Berg Catchment that are drilled in unconfined aquifer system and Confined Aquifer System. These boreholes were selected for demonstration purposes. Such information on the map provided key insight on the existence of unconfined and confined aquifer systems in the catchment for calculating Groundwater Stress Index and Environmental Stress Index in addition to setting Reserve and RQOs. This report recommends such approach in all quaternary catchments.

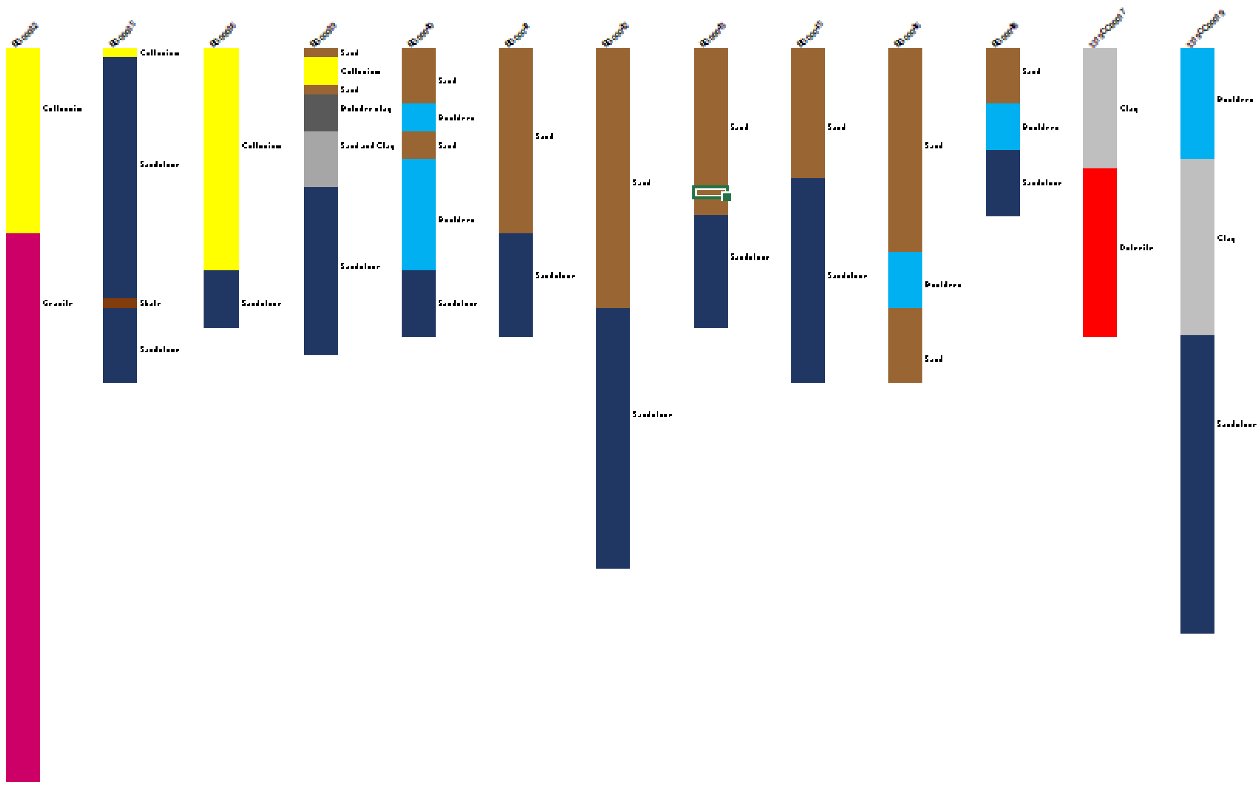


Figure 13:Borehole logs for boreholes in the Upper Berg Catchment

Figure 13 above shows lithological cross-section of the selected boreholes in the Upper Berg Catchment that are drilled in unconfined aquifer system and Confined Aquifer System. These boreholes were selected for demonstration purposes. Such information on the map provided key insight on the existence of unconfined and confined aquifer systems in the catchment for calculating Groundwater Stress Index and Environmental Stress Index in addition to setting Reserve and RQOs. Although detailed boreholes information requires update [screen in each borehole, borehole depth among others, this report recommends such approach for all boreholes in all quaternary catchments. Accurate, adequate, and comprehensive data or information remain vital for making relevant and practical decisions in water management.

In the 2011 GRDM training manual, groundwater quality classification was mainly based on EC parameter. This has a limitation as not only EC is responsible for the apparent water quality of a particular system, but also other parameters influence the groundwater quality. A holistic approach is proposed to use a Groundwater Quality Index (GQI). This approach combines multiple parameters to get the overall water quality. The results are then interpreted using table 10. The approach allows the user to select the parameters for their specific site and give weight to the different parameters. In the current manual this approach was tested in two separate catchments i.e., G10A and G50. In previous studies (Saleem et al., 2016;Ram et al., 2021; Nzama et al., 2021), the limit when using this approach is set using the water quality standards, however, since the water is coming from the aquifer then environment should set the limit. In this manual the maximum from long term monitoring data is used to the limit. In figure 14 below, the quality of water is between 0 and 25 for much of the catchment. The upper Berg is a pristine environment. It was expected that a large portion of the catchment would fall in this category. The other part is between 26 – 50, this suggests that the section is minimally impacted. This was expected as that section falls with the Franschhoek area, in the area farming takes place and there are settlements in that part. The section below the confluence also shows signs of being impacted; across the road from the confluence a wastewater treatment plant can be found.

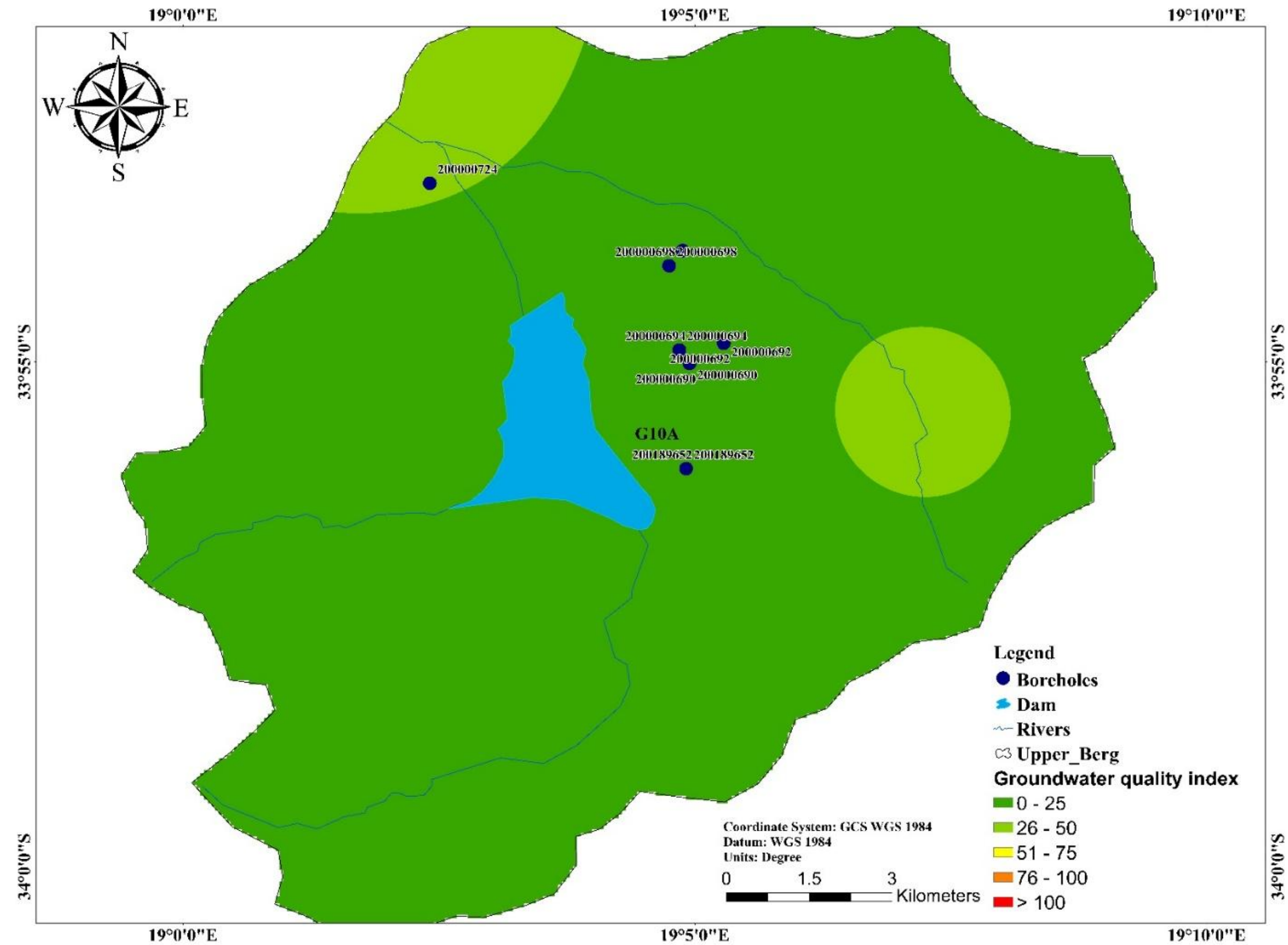


Figure 14:Groundwater quality index for the Upper Berg catchment using background condition data

It is understood that not all catchments have historical data, in case like that it is suggested that the water quality standards be used with caution until background data is available. Based on the analysis of groundwater quality using the drinking water guidelines, figure 15 below shows that the catchment has shifted from the range of 0 to 25 and now includes values greater than 100. This means that the water is not good for drinking but good for environment, this is why guidelines in such cases should be applied with caution. One needs to understand the use of the water when monitoring, the guidelines tend to more stringent on the environment.

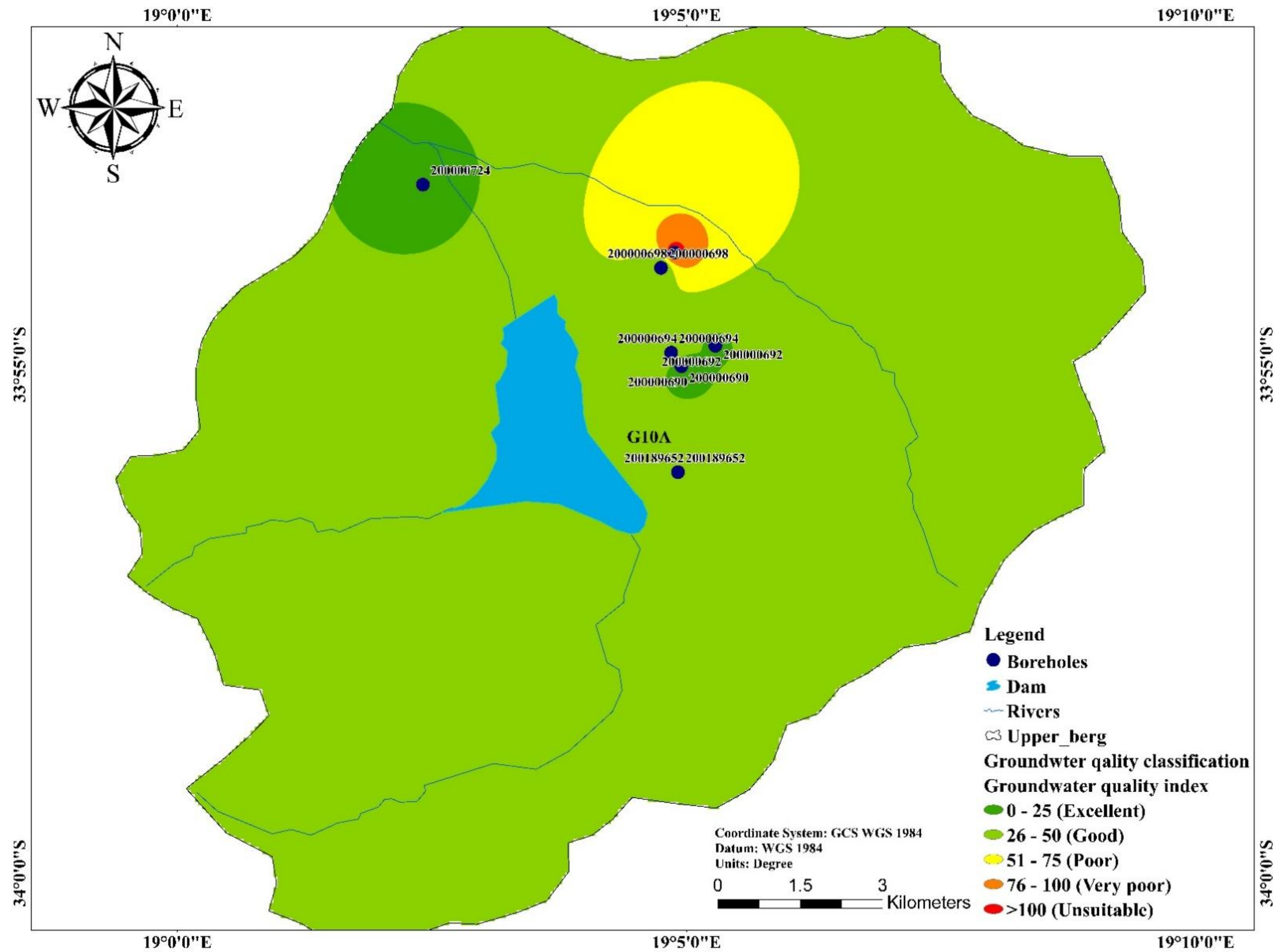


Figure 15: Groundwater quality index for the Upper Berg catchment using drinking water standards

4.3 Groundwater reserve determination — quality component for upper berg catchment

The water quality component of this Reserve is based on data obtained from the Water Management System (WMS), and the National Groundwater Archives (NGA) of the Department of Water and Sanitation (DWS). The ambient groundwater quality values used are median values from the statistical analysis of between 9 data sets from the catchment as shown in Table 10. The ambient groundwater quality in the quaternary catchment G10A falls in Class 0 of the DWS water quality guidelines, due to the pristine environment that produces fresh water as shown in the Table below. Water in Class 0 is classified as fresh water which is suitable for domestic use and has not health implications.

Table 10: Groundwater reserve determination — quality component for upper berg catchment

Parameter	**Ambient Groundwater Quality**		**Basic Human Needs Reserve[2)]**	**Groundwater Quality Reserve**	
	Unconfined	**Confined**		**Unconfined**	**Confined**
Calcium (mg/L)	7,857	7,86	<150	8,64	8,6427
Magnesium (mg/L)	1,7717	1,77	<100	1,95	1,94887
Sodium (mg/L)	12,9	12,90	<200	14,19	14,19
Chloride (mg/L)	18,3	18,30	<200	20,13	20,13
Sulphate (mg/L)	1,9	1,90	<400	2,09	2,09
Nitrate (mg/L)	0,3645	0,36	<10	0,40	0,40095
Fluoride (mg/L)	0,2645	0,26	<1,0	0,29	0,29095
pH	7,386	7,39	5.0 – 9.5	6.65-8.12	6.65-8.12
Electrical Conductivity	14,2	14,20	<150	15,62	15,62

It should be noted that the generic groundwater quality Reserve determined will have natural spatial water quality variations dictated by the geology in the catchment. Under these circumstances, site-specific data should be obtained and used to determine more representative local ambient groundwater quality conditions at the site. This Chief Directorate should be notified of such incidence, to revise the Reserve accordingly.

Table 11: Groundwater reserve determination — quantity component for upper berg catchment

Catchment	Delineated Aquifer		Area (km^2)		Recharge (Mm^3/a)		Population		GWC-baseflow (Mm^3/a)		BHN Reserve (Mm^3/a)	
	Unconfined	**Confined**	**Unconfined**	**Confined**	**Unconfined**	**Confined**	**GW_Pop**	**Gn_Pop**	**Unconfined**	**Confined**	**Unconfined**	**Confined**
G10A	□	□	1500	1500	68.335	68.335	110	166825		14.229		18.13732

Table 11 above shows the updated summary of the Reserve in the updated GRDM Methodology Training Manual 2024

Take note of the suggested columns and the columns that need to be removed when stakeholders agree.

NB* Recharge and GWC to Baseflow values are estimated from research work and where not available, the DWS database is consulted.

NB**Population data were obtained from the Population Census database and WARMS. Such data were not verified. Data on the groundwater Dependant population were taken from the WARMS database for the delineated aquifer system. Such datasets assume that the population that is registered for water use is the population that depends on groundwater. Given the issues of schedule and existing lawful water use along the validation and verification process, such datasets require precautionary principles during interpretation.

NB**** BHN based on a consumption of 25 litres per person per day.

4.4 Data Collection in the G50 i.e., Heuningnes Catchment (Aquifer delineation)

Aquifer delineation refers to the process of identifying the boundaries, extent, and characteristics of an aquifer. This information is essential for managing and protecting groundwater resources. The following are the steps involved in aquifer delineation: The first step is to identify the study area and define its boundaries. This could be a specific location or a larger region. Data collection is a crucial step in aquifer delineation. The data collected included geological maps, hydrogeological reports, well logs, and water quality data. A geophysical survey was used to identify the thickness and depth of the aquifer. This involves using equipment that can detect changes in the subsurface geology, such as electrical resistivity, magnetic susceptibility, and seismic waves. A pumping test involves pumping water out of a well and monitoring the rate of water level decline over time. This test provided information about the hydraulic properties of the aquifer, such as transmissivity and storativity.

Once the data had been collected, it needed to be analyzed to determine the boundaries of the aquifer. This involved creating a conceptual model of the aquifer based on the available data. A groundwater model is a computer simulation of the aquifer that can be used to predict how the aquifer will respond to changes in pumping rates or other stresses. This model can help refine the conceptual model and identify areas where further data collection may be needed. Once the boundaries and characteristics of the aquifer have been determined, they can be mapped to create a visual representation of the aquifer. The final step is to report the results of the aquifer delineation study and communicate them to stakeholders, such as government agencies, water resource managers, and the public.

Groundwater resource units' delineation

Figure 16: Locality map of the Heuningnes catchment

The Heuningnes catchment consists of four catchments (G50B to G50F), The Heuningnes Catchment is largely dominated by the following main geological formations as shown in Figure

17. Malmesbury Group, Table Mountain Group, Cape Granite Group, Bokkeveld Group, Bredasdorp Group. The basement rocks of the Malmesbury and Cape Granite Groups are overlain by the Table Mountain and Bokkeveld Groups. The Table Mountain Group (TMG) is made up of quartzitic sandstones formed by coarse sands deposited in the Agulhas Sea and along the coastal plane. It was formed during the Ordivician, Silurian, and early Devonian epochs. The TMG is under the Malmesbury and Cape Granite Suite basement formations (Greese et al, 2006). Although the outcrop area is limited, these rocks underpin the whole coastal plane at depths of up to 100 m.

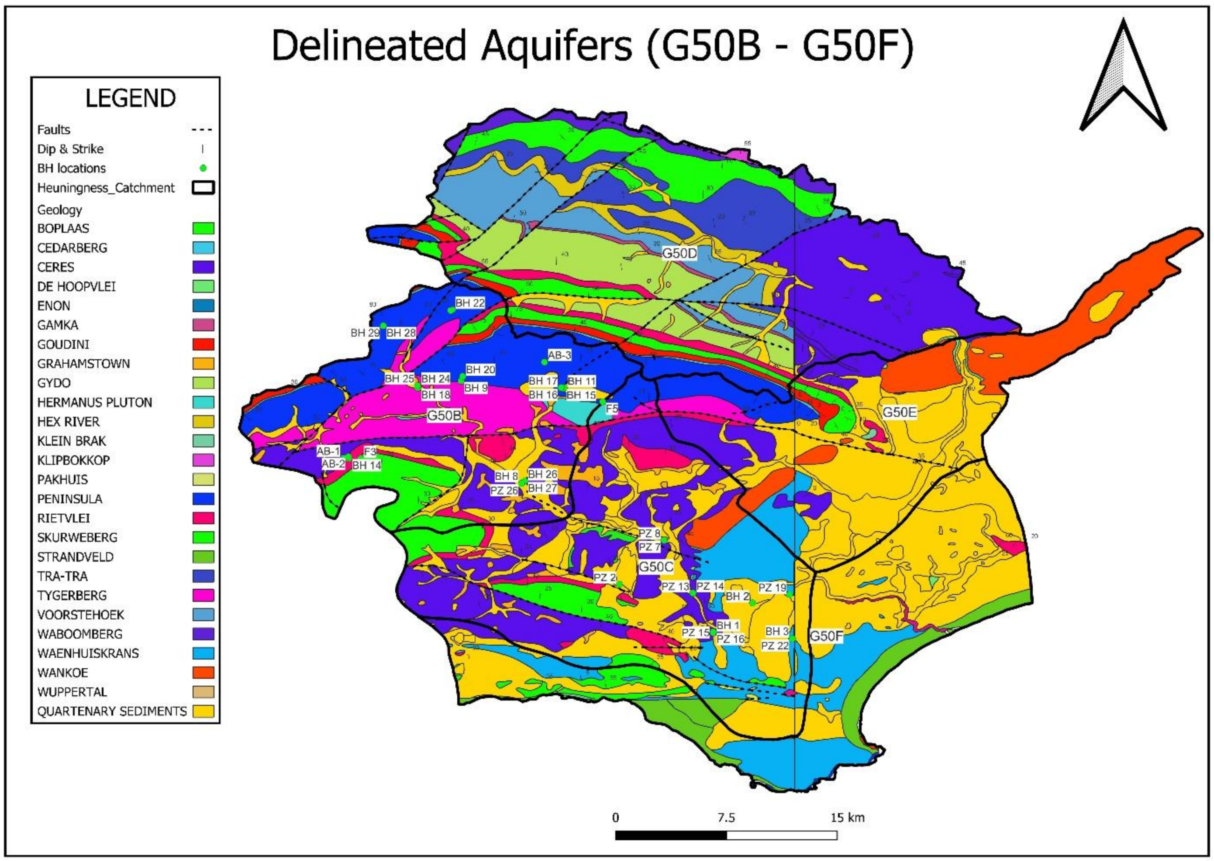


Figure 17: Delineated aquifers in the Heuningnes catchment (G50B - G50F)

The Bokkeveld Group constitutes the middle subdivision of the Cape Supergroup, comprising a cyclic alternation of fine-grained sandstone and mudrock units that conformably overlie the TMG in an off-lapping succession (Thamm and Johnson, 2006). Bokkeveld strata consists largely of shales and thin interbedded sandstones derived from marine continental slope muds of early to mid-Devonian. In the Heuningnes Catchment, the Bokkeveld formation lies between the TMG and the Bredasdorp Group. The Bokkeveld Group rocks occupy the largest area, comprising an alternating sequence of shales and sandstones. (Figure 2).

The Bredasdorp Beds are characterized by calcified dune sand, calcrete, calcarenite and basal conglomerate. In the Heuningnes Catchment, this formation occurs around Soetendalsvlei and towards the mouth of the Heuningnes River. It forms an important component of the southern part of the catchment. Several faults cut the TMG of the Napier-Bredasdorp Mountains, trending northeast-southwest and east-west (Figure 18).

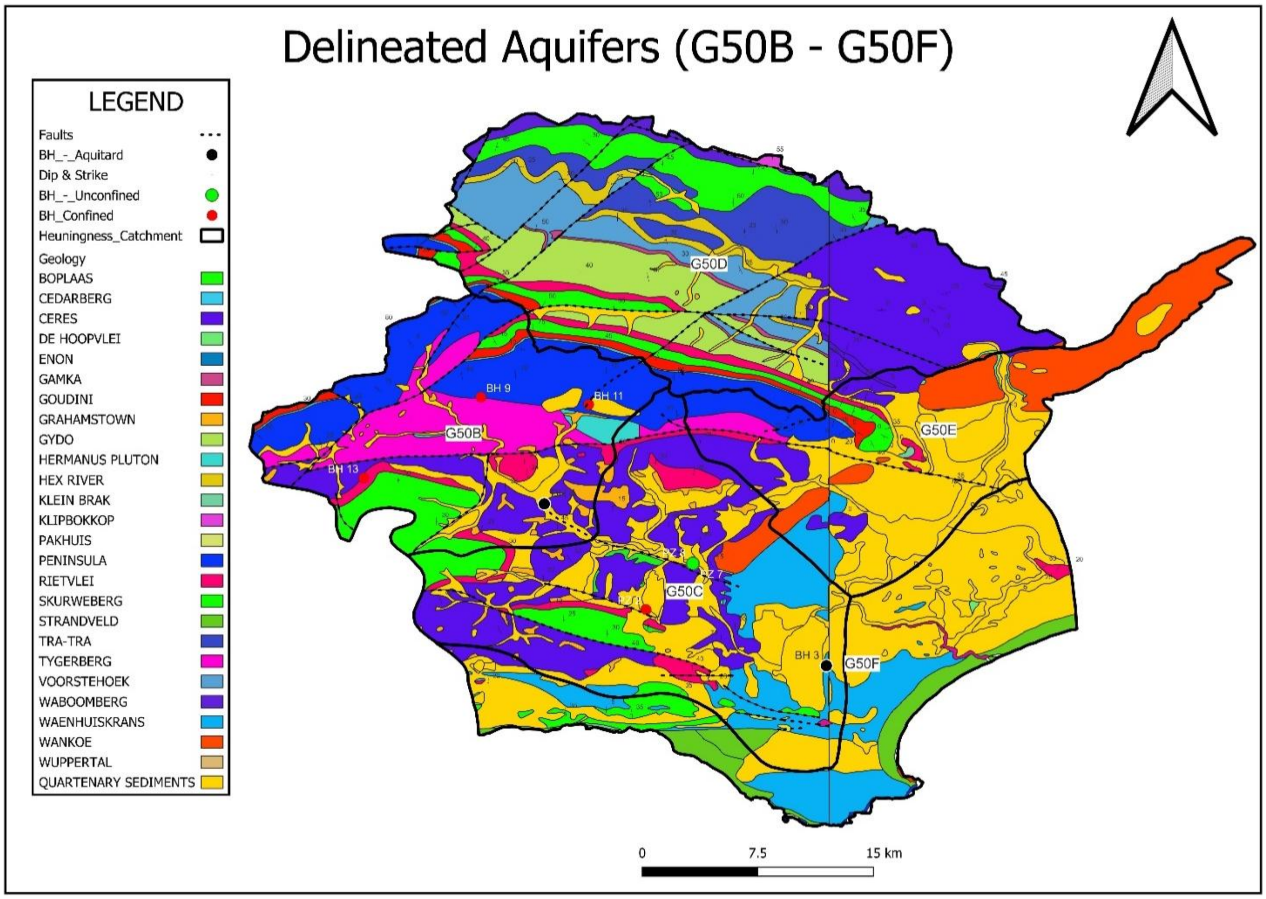


Figure 18: Geological maps of the Heuningnes catchment showing the faults in dotted lines

The same approach was used to delineate groundwater resource units, for Heuningnes catchment. The catchment has both primary and secondary aquifers. Unconsolidated sediments deposited as alluvium in floodplains of major river systems and ocean deposition during sea level fluctuations form primary aquifers. Sand channels are linked with fresh water, whereas clay layers relate to saltier water. The aquifer thins out at the river valley's margin. Aquifers formed by fractured bedrock are thought to be semi-confined, anisotropic, and secondary in character. The high yielding aquifers of more than 5 l/s in the Heuningnes catchment is associated with the fractured aquifers of TMG which occur along the Struisbaai and Bredasdorp. The sandstones outcropping along Spanjaardskloof, Napier, Sandfontein, Tuisenberg are yielding 1 to 2 l/s. Figure 19 shows the aquifer yield and type map.

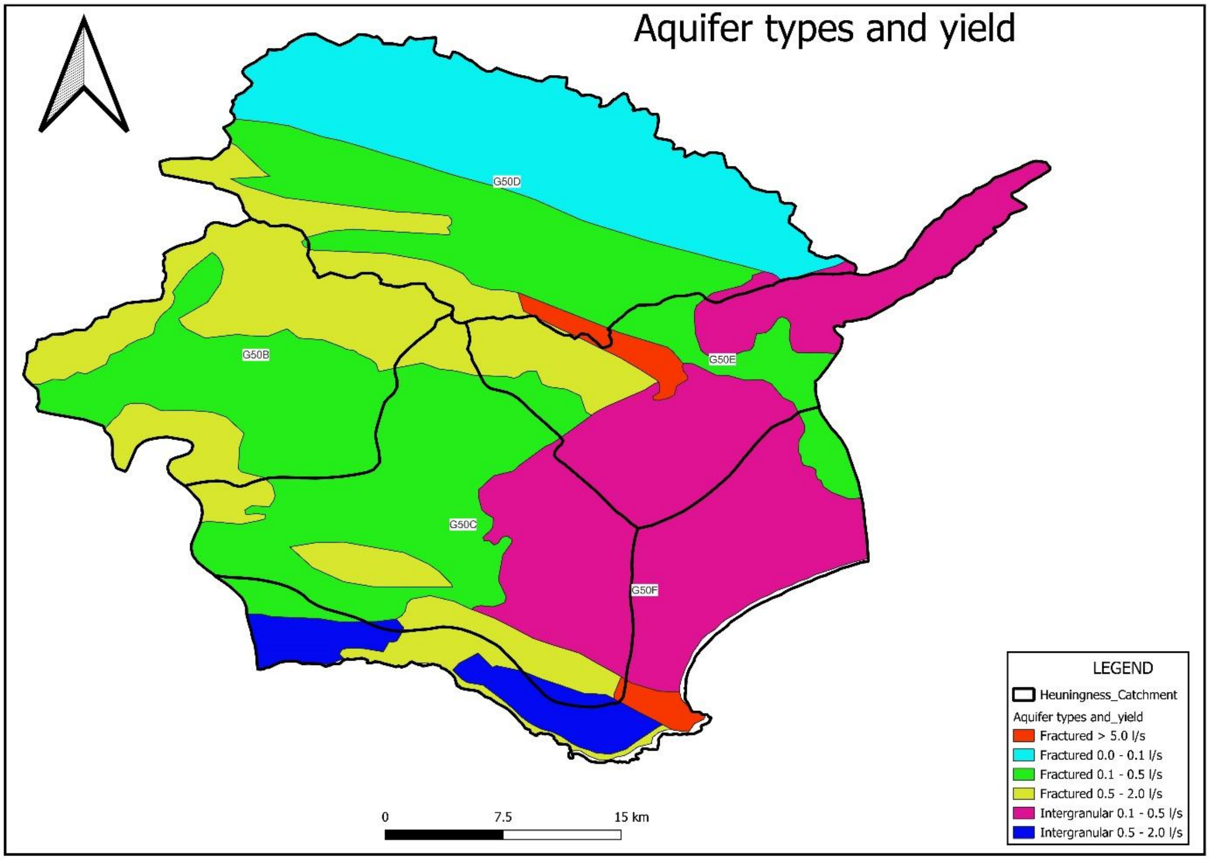


Figure 19:Aquifer yield and type map in the Heuningnes catchment

The geological logs obtained from records were used to better understand the aquifer system of the catchment. The unconfined aquifers in the catchments consist of (alluvium, sandy clay, loamy clay, sand clay with shells, clay sand). These aquifers occur along the rivers, valleys, and flat lying areas such as Elim. The unconfined aquifers in the Heuningnes catchment intersect from the surface to the depth of 10 m except in the areas dominated by sand dunes such as Struisbaai where these aquifers can reach total thickness of more than 60 m. Unlike the G10A the presence of Bokkoveld Group which was generally deposited during the sea regression and deposited shales which act as aquitard as shown in the Figure 20 and 21.

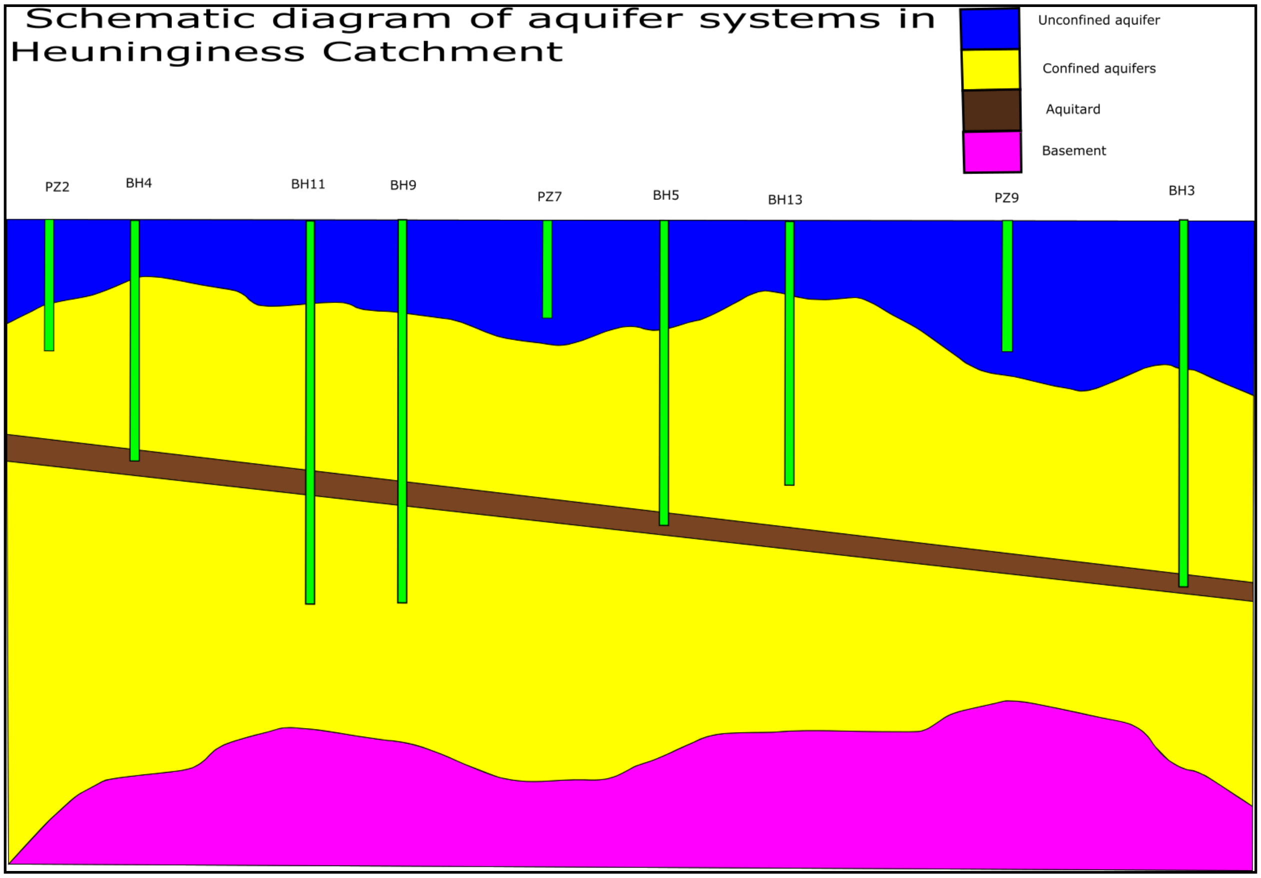


Figure 20: Aquifer system of the Heuningnes catchment

The confined system in the Heuningnes catchment is distorted by the faults that

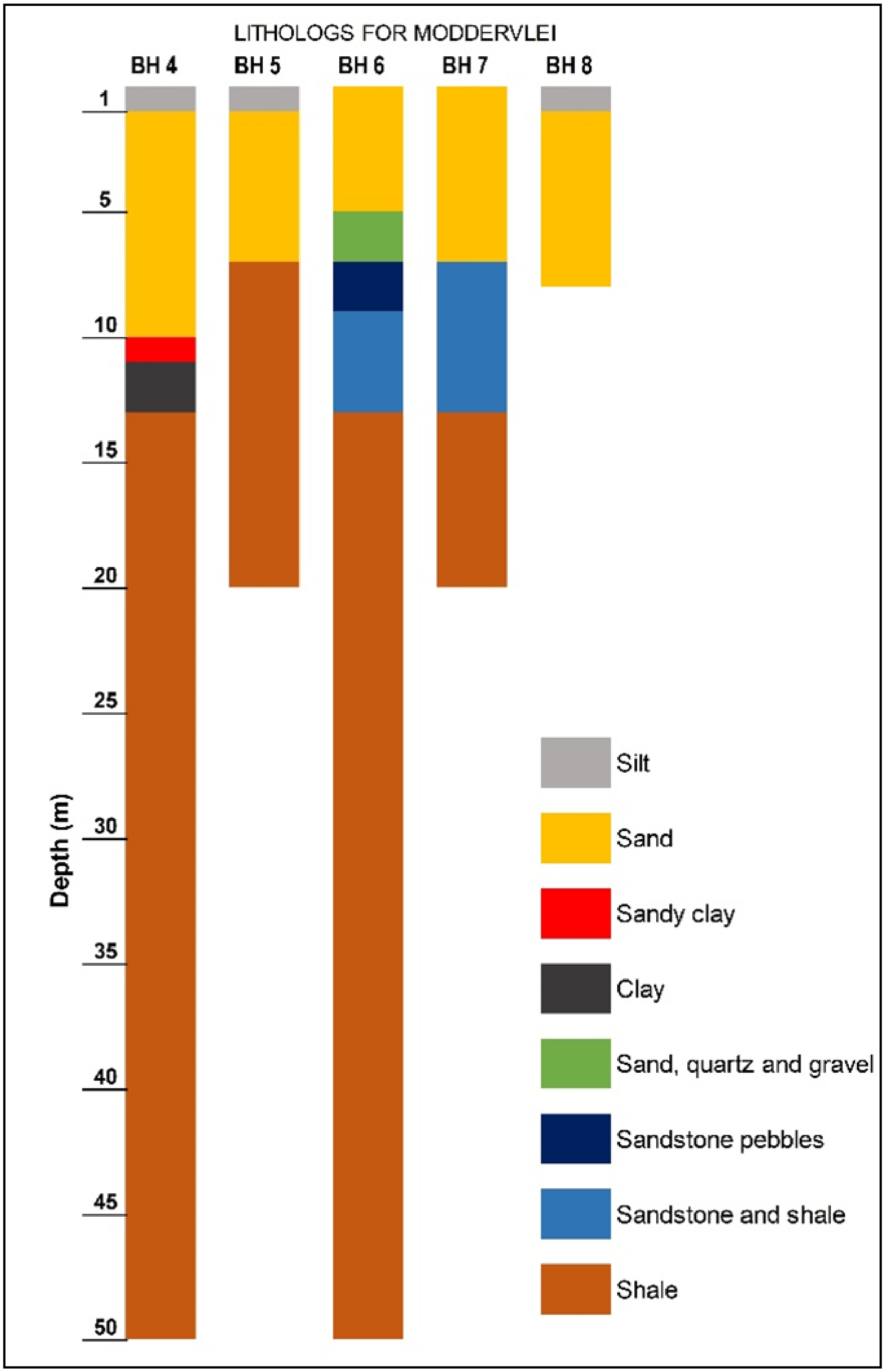


Figure 21: Borehole logs of different boreholes drilled in Heuningnes catchment

Status of the system (quantity)

Groundwater Use

According to the number of registered users and the overall volume per GRU, 2 presents the registered groundwater consumption from the WARMS dataset. **Error! Reference source not found.** and 13 provides the proportion of total registered volume per GRU for registered groundwater use by water use sector. Figure 22 shows the registration distributions and the related water use sectors.

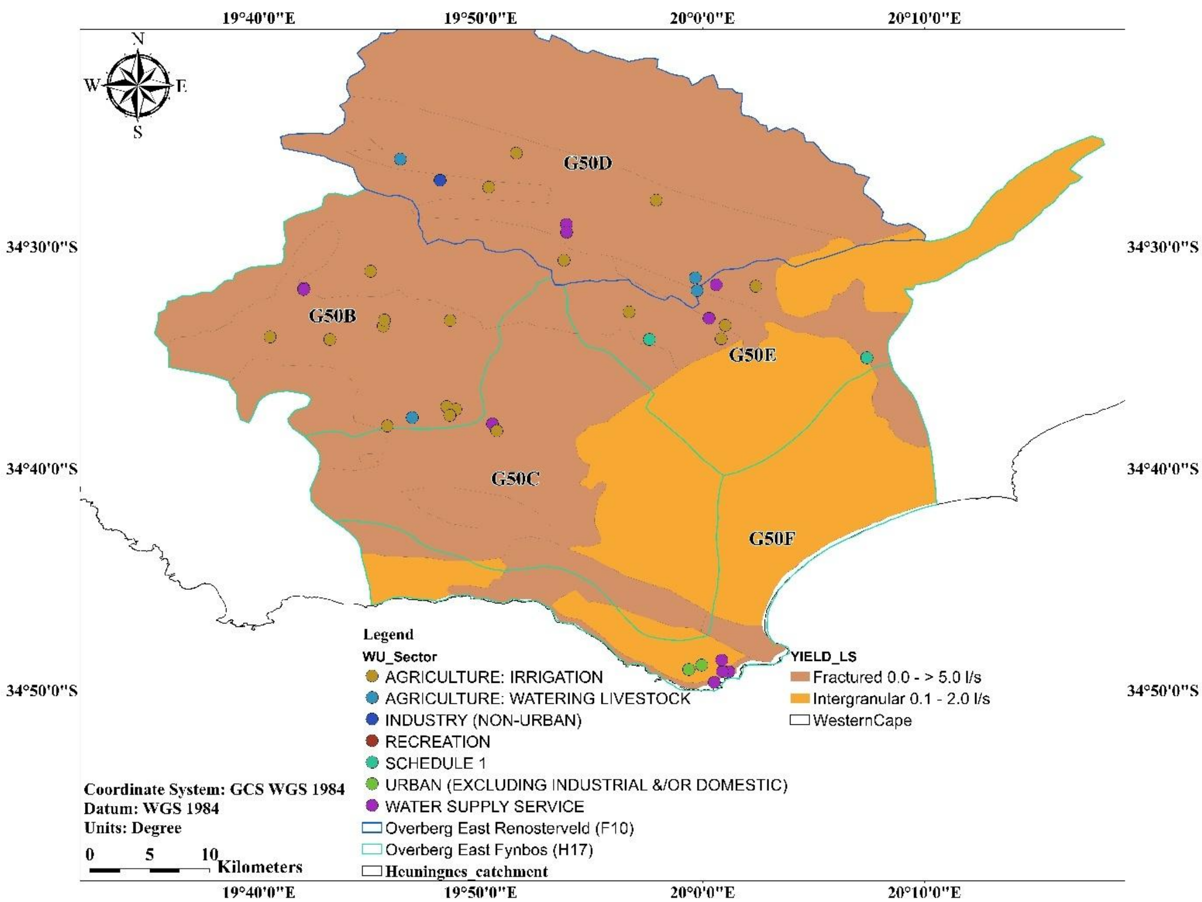


Figure 22: Total groundwater use reported in WARMS, per GRU, indicating boreholes and related water use sectors

Table 12: Number of registered groundwater use sectors within delineated resource units

GRU	No. of Registered users	Total volume (Mm^3/a)
Primary/intergranular aquifers		
Overberg East Fynbos	4	0.2
TMG/fractured aquifers		
Overberg East Fynbos	41	2.7
Overberg East Renosterveld	**9**	0.3

Table 13: Volume (%) of water use per delineated groundwater resource unit

GRU	Agriculture: Irrigation (% of Total Volume)	Agriculture: Watering Livestock (% of Total Volume)	Industry (Non-Urban) (% of Total Volume)	Recreation (% of Total Volume)	Schedule 1 (% of Total Volume)	Urban Excluding (Industrial &/Or Domestic) (% of Total)	Water Supply Service (% of Total Volume)
Primary/intergranular aquifers							
Overberg East Fynbos	0.0	0.0	0.0	0.0	0.0	65.3	34.7
TMG/fractured aquifers							
Overberg East Fynbos	69.8	0.8	0.0	0.5	0.7	0.0	28.1
Overberg East Renosterveld	62.5	5.6	8.7	0.0	0.0	0.0	100.0

Groundwater recharge

For groundwater use to be sustainable, there must be enough recharge. Recharge varies depending on the geology and aquifer type (intergranular or fractured rock). The direct infiltration of water through the ground surface, influent seepage from rivers and streams, as well as interflow from the bedrock, all contribute to the recharge of an intergranular aquifer. Recharge to fractured rock aquifers occurs by interflow from overlying alluvial aquifer, rainwater infiltration into the bedrock in the higher mountainous locations (especially the fragmented arenaceous TMG sandstone), and subsurface groundwater flow caused by pressure gradients and gravity. **Error! Reference source not found.** depicts the recharge estimations for groundwater resource units.

Table 14: Estimated recharge values for the delineated groundwater resource units

GRU	Source	Area (Ha)	MAR (mm)	MAP (mm)	Recharge (mm/a)
Primary/ intergranular aquifers					
G50C		41561.75	34.9	488.76	20.27
G50E	Cape farm Mapper	30418.19	30.4	448.41	19.46
G50F		28880.71	27.2	453.14	23.71
Average recharge					**21.15**
TMG/ Fractured aquifers					
G50B	Cape farm Mapper	34714.73	45.1	531.07	17.38
G50C		30418.19	30.4	448.41	20.27
G50D	Cape farm Mapper	57276.53	27.1	431.43	11.07
G50E		30418.19	30.4	448.41	19.46
Average recharge					**17.05**

Aquifer Stress Index (groundwater use)

Primary/ Intergranular aquifers stress index

- Groundwater use = 0.2 Mm^3/a shown in table 2
- Groundwater recharge = 21.15 mm/a = 0.02115 m/a shown in table 4

To convert groundwater recharge from m/a to m^3/a, groundwater recharge in the primary aquifer system was multiplied by the area covered by the Heuningnes catchment (1400000000 m2) as the area covered by the primary aquifer system was unknown. Where the area covered by the aquifer system is known then it is recommended to be used rather than the usage of the catchment area.

- Heuningnes catchment area: 1400000000 m^2
- Groundwater recharge: 0.02115 m/a x 1400000000 m^2 = 29610000 m^3/a = 29.61 Mm^3/a

Therefore,

Primary / intergranular aquifer stress index of Heuningnes Catchment (%)

$= \frac{gwUse}{Recharge}\ x\ 100$

$= \frac{0.2\ Mm3/a}{29.61\ Mm3/a}\ x\ 100$

= 0.68 %

This index shows that the unconfined aquifer (inter granular) receives more groundwater recharge than it is being used within the system. This implies that the unconfined system is not stressed with more groundwater availability for abstraction; therefore, a license can be issued from this aquifer.

TMG/fractured aquifers stress index

- Groundwater use = 3 Mm^3/a as shown in table 2
- Groundwater recharge = 17.05 mm/a = 0.01705 m/a as shown in table 4

To convert groundwater recharge from m/a-m^3/a, groundwater recharge in the fractured aquifer system was multiplied by the area covered by the Heuningnes catchment (1400000000 m^2) as the area covered by the TMG / fractured aquifer system was unknown. Where the area covered by the aquifer system is known then it is recommended to be used rather than the usage of the catchment area.

- Heuningnes catchment area: 1400000000 m^2
- Groundwater recharge: 0.01705 m/a x 1400000000 m2 = 23870000 m^3/a = 23.87 Mm^3/a

TMG / fractured aquifer stress index of Heuningnes Catchment (%)

$= \frac{gwUse}{Recharge}\ x\ 100$

$= \frac{3\ Mm3/a}{23.87\ Mm3/a}\ x\ 100$

= 12.57 %

This index less than 20 % shows that the TMG/ Fractured aquifer (confined) system of the Heuningnes catchment is not stressed which implies that the water abstracted from this system is less than the water coming into the system. This provides the insurance of groundwater availability in the system to sustain the ecosystem.

Environmental Stress Index

The environmental stress index was computed for the confined aquifer system (TMG/ fractured) of the Heuningnes quaternary catchment of G50B for the year 2020.

- EWR_MLF = 1.383 Mm^3/a (Spatsim program)
- Annual flows received by the aquifer system in 2020 = 9.060 Mm3/a (Mazvimavi et al.,2021)
- Baseflow index estimated using the mass balance equation using natural EC = 28% (Mazvimavi et al., 2021)

To get the flows contributed to annual river flow by the aquifer system, the annual flows received were multiplied by the baseflow index.

- Groundwater contribution to baseflow by the confined aquifer system of the G50B quaternary catchment of the Heuningnes catchment in 2020 = 2.5368 Mm^3/a

$$Environmental\ Stress\ Index = \frac{EWR - MLW}{Groundwater\ contribution\ to\ Baseflow} x\ 100$$

$$= \frac{1.383\ Mm3/a}{2.5368 Mm3/a} \times 100$$

$$= 54.52\%$$

This index indicates that groundwater from the confined aquifer system of the GB50 sustains the ecosystem in the area. This represents the non-perennial river system whereby the river dries up in dry seasons, resulting in the ecosystem total dependence on groundwater.

Status of the system (quality)

The procedure for determining GQI has been stated in the above sections and the importance of using such an approach over the use of EC alone has been stated in the case of upper Berg. The one element that was not demonstrated in the above case study is the application of the GQI on different aquifer system. The reason for this was the lack of lithological logs for the unconfined aquifer system in the upper Berg. In the delineation step, aquifer systems need to be delineated and as such groundwater quality index needs to be determined for the delineated aquifer systems.

In figure 23 below, the quality of water is between 0 and 25 for much of the catchment. The Heuningnes catchment is a rural environment and there are not many activities taking place in that area. It was expected that a large portion of the catchment would fall in this category. The other part is 26 – 50; this suggests that the section is minimally impacted. The section that is minimally impacted forms part of the area that has the highest salinity levels in the unconfined aquifer system.

Unconfined aquifer system

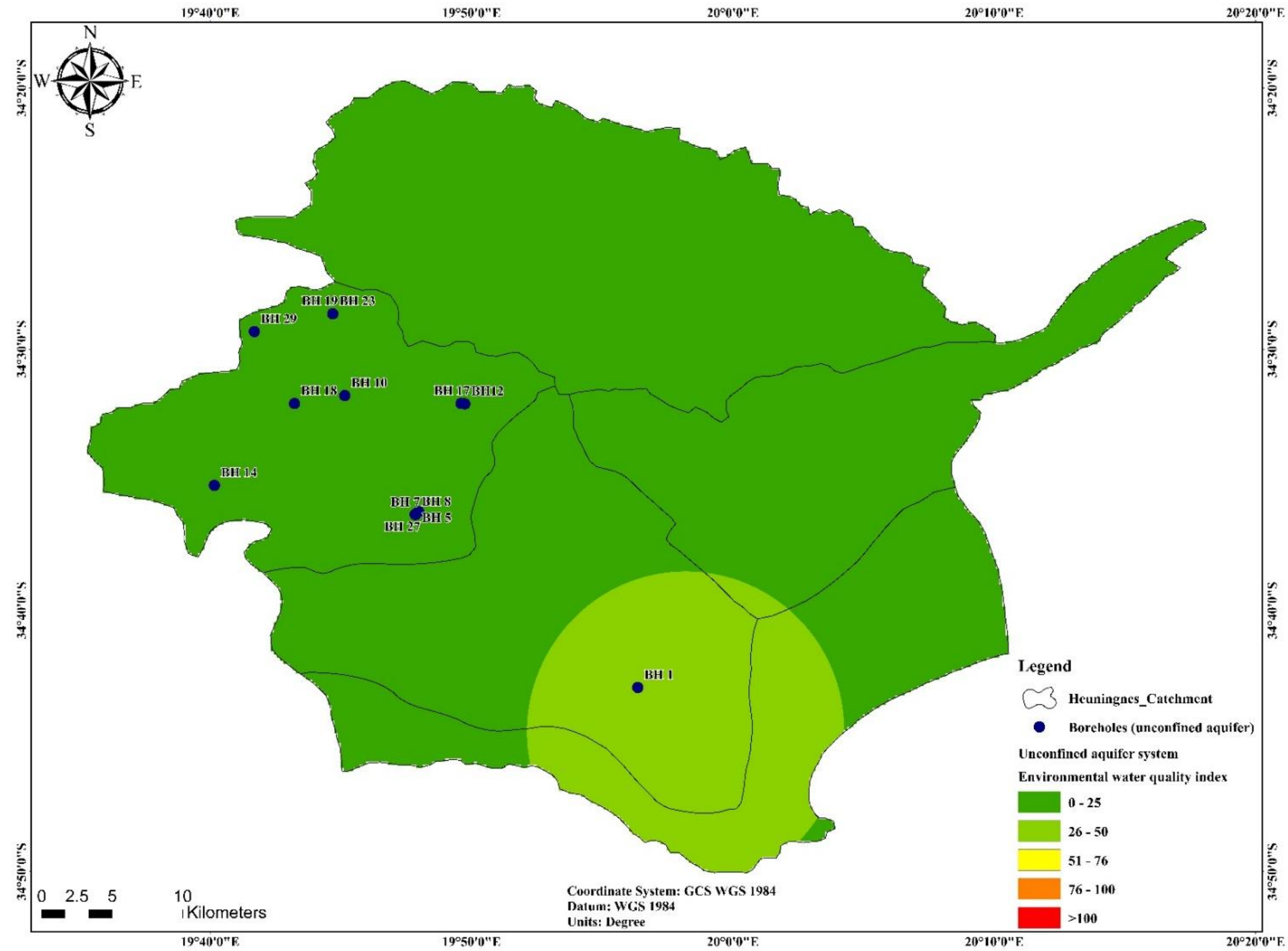


Figure 23: Groundwater quality index based on the background condition of the unconfined aquifer system

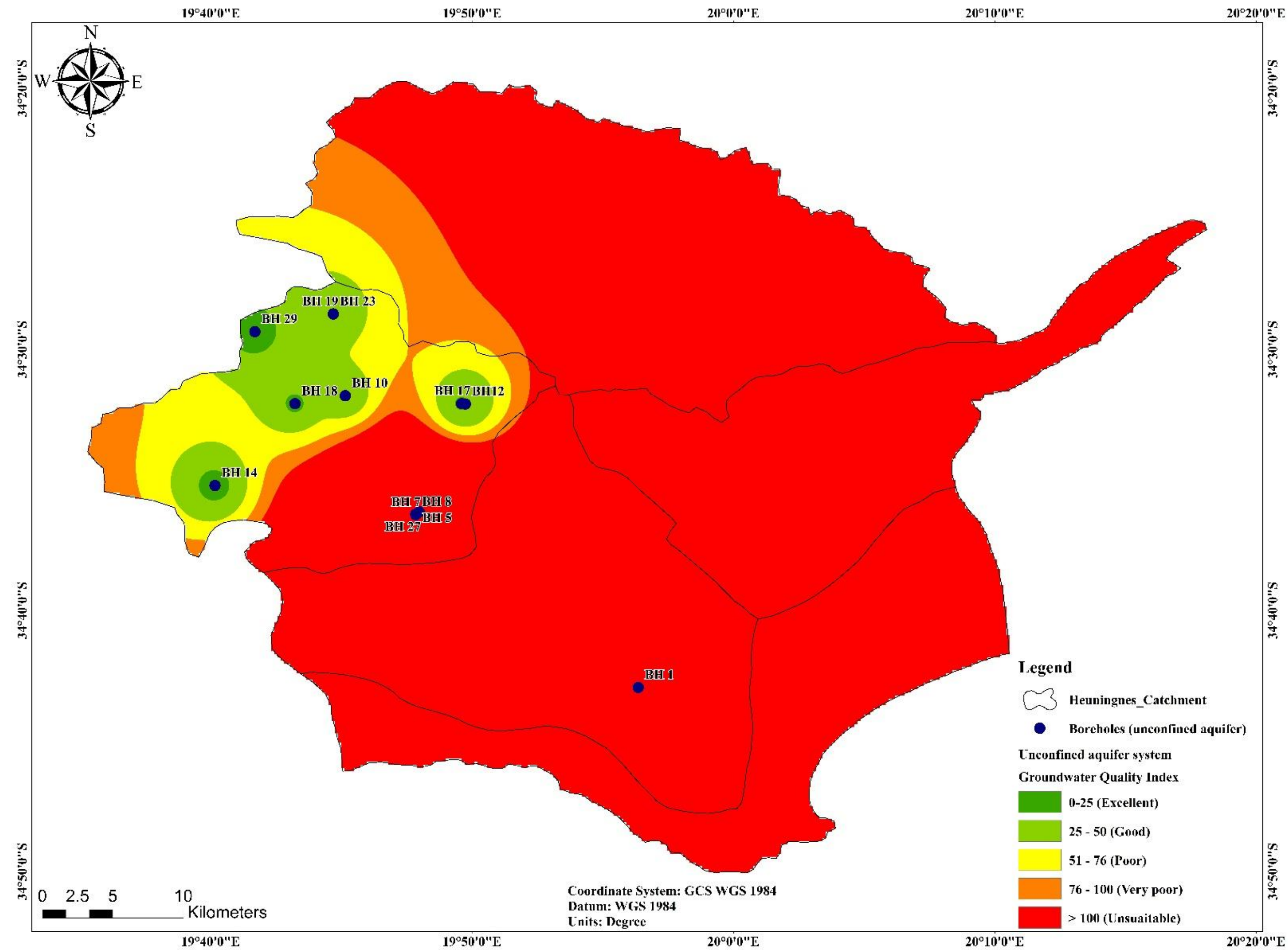


Figure 24: Groundwater quality index based on the water quality standards for drinking water

Figure 24 shows that the catchment has shifted from the range of 0 to 25 and now includes values greater than 100. The high range is a result of the high salinity levels.

Confined aquifer system

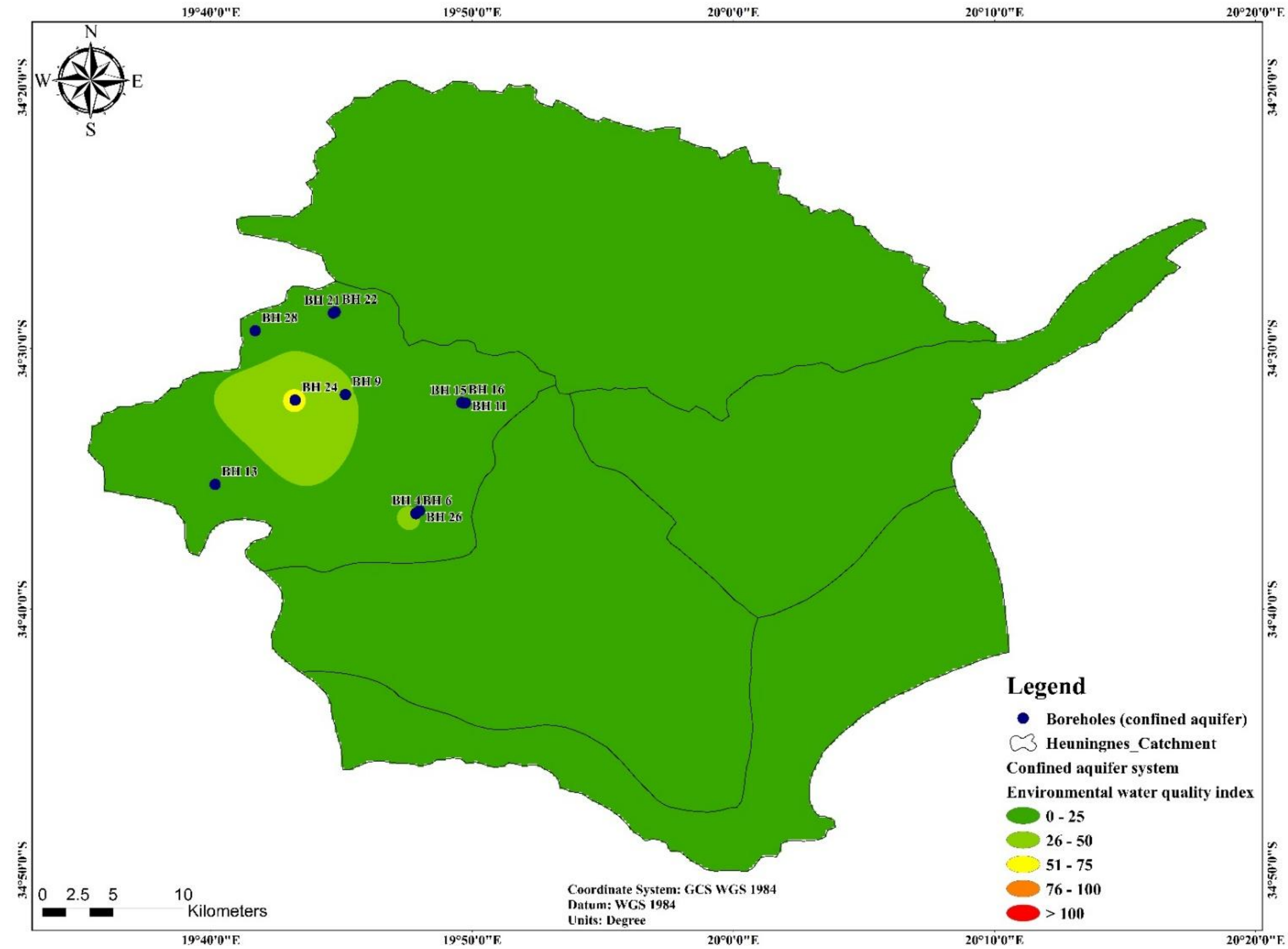


Figure 25: Groundwater quality index based on the background condition of the confined aquifer system

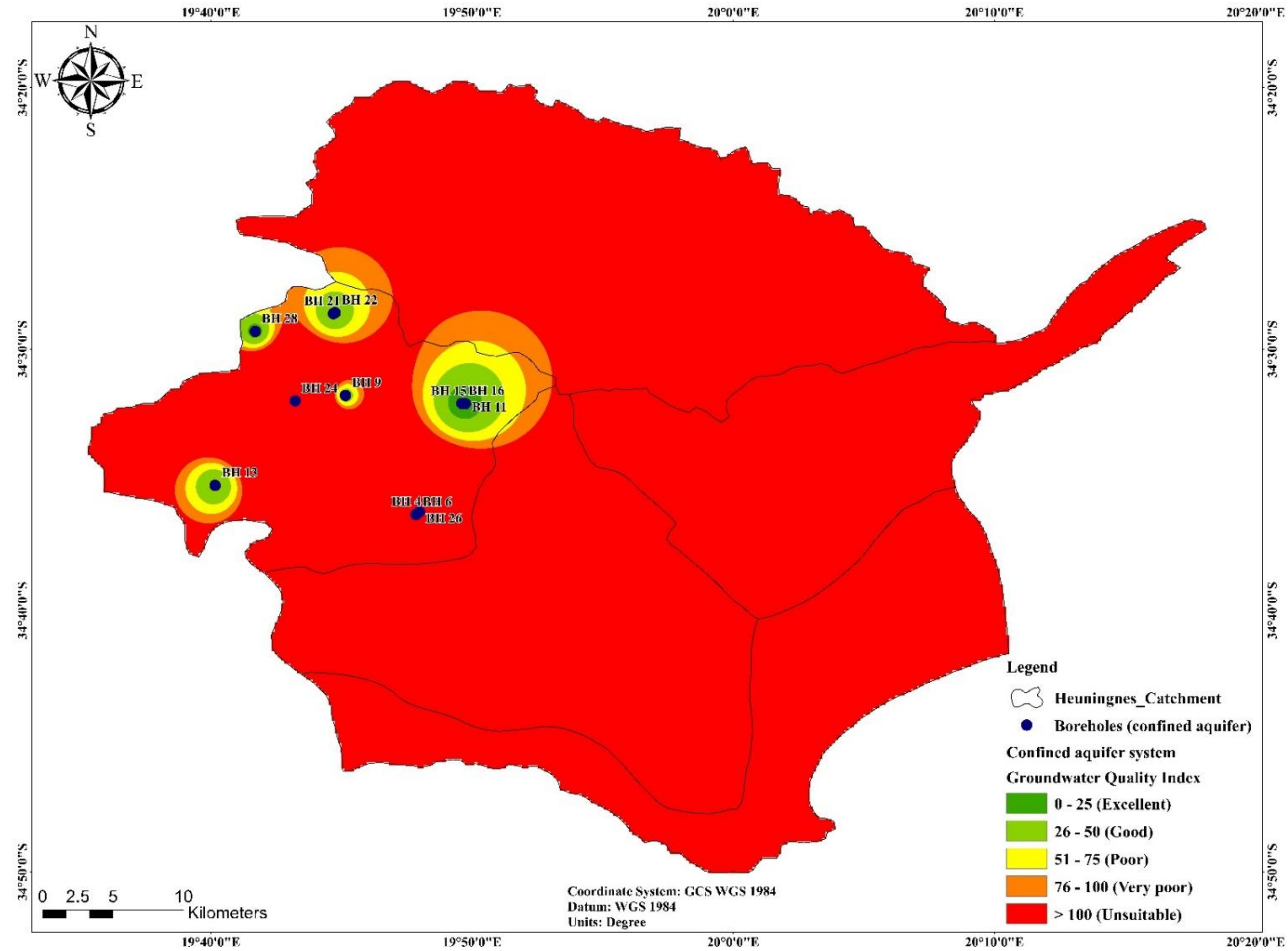


Figure 26: Groundwater quality index based on the water quality standards for drinking water

Monitoring groundwater quality needs to be done at the delineated aquifer systems. This has been demonstrated in this case study as in the unconfined aquifer system the range of 26 to 50 was closer to the coast. Whereas the confined aquifer system it is in the upper section of the catchment (Figures 25 and 26). So, if monitoring is not done based on the delineated aquifer systems the in accurate conclusions could be drawn from such studies.

Groundwater reserve determination — quantity component for Heuningnes catchment

Recharge estimation (Aquifer recharge)

Here are the general steps for estimating groundwater recharge: Identify the area where you want to estimate groundwater recharge and collect necessary data, such as climate data, land use information, topography, soil type, and vegetation cover. Calculate the water balance of the study area by estimating the inputs (precipitation, surface runoff, and irrigation) and outputs (evapotranspiration, surface water bodies, and groundwater pumping) of the water cycle. Determine the infiltration rate of the study area by conducting soil tests, using empirical equations or analytical models, or using remote sensing and GIS techniques. Calculate the recharge rate by multiplying the infiltration rate with the area of the study area.

Validate the recharge estimate by comparing it with the available groundwater data or conducting field tests such as aquifer pumping tests, soil moisture measurements, and water level measurements. Refine the recharge estimate based on the validation results and adjust the parameters used in the calculations. Report the recharge estimate along with the methodology, assumptions, and limitations of the study. Note that the procedure and steps for estimating groundwater recharge may vary depending on the study area, available data, and methodology used. It is recommended to consult relevant literature and experts in the field for detailed guidance.

***This section has been quantified in the classification section above.

Groundwater dependent *population*

Determining the groundwater dependent population involves a comprehensive assessment of the dependence of people on groundwater for their daily water needs. The following are the general steps involved in the procedure for determining the groundwater dependent population: the first step is to define the study area, which could be a city, town, or region where groundwater is an important source of water supply. Collect relevant data such as population density, water use data, and groundwater resources information. Identify the groundwater sources available in the study area, including wells, boreholes, and springs. Determine the water use patterns in the study area by collecting data on the amount of water used for domestic, commercial, and industrial purposes.

Analyze the data collected to determine the extent of dependence on groundwater as a source of water supply. This could involve calculating the percentage of water supplied by groundwater sources compared to other sources. Using the results, the analyzed data, identify the population that relies on groundwater as their primary source of water supply. This could involve determining the percentage of the population that relies solely on groundwater for their water needs or those that rely partially on groundwater. Finally, assess the vulnerability of the groundwater-dependent population to changes in groundwater resources such as drought, contamination, or overuse. This could involve assessing the availability of alternative sources of water supply and the ability of the population to access these sources. Overall, determining the groundwater dependent population requires a comprehensive analysis of the water supply situation in a given area and the extent to which the population relies on groundwater as a source of water supply.

Groundwater dependent *population (quantification)*

Basic Human Needs (BHN) (25 l/p/d is accounted for in determining the Reserve; this volume is the minimum and may be gradually increased as necessary, this method is an oversimplification. The assumption that everyone uses groundwater leads to the over allocation of the resource. Alternatively, a more accurate method is using the groundwater dependent population. The data for this method is acquired from the NGA and WARMS. For this example, the abstraction data from the WARMS database was used to determine the allocation of water per GRU. 9 and 10 depict data and information pertaining to the basic human needs for the catchment areas (Tables 15 and 16).

Table 15: Basic Human Needs for G50B, G50C and G50E

GRU	Water resource	BHN (%NMAR)
Primary/intergranula aquifers		
Overberg East Fynbos		
G50C	Heuninges	0
G50E	Kars	0.84
TMG/fractured aquifers		
Overberg East Fynbos		
G50C	Heuninges	0
G50B	Nuwejaar	1.12
G50E	Kars	0.84

Table 16: Basic Human Needs for G50B, G50C and G50E

GRU	No. of Registered users	Total volume (m^3/a)
Primary/intergranula aquifers		
Overberg East Fynbos	4	175455

TMG/fractured aquifers		
Overberg East Fynbos	41	2690670
Overberg East Renosterveld	**9**	258875.65

Groundwater Contribution to Baseflow

Determining the groundwater contribution to baseflow involves several steps and procedures. Here are the general steps involved: the first step is to identify the area of interest where the baseflow and groundwater contribution will be estimated. The study area should have a well-defined boundary and include the catchment or catchment area that contributes to the stream as well as the aquifer layers for that catchment. The next step is to gather data on the hydrologic conditions in the study area. This includes precipitation, temperature, evapotranspiration, soil properties, and streamflow data. The next step is to analyze the streamflow data to determine the baseflow component. This can be done using several methods, including the recession curve analysis and the digital filter method.

The next step is to identify the areas where groundwater recharge occurs. This can be done by mapping the geology and soils of the study area and identifying areas where the water table is close to the surface. The final step is to estimate the groundwater contribution to baseflow (Table 17). This can be done using several methods, including groundwater flow modeling, isotope analysis, and the chloride mass balance method. Overall, determining the groundwater contribution to baseflow is a complex process that requires a combination of field measurements, data analysis, and modeling. It is essential to carefully follow the steps involved to ensure accurate results.

Combining all the information of the above determined parameters, one can determine the quality and quantity components of the reserve for a particular GRU (Tables 17 and 18).

Table 17: Groundwater reserve determination — quantity component for Heuningnes catchment

Catchment	Delineated Aquifer		Area (km^2)		Recharge (Mm^3/a)		Population		GWC-baseflow (Mm^3/a)		BHN Reserve (Mm^3/a)	
	Unconfined	Confined	Unconfined	Confined	Unconfined	Confined	GW_Pop	Gn_Pop	Unconfined	Confined	Unconfined	Confined
G50B	□	□	1500	1500	17.38	17.38	50	33038		2.5368		5.5368

Table 18: Groundwater reserve determination — quality component for Heuningnes catchment

Parameter	Ambient Ground Water Quality[1)]		Basic Human Needs Reserve[2)]	Ground Water Quality Reserve[3)]	
	Unconfined	Confined		Unconfined	Confined
Calcium (mg/L)	8.7	5.6	≤150	9.57	6.16
Magnesium (mg/L)	11.00	7.324	≤70	12.1	8.0564
Sodium (mg/L)	82.417	58.5	≤200	90.6587	64.35
Chloride (mg/L)	14.299	118.2925	≤300	15.7289	130.12175
Sulphate (mg/L)	20.86	15.9145	≤500	22.946	17.50595
Nitrate (mg/L)	0.153	0.211	≤11	0.1683	0.2321
Fluoride (mg/L)	0.05	0.05	≤1.5	0.055	0.055
pH	6.49	6.37	5 – 9.7	5.84 - 7.14	5.733-7.007
Electrical Conductivity	68.8	51.2	≤170	75.68	56.32

Data requirements and sources

To determine the quality of groundwater reserve, you will need to collect and analyze data from a variety of sources. Here are some common data requirements and sources for determining groundwater reserve quality: The most direct way to determine groundwater quality is to collect samples from the aquifer and analyze them for various parameters such as pH, dissolved oxygen, total dissolved solids (TDS), hardness, alkalinity, and various contaminants like heavy metals, pesticides, nitrates, and bacteria. These samples can be collected through well drilling or monitoring wells and sent to a laboratory for analysis. Understanding the geology and hydrogeology of the aquifer can help you determine the source, age, and potential contamination of the groundwater. This data can be collected through geologic mapping, borehole logs, pumping tests, and geophysical surveys. Understanding the land use and hydrological conditions of the area around the groundwater reserve can help you determine the potential sources of contamination and the potential for recharge. This data can be collected through satellite imagery, topographic maps, land use records, and stream gauges.

Many groundwater reserves are regulated and monitored by local or provincial agencies. These agencies may collect data on groundwater quality, quantity, and use, as well as any regulations or restrictions on pumping or contaminant levels. Historical data on groundwater quality and use can provide valuable insights into the long-term trends and changes in the aquifer. This data can be collected through records of well drilling, water use permits, and historical land use records. Overall, determining groundwater reserve quality requires a multidisciplinary approach and the integration of data from a variety of sources. A thorough understanding of the aquifer and the potential source of contamination is essential for ensuring the sustainable use and protection of groundwater resources.

Procedure and steps for data acquisition from Heuningnes Catchment

The following are the steps involved in determining the quality of groundwater: the first step is to identify the location where groundwater quality testing will be performed. This can be done by reviewing existing data, maps, and reports, or through on-site exploration. Groundwater samples are collected using specialized equipment, such as a bailer or a pump. It's important to follow strict guidelines for sample collection, handling, and preservation to ensure accurate results. The groundwater samples are sent to a laboratory for testing. Depending on the parameters of interest, tests may be performed for various physical, chemical, and biological characteristics. Common tests include pH, conductivity, alkalinity, total dissolved solids (TDS), hardness, turbidity, and various contaminants such as heavy metals, pesticides, and bacteria.

The laboratory results are compared with established standards for drinking water quality, environmental regulations, and other relevant guidelines. This helps to identify any potential risks or issues that need to be addressed. The results of the laboratory analysis are interpreted by trained professionals, who can provide a detailed report of the findings. This report should include recommendations for action, such as treatment options, monitoring programs, or changes in land use practices. The findings and recommendations are communicated to stakeholders, such as government agencies, landowners, and water users. This helps to raise awareness about potential risks and encourages responsible management of groundwater resources. Overall, the process of determining groundwater reserve quality requires a multidisciplinary approach, involving expertise in hydrology, chemistry, biology, and environmental regulations. It's important to follow standardized procedures and guidelines to ensure accurate and reliable results.

Groundwater resource quality objectives

Data Analysis on results from Heuningnes Catchment

Groundwater quality assessment is important to assess the suitability of water for various purposes, such as drinking water, irrigation and industrial uses Assessment involves the collection and testing of water samples for physical, chemical and biological properties in the various dimensions. Here is a step-by-step guide on how to perform data analysis for groundwater quality indicators:

Define the scope of the study by clearly defining the purpose of the research. Are you looking to assess drinking water quality, environmental impact, or agricultural suitability? The understanding of the objectives will guide the selection of parameters and analytical methods. Common parameters include pH, electrical conductivity (EC), total dissolved solids (TDS), temperature, turbidity, hardness, alkalinity, dissolved oxygen (DO), major ions (e.g., calcium, magnesium, . sodium, synthetic chloride). , sulfates), trace metals (e.g., iron, manganese, arsenic), nitrates, and trace elements (e.g., coliform bacteria). Obtain representative groundwater samples from various locations and depths within the study area. Samples should be collected in sterile clean containers and follow proper sampling procedures to prevent contamination. Send the collected samples to an accredited laboratory for analysis. Different tests and techniques are used to measure different parameters, so make sure the lab has the necessary equipment and expertise.

Quality control methods were used to ensure the accuracy and reliability of the information provided. This includes the use of blank samples, duplicate samples, and validated reference materials during the analysis. Arrange the results in a structured format, where the value of each parameter is recorded for each sampling location. Properly store data and keep a record of the analytical methods used. Compare results to appropriate water quality standards, guidelines, or regulations. For example, you might consult World Health Organization (WHO) guidelines on safe drinking water or local environmental regulations. Use statistical methods to analyze data and identify trends, patterns, and relationships among different dimensions. Typical statistical analyzes include mean, standard deviation, regression analysis, and spatial mapping.

Create graphs, charts, and maps to visually represent data and make results easier to interpret. Visualization helps participants better understand what they have seen. Summarize findings in a comprehensive report, including methodology, results, and conclusions. If water quality doesn't meet desired standards, make recommendations, and suggest mitigation options. Share the results with relevant stakeholders, such as local authorities, communities, or organizations involved in water management. Remember that groundwater quality assessment is an ongoing process, and periodic monitoring of aquifers is necessary to ensure that aquifers are safe to monitor changes over time Additionally, measure hydrological data around the study area as it may affect water quality parameters.

Concentration duration curves

In this section, a case study where steps for setting numerical limits for the groundwater quality component of RQOs were applied is provided. The step-by-step guide that was provided in section 8.4 was practically implemented in this section using measured data from the study catchment, namely, the Heuningnes Catchment, G50 in Western Cape, South Africa. Summary of the recommended numerical limits for the Heuningnes Catchment is provided in table 18.

Electrical Conductivity (EC) and pH are regarded as general indicators of water quality in domestic water use by the South African water quality guideline (WRC 1998). As a result, these parameters were given a far more liberal target level of management requiring a length of time of 95% compliance, as they were assessed to not require strict conditions for compliance. The baseline limit for the EC, pH upper limit and lower limit for groundwater in Heuningnes catchment are:

4938 mS/m, 8.4 and 5.8 respectively. These parameters require less stringent conditions for compliance, and thus can be assigned *less stringent target level* of management corresponding to 95% compliance over a period of interest. In general, chances for compliance are high for these parameters (figures 27, 28 and 29).

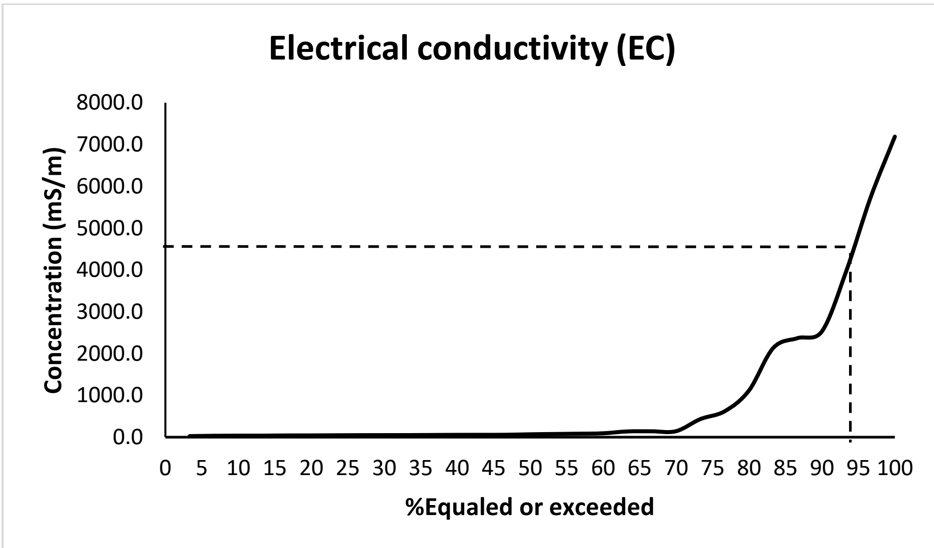


Figure 27: Concentration compliance probability curve for Electrical Conductivity-Heuningnes Catchment

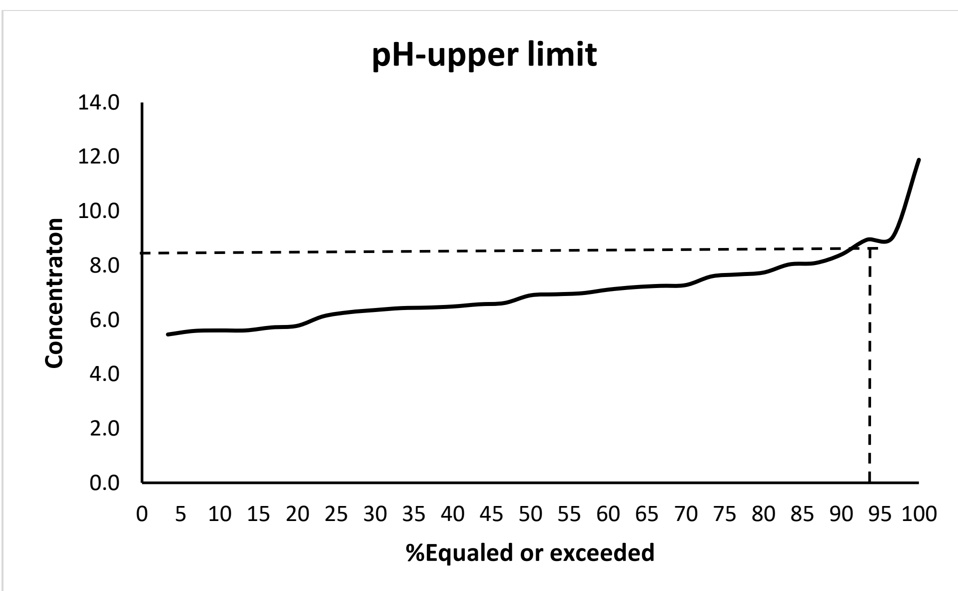


Figure 28: Concentration compliance probability curve for pH upper limit-Heuningnes Catchment

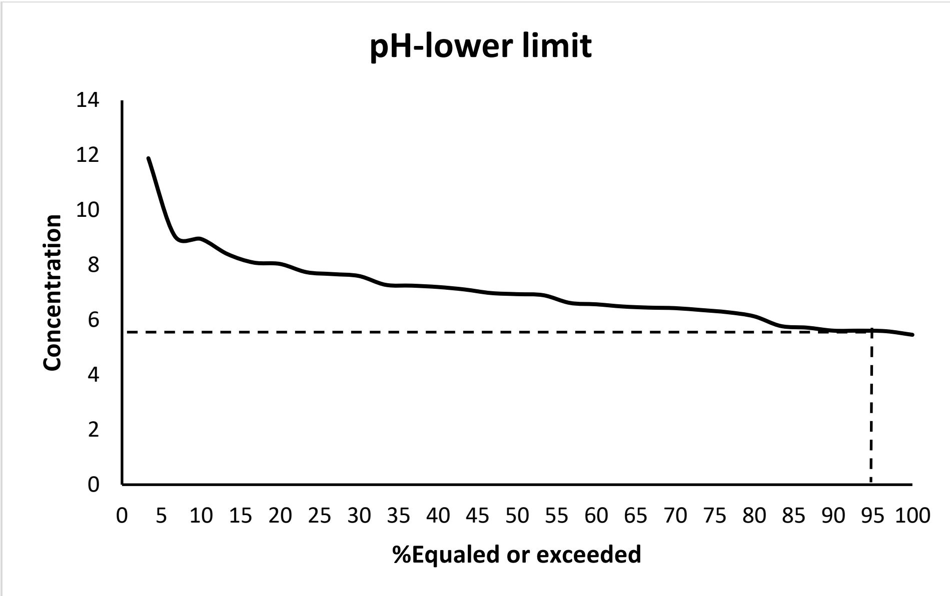


Figure 29: Concentration compliance probability curve for pH lower limit-Heuningnes Catchment

In domestic water use, Calcium, Magnesium, and Sodium may frequently be present at levels that raise aesthetic or economic concerns. As a result, these requirements have stricter goal levels of management and call for at least 85% compliance over time.

The RQO limits for Calcium, Magnesium, and Sodium for groundwater in the Heuningnes Catchment, G50 were set as follows: 197.6, 304.5 and 5887.8 mg/l respectively. The stringent target levels of management corresponding to at least 85% compliance over a period of interest are expected (Figures 30, 31, and 32). However, in general chances for compliance are not always guaranteed and the need to discuss and agree with stakeholders remains critical because of the economic concerns of such water quality.

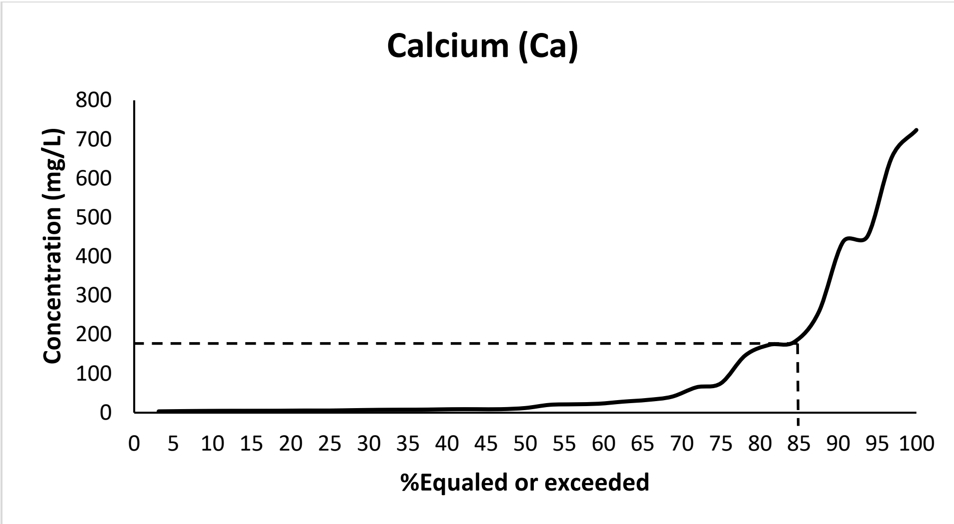


Figure 30: Concentration compliance probability curve for Calcium-Heuningnes Catchment

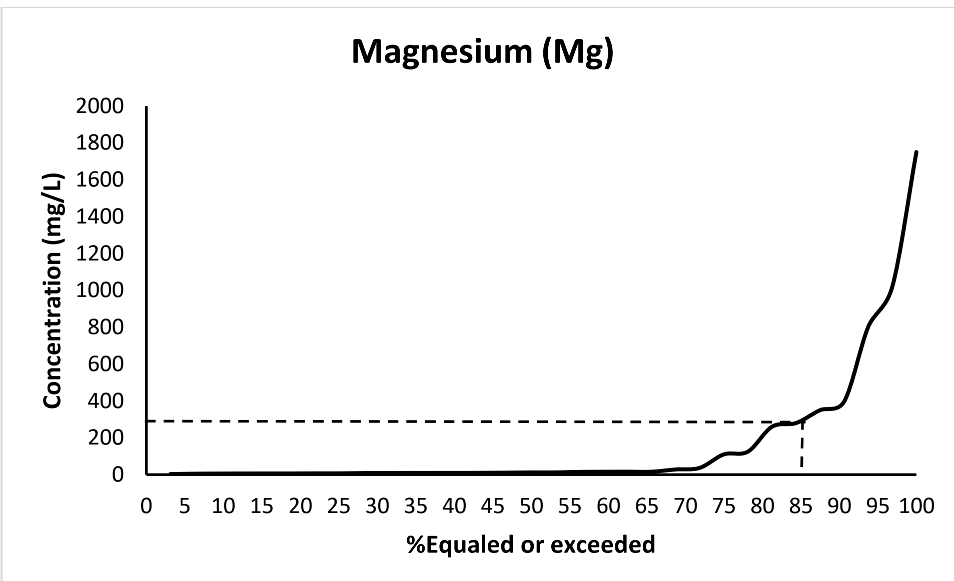


Figure 31: Concentration compliance probability curve for Magnesium-Heuningnes Catchment

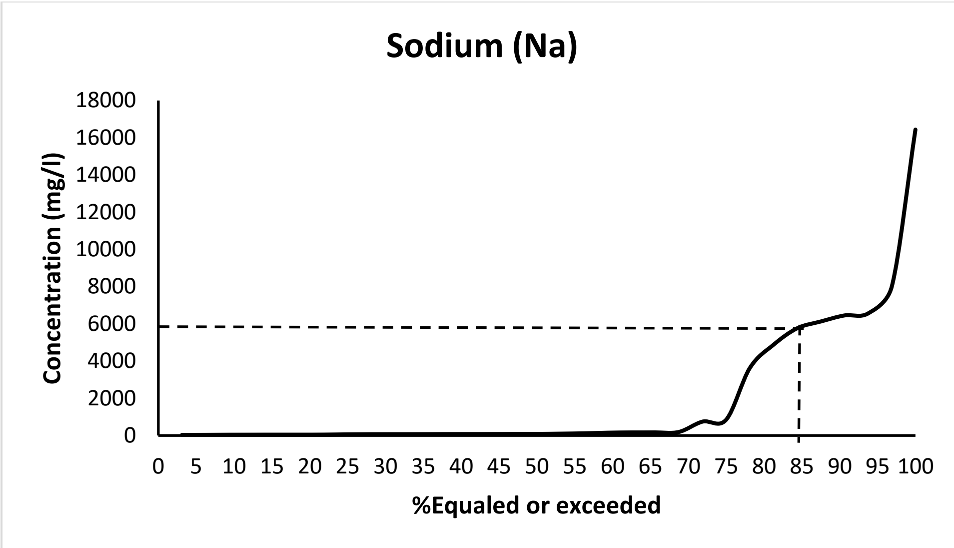


Figure 32: Concentration compliance probability curve for Sodium-Heuningnes Catchment

The guidelines (WRC 1998) consider Chloride, Sulphate, Nitrate, and Fluoride as parameters that are commonly present at concentrations that may lead to health problems in domestic water use. Therefore, these water quality parameters were assigned much more stringent levels of management requiring at least 75% compliance over a period. The RQO limits for Chloride, Sulphate, and Fluoride of groundwater in the Heuningnes catchment, G50 were set as follows: 2040, 103 and 0.14 mg/l respectively. Compliance probability curves are presented in figures 33 to 35.

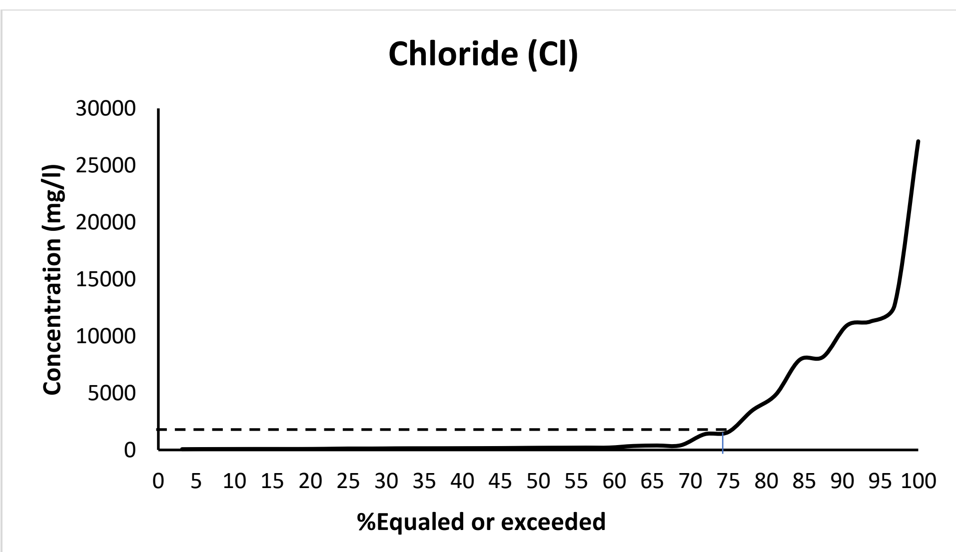


Figure 33: Concentration compliance probability curve for Chloride-Heuningnes Catchment

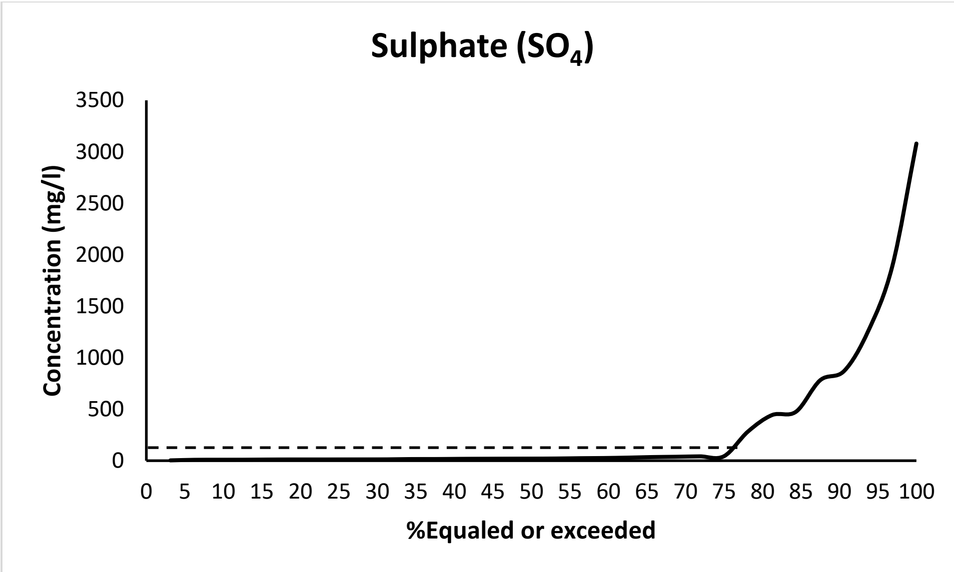


Figure 34: Concentration compliance probability curve for Sulphate-Heuningnes Catchment

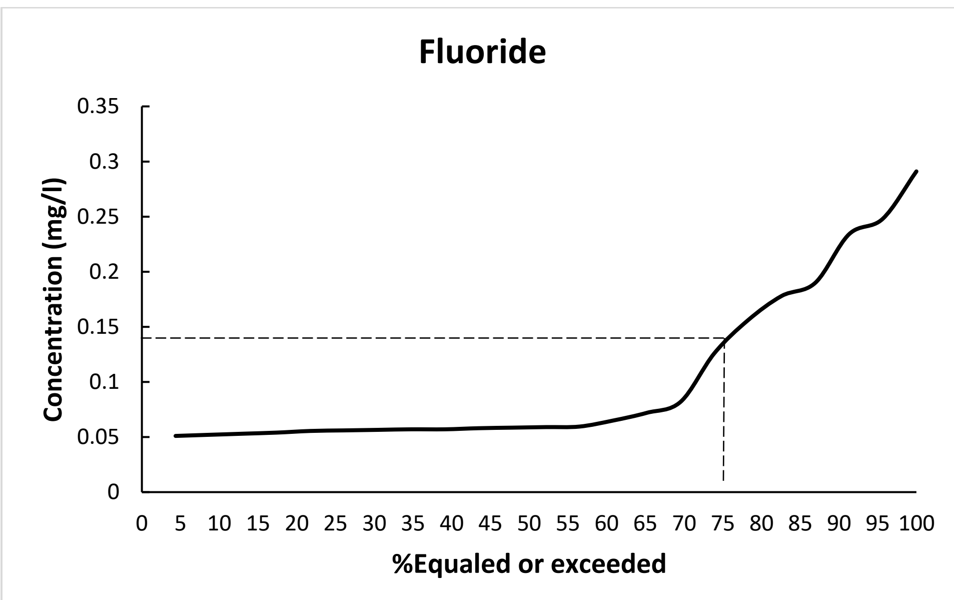


Figure 35: Concentration compliance probability curve for Fluoride-Heuningnes Catchment

The higher stringent target levels of management corresponding to at least 75% compliance over a period of interest are expected. However, in general chances for compliance are not always guaranteed. Therefore, the need to discuss and agree with stakeholders remains critical because such parameters have impact on human health. During stakeholder engagement meetings, the constitution of South African comes into play.

Section 24 of the Bill of Rights refers to safe environment and implication on human beings. This section 24(a) and 24(b) state that. "*Everyone has the right – (a) to an environment which is not harmful to their health or well-being; (b) to have the environment protected for the benefit of present and future generations through reasonable legislative and other measures that: (i) prevent pollution and ecological degradation; (ii) promote conservation; and* (iii) *secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development".* In summary, these higher stringent target levels of management requiring at least 75% compliance over a period of interest may not be fulfilled. Therefore, frequent monitoring should be encouraged for water sampling and testing for those parameters so implement appropriate intervention should the conditions deteriorate in the study catchment.

Table 19 shows the summary of the numerical limits for groundwater quality component of the RQOs for the Heuningnes Catchment.

Table 19: Summary of the numerical limits for groundwater quality component of RQOs established for the Heuningnes Catchment

Water Quality Parameter	**Recommended Numerical Limits**	**Recommended compliance per period**	**Keynote**
pH (upper limit)	8.40	95%	The parameter is considered as a general indicator of water quality in domestic water use
pH (lower limit)	6.00	95%	The parameter is considered as a general indicator of water quality in domestic water use
Electrical conductivity (EC)	42.00	95%	The parameter is considered as a general indicator of water quality in domestic water use
Calcium (Ca)	25.30	85%	The parameter may commonly be present at concentration of aesthetic or economic concern in domestic water use
Magnesium (Mg)	4.90	85%	The parameter may commonly be present at concentration of aesthetic or economic concern in domestic water use
Sodium (Na)	26.20	85%	The parameter may commonly be present at concentration of aesthetic or economic concern in domestic water use
Chloride (Cl)	30.00	75%	The parameter is commonly present at a concentration which may lead to health problems in domestic water use
Sulphate (SO_4)	8.00	75%	The parameter is commonly present at a concentration which may lead to health problems in domestic water use
Fluoride (F)	0.70	75%	The parameter is commonly present at a concentration which may lead to health problems in domestic water use

Data Quality Assurance/Control from the Heuningnes Catchment

In the context of water quality data analysis, quality assurance refers to the processes and procedures that are put in place to ensure that the data being collected, analyzed, and reported is accurate, reliable, and of high quality. This is essential to ensure that decisions made based on the data are sound and that the health of people and the environment is protected. There are several key steps involved in quality assurance for water quality data analysis, including: the first step in quality assurance for water quality data is to ensure that the sampling process is properly designed and executed. This includes selecting appropriate sampling sites, following proper sampling protocols, and ensuring that equipment is properly calibrated and maintained. Once the samples are collected, they must be analyzed in a laboratory to determine their quality. This process should be conducted using appropriate methods and equipment that have been verified and validated. Quality control procedures should also be in place to ensure that the results obtained are accurate and reliable. Once the data has been collected and analyzed, it must be managed in a way that ensures its quality and integrity. This includes storing the data in a secure and accessible location, documenting all quality control procedures, and performing regular checks to ensure that the data is accurate and up to date.

The final step in quality assurance for water quality data is to report the results to stakeholders in a clear and concise manner. This should include a description of the sampling and analysis procedures, as well as any quality control measures that were taken. The report should also include a summary of the results and any conclusions or recommendations that can be drawn from them. Overall, quality assurance is an essential part of water quality data analysis, as it ensures that decisions made based on the data are sound and that the health of people and the environment is protected.

Procedure and steps

Establishing quality assurance for water quality data analysis is crucial to ensure the accuracy and reliability of the results. Here are the general steps involved in establishing quality assurance for water quality data analysis: The first step in establishing quality assurance for water quality data analysis is to define the scope and purpose of the analysis. This includes defining the parameters to be measured, the frequency of measurements, the locations where measurements will be taken, and the intended use of the data. The next step is to develop a sampling plan that outlines the procedures for collecting water samples, including the equipment to be used, the sampling location, and the sample preservation and transportation procedures. A quality control plan should be developed to ensure that the data collected is of high quality. This plan should include procedures for checking the accuracy and precision of the data, identifying and correcting errors, and validating the results.

All personnel involved in collecting and analyzing water quality data should be trained in the sampling and analysis procedures, as well as the quality control procedures. Regular quality control checks should be performed to ensure that the data collected is accurate and reliable. This includes calibrating instruments, checking for contamination, and verifying the accuracy of measurements. Once the data has been collected and quality control checks have been performed, the data can be analyzed using appropriate statistical methods. The final step is to interpret the results of the analysis and communicate them effectively to stakeholders. By following these steps, a comprehensive quality assurance program for water quality data analysis that ensures the accuracy and reliability of the results is established.

4.5 Database Management System

A records management system is a software program or set of tools that permits users to efficiently keep, organize, retrieve, and manage records. It facilitates ensure facts integrity, safety, and accessibility, facilitating duties like statistics access, storage, retrieval, and analysis. Data management structures can range from simple spreadsheet software to state-of-the-art database management system (DBMS) used for complex records coping with in large organizations. In the prevailing catchment, facts control is facilitated thru the utilization of a Google Drive folder, serving because the centralized repository for storing all applicable information. Google Drive can be used as a simple information management system, but it is appropriate for record storage and collaboration in place of a comprehensive statistics management solution. While you can organize documents into folders, share them with others, and use search capability, it lacks superior database capabilities for dependent information control. For robust data management needs, a specialized database software or cloud-based data management systems is needed.

5. ENHANCEMENT OF THE GRDM SOFTWARE

Introduction

In 2005, a research study to develop the methods to assess the groundwater component of the RDM was initiated. This study was funded by the DWS, implemented by the Water Research Commission (WRC) and undertaken by a Professional Service Provider (PSP). As the methods of this study were applied and tested, gaps were identified, for example, the issue of scale i.e. regional scale versus local scale. Subsequently in 2011, a new project was conducted to build on the existing information, address the gaps identified in the methods and include new methods which could be applied to assess GRDM. The outcomes of the project were a revised methodology as well as updated GRDM software. This study was completed in 2013. There has been a gradual improvement in methodologies for groundwater modelling and protection thereof.

With the continuous use of the 2013 GRDM methodology and software version, some serious issues with the methodology have come up and gaps identified. Furthermore, the software presented serious short-comings in application by the users.

These issues include, but not limited to; addressing the issue of quaternary catchments delineation whilst groundwater is not bounded by them; groundwater contribution to baseflow (or ecological water requirements – EWR); capability to update data used as new data becomes available; formatting of the quality component of groundwater Reserve; accommodating groundwater-surface water interaction in the assessment of the resource; and linking of GRDM to the existing databases of the DWS where possible. In addition to that, various review exercises by experts in the groundwater field, in studies commissioned by the WRC, have highlighted issues with the current GRDM methodology which need to be addressed in order to protect the groundwater resource effectively. All these have necessitated the updating of the GRDM methodology, which entails the enhancement of the software as well.

The DWS officials are the target users for the system when determining groundwater resource classes and the Reserve, and setting the RQOs. With challenges relating to staff turnover in the DWS and required training to DWS officials on the use of the GRDM methodology and software, it was deemed necessary that a formal training programme be developed as part of this project.

5.1 Software Evolution

The first version of the GRDM software was released in 2005 under WRC Project K5/1427. In 2010 FETWater sponsored various training workshops and at this time minor software changes were made compared to the first official release in 2005. In 2011 the WRC sponsored a project for the review of the GRDM methodology and software under WRC Project K8/891. After the update and release of the software only one training workshop was held at DWA at the time. After 2011 the GRDM component was moved into a software package called Aquiworx which evolved from the Aquifer Management System which was developed through DWAF at the time. This decision was taken as no further projects were issued from DWAF to maintain any of the aforementioned software packages and since the two packages complemented each other it was the logic step as only one software package required updating and bug fixes where required.

Since many previous versions of the GRDM exists, this report will refer to generations of the software rather than versions to avoid confusion. A summary of the software generations and version is presented **Error! Reference source not found.** A feature matrix is presented in **Error! Reference source not found.** to compare functionality between the G1 and G2.

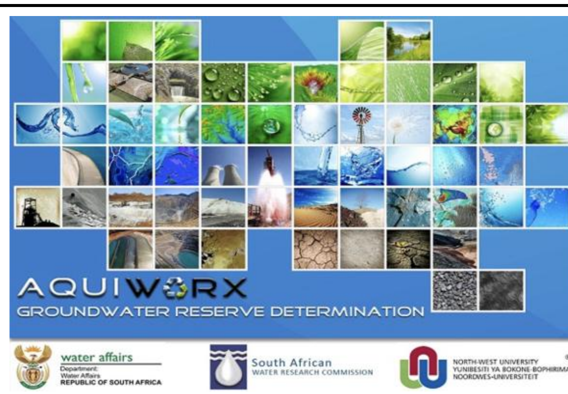
5.2 Purpose of the Software Update

Currently the G2 is 12 years old and during this time various datasets were updated and research has revealed alternative methodologies for some of the subcomponents used in the GRDM methodology.

Chapter 3 of the National Water Act (Act 36 of 1998) (NWA) focuses on the protection of South Africa's water resources. This is meant to ensure that water is available for current and future use. Protection therefore involves the sustaining of a certain quantity and quality of water to maintain the overall ecological functioning of rivers, wetlands, estuaries and groundwater.

Since groundwater practitioners have a legal obligation to protect South Africa's water resources, the purpose of the GRDM update is to enhance the existing software with both methodological changes identified by the project team in consultation with DWS, as well as identified issues from the users to enable DWS to validate RDM studies as well as evaluate WULA applications.

Table 20: GRDM generations and versions

Generation	Year	Version	Splash Screen
G1	2005	v3.3.0.6	
	2010	V4.0	
G2	2011	v2.5.x	

	2012	v2.5.3	

Table 21– Software generation feature matrix

Feature	**G1**	**G2**
GIS based system supporting general vector and raster formats	✓	✓
Quaternary shape file with default values (GRA2 & WRx)	✓	✓
Auxiliary shape file library	✓	✗
Rainfall and flow database (WRx)	✓	✓
Present monitoring data in GIS with thematic rendering	✗	✓
Time series graphs of monitoring data	✗	✓
Water chemistry analysis (Piper, Pie and Radar diagrams)	✗	✓
Basic water balance calculation	✓	✓
Assured Aquifer Yield Model	✗	✓
Cooper-Jacob Wellfield Model	✗	✓
Protection zone calculations	✓	✓
Protection zone visualization	✗	✓
Reserve determination for single and multiple quaternaries	✓	✓
Reserve determination for custom delineations	✓	✓
Single Herold baseflow separation	✓	✓
Multiple Herold baseflow separation	✗	✓

Provide modelled baseflow values (Pitman, Hughes, Schultz)	✘	✓
Single recharge estimation (Cl, EARTH, SVF, CRD, Isotope)	✘	✓
Multiple recharge estimations (Cl, EARTH, SVF, CRD, Isotope)	✓	✓
Basic human need calculated making use of census data	✓	✓
Multiple scenario analysis (using different parameters)	✘	✓
Reserve determination roadmap	✓	✘
Providing descriptive input parameters	✓	✘
Generic RQO suggestions with examples	✓	✘

The main objectives of the software update were as follows:

- Make the software more user-friendly, improve functionality, and implement ability.
- Update the underlying database with new data where available.
- Test the software against case studies conducted as part of the research component of the overall project.
- Provide documentation on the software development for future maintenance of the produced product.

5.3 Software development

The software executable is considered to be a self-contained executable (all dependencies reside within the executable) with the exception of the MS Access database driver required on some target computers. The required driver is deployed to the target computer through the *AccessDatabaseEngine2007* installer.

The advantage of a true self-contained executable is that the software does not have to be deployed by an installer which manages all the software dependencies during the deployment. This means the software can simply be copied to the target computer and the executable will run. The reason that this behaviour is attractive, is the fact that many companies and institutions, including DWS, cast an image on their employees computers which prevents the users to install any software without having administrator rights. Even though this is good practice from an IT point of view, it has caused a lot of frustration during past training sessions as the attendees cannot install the software on their computers and the self-contained executable has circumvented this problem.

Since the software consists of more files than just the executable e.g. database files, the installer consists of a self-extracting executable (**Error! Reference source not found.**) which contains all required files and will create the directory structure shown in **Error! Reference source not found.** on the target computer where the software is deployed.

The self-extracting executable (**Error! Reference source not found.**) has the option to automatically start the software once deployed, but in the absence of the correct MS Access driver an error message may appear as shown in **Error! Reference source not found.**. To resolve this problem the correct MS Access driver can be installed by running *AccessDatabaseEngine2007.exe* contained in the *3rd Party* directory (**Error! Reference source not found.**). Note the screenshots referred to relates to Aquiworx as the GRDM is contained in Aquiworx since the final G2.

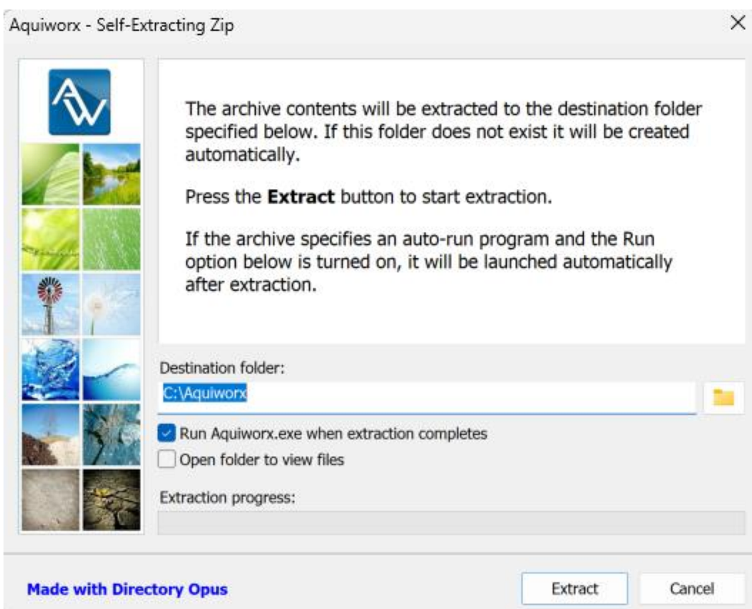


Figure 36– G2 self extracting execuatbale used for software deployment

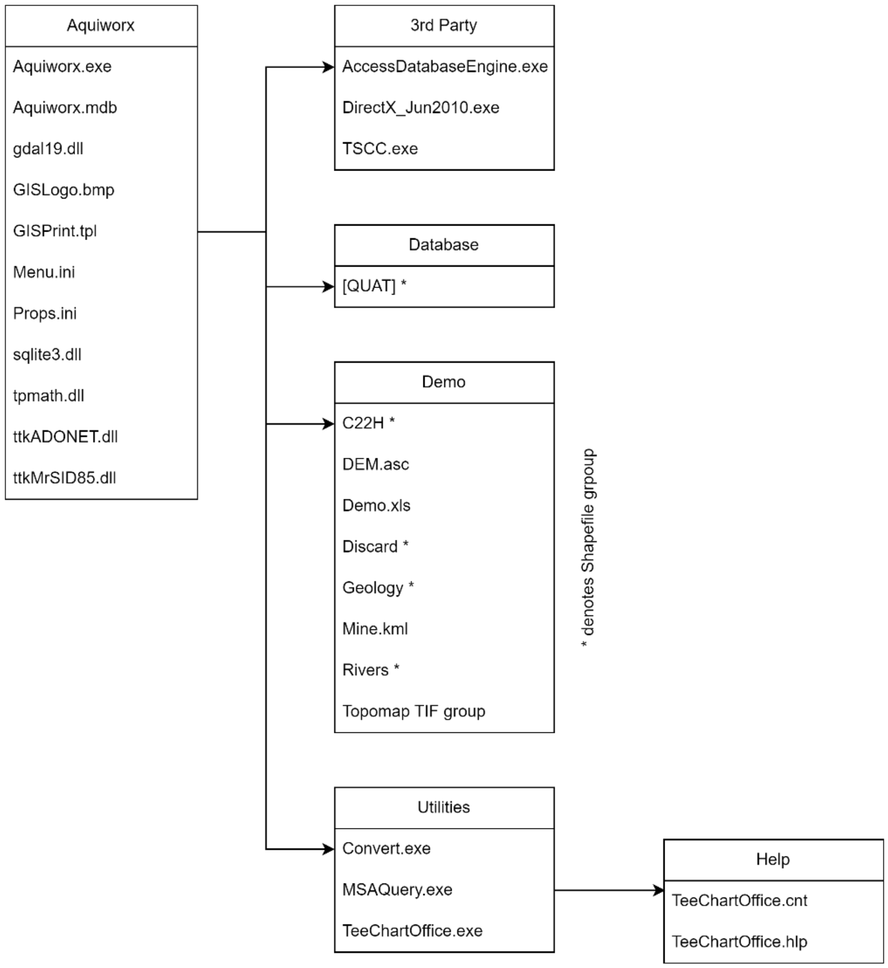


Figure 37– G2 deployment directory structure

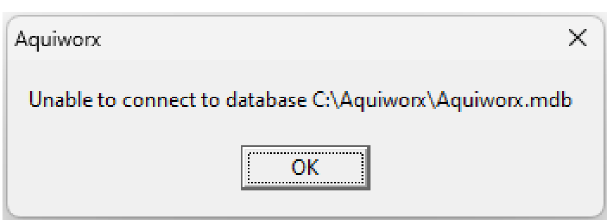


Figure 38– G2 error message related to missing MS Access driver

As summary of the deployed directory structure and associated content is presented in **Error! Reference source not found.**.

Table 22– G2 folder structure summary

Directory	Contents
Aquiworx	Aquiworx.exe → Main executable Aquiworx.mdb → Local database housing WR2005 data

	GISLogo.bmp → Logo displayed on printed GIS map GISPrint.tpl → GIS printing template *.ini → Ribbon component settings *.dll → Library files required for GIS component
3rd Party	AccessDatabaseEngine2007.exe → MS Access Driver DirectX_Jun2010.exe → Drivers for 3D functionality of GIS TSCC.exe → Installation of screen capture Codec for video help
Database	[QUAT] Shapefile group → Quaternary shape file used as spatial database for GRAII and WR2005 selected data.
Demo	Demo.xls → Excel user database The remainder of the files are GIS files related to the C22H quaternary catchment.
Utilities	Convert.exe → Unit conversion utility MSAQuery.exe → Access Database Utility used to open *mdb* files created from the Excel user database. TeeChartOffice.exe → Charting component allows for saving of layouts and the TeeChartOffice allows for configuring saved chart layouts.
Help	TeeChartOffice help files.

5.2 Overview of the GUI

5.2.1 Layout of the Main Form

The high level architecture for the current GUI presented in **Error! Reference source not found.** and consists of the following main components:

- *Main Form* – Parent component for all other GUI components.
- *Quick Access Toolbar* – Popup menu that provides access to file functions (project and user database) as well as 3rd party utilities and the help file.
- *Ribbon Style Toolbar* – Main menu for software categorising the software into the following categories:
    - *Spatial* – The spatial toolbar relates to the *GIS Interface* and provide access to map elements, search and export functions.
    - *Monitoring* – The monitoring toolbar relates to the loaded user database and provide access to parameter and date selections as well as evaluation and charting types to visualise the selected parameter in the context of the specified criteria.

    - *Aquifer Yield* – The aquifer yield toolbar provide access to the yield model execution as well as the various output stages in graph format.
    - *Well Field* – The well field toolbar relates to the Cooper-Jacob well field model and provides access to execute the model and visually evaluate the results in a few formats.
    - *Options* – The option toolbar provides access to the settings used in the evaluation functionality mentioned in the preceding bullet points as well as specifying the units in which volumes are expressed.
- *Tab Sheets* – Represents the different data views of the system and they are summarised as follows:
    - *GIS Interface* – This interface allows for the display and thematic rendering of all GIS files. In addition it also allows for creating and editing of both vector and associated attributes. The base layer containing all required in formation on quaternary level is automatically loaded on application start-up. The interface has its own toolbar with the expected GIS related functions for navigation and editing and also features its own status bar displaying the current coordinate system, scale, topographic reference and coordinate.
    - *Graphing* – This tab houses a charting component that is used to display data in chart format where required. The component makes provision for the usual navigation like pan and zoom. It also features an export function where the user can save the current chart to manipulate it outside of the software for reporting purposes.
    - *Data* – The data tab provides access to the loaded user database and support editing of the data. Once the user database (Excel) is loaded it is converted to a MS Access database which is what is used as the data source and also edited in the data tab.
    - *Log* – The log provide access to the yield model output after the model has been executed. The log also provide the ability to clear, save and open the generated output and a primary and secondary log exits to compare output side by side.
- *Object Tree* – The object tree allows a user to build a scenario making use of selected objects. By default the root object is the *Study Area* which is then further defined making use of available objects. The object popup menu contains functionality to create a scenario

or well field, delineation of integrated units of analysis, recharge and baseflow calculation tools and protection zones.

- *Object Inspector* – The object inspector allows access to the properties of any object in the object tree.
- *Main Form Status Bar* – Providing project and database name and a progress bar for lengthy operations.

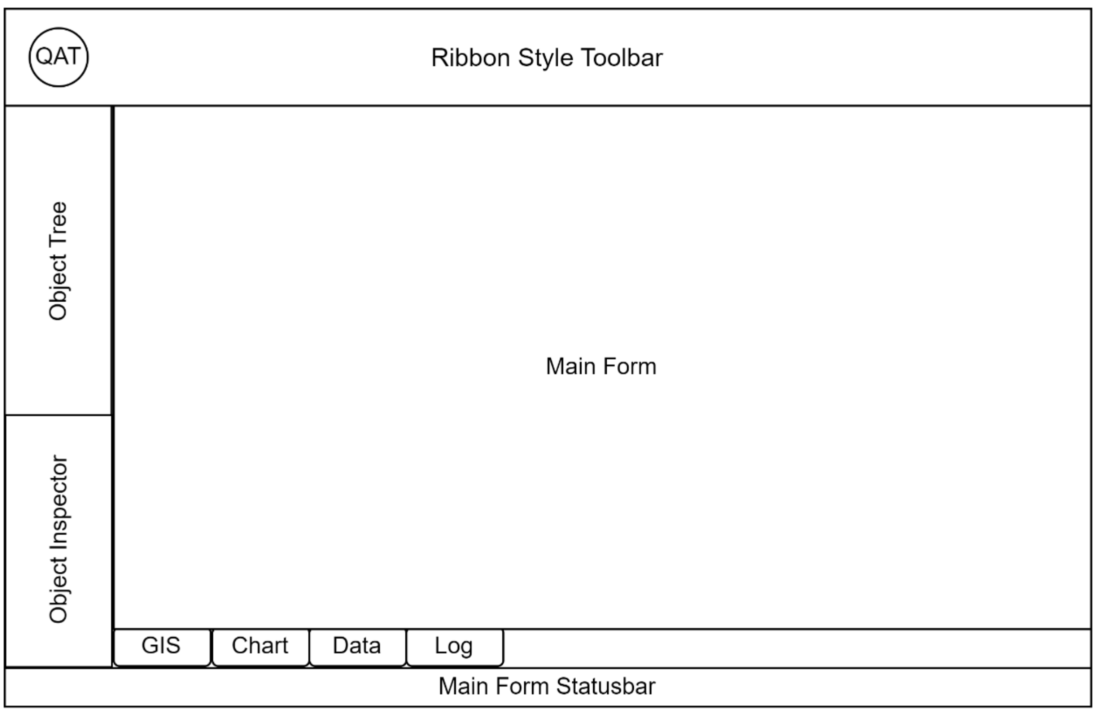


Figure 39– G2 layout of the Main Form in design

5.2.2 Navigating the GUI

Navigation of the GUI takes place through the following components:

- Quick Access Toolbar (see 5.2.1) for accessing file operations, 3rd party utilities and the help system.
- Ribbon Toolbar (see 0) for selecting software categories.

- Tab Sheets (see 0) for switching between data views, each with its own toolbar for navigation. The *Spatial* view has an additional popup menu related to the layer legend of the GIS interface for managing layers and each layer can be double clicked to access thematic rendering and other formatting options.
- Object Tree popup menu that allows the building of the object tree.

5.2.3 High Level Component Interaction

The high level component interaction is depicted in **Error! Reference source not found.**. The purpose of this diagram is not to present the flow of information, but merely show the interaction between the major GUI components. At the bottom of the diagram all the databases are listed and will be discussed in a later section.

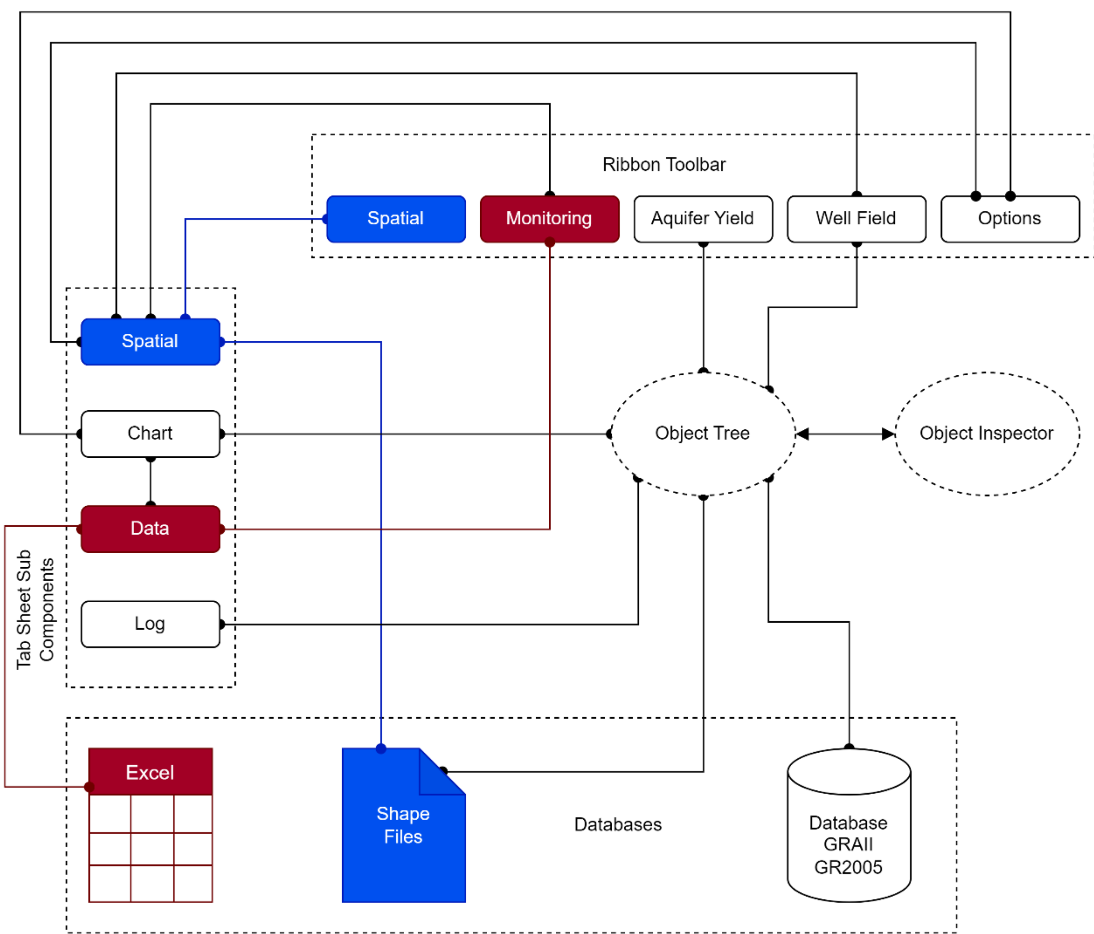


Figure 40– G2 high level component interaction

The majority of the components interact with the object tree (**Error! Reference source not found.**), but there are some sub systems that interact in isolation from the object tree e.g. the monitoring, since monitoring does not explicitly form part of the GRDM methodology and merely serves as an additional source of information when considering classification.

5.3 Software Framework- The development environment

The development environment used is the Delphi personality of Embarcadero RAD Studio. The reason for the choice in development language was that DWAF at the time standardised on Delphi as the official development language for hydrological and geohydrological software. Since most of these system required a GIS interface a Delphi wrapper was developed around the *ESRI MapObjects Lite* and was known as the *GISViewer* component with in DWAF. The initial version of G2 was developed using the *GISViewer* component, but later versions made use of *TatukGIS* which is written in native Delphi code and had more power than the *ESRI MapObjects Lite* counterpart.

Some off-the-shelf components are used in G2 and **Error! Reference source not found.** lists these components and prices quoted are those at the time of this report. Please note that some components are commercial and require a developer licenses, the finished product may be distributed free of any license requirements.

Table 23– G2 off-the-shelf components

Component	**Purpose**	**Price ($)**
TatukGIS Developer Kernel	Provides the GIS interface for G2. A custom wrapper was written around the basic GIS methods, to standardise the interface along the lines of the previous GISViewer component.	$3500*
Steema TeeChartPro	Charting component allowing saving and editing of charts. Delphi ships with the standard version, but the pro version is used since it allows for chart configuration both in runtime and on saved charts.	$600
JAM Software Virtual Tree View	A visual tree view component that represents the object tree. It can handle very large trees and the size of the tree does not have to be known upfront, thus making use of dynamic memory allocation. The tree view is streamed to a file which saves all objects and associated properties which constitutes the GRDM project file.	Free

Bergsoft NextInspector	A visual component that can display all the properties of an object in the object tree. This component serve as the editor or input dialog for all the objects comprising the object tree.	$110
DevExpress Toolbars	A component set that provides a ribbon style toolbar that can be styled, that provide a modern look and feels similar to the new Microsoft Office style toolbars.	$1500*

* Note, initial purchase cost is indicated and annual renewals are substantially lower once purchased

The layout of the Main Form in the finished product making us of the specified components is presented in **Error! Reference source not found.**

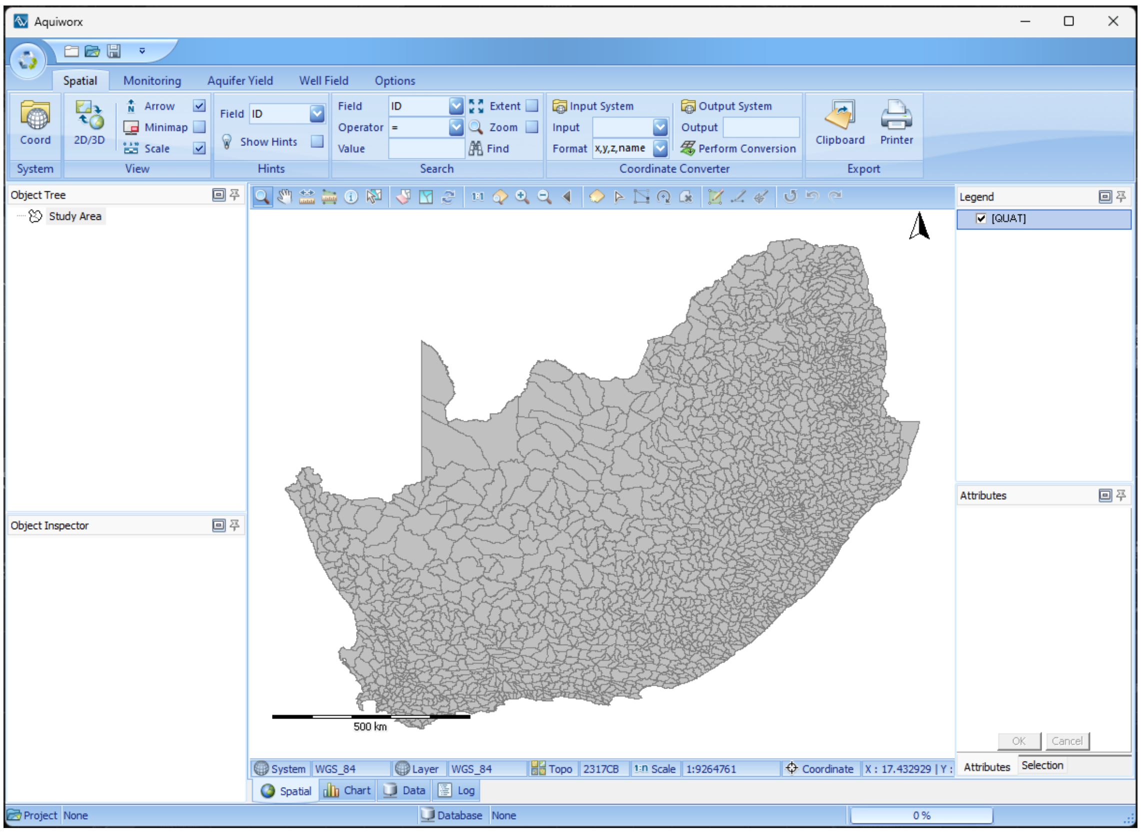


Figure 41– G2 Layout of the Main Form in the actual application

5.4 Data requirements and formatting for the Software

Various databases exist that provide valuable information to the GRDM, these include, WR2012, GRAII, NGA, GRIP, WARMS, DWS Hydrological Services and DWS Resource Quality Services. These databases are either online where a request is sent for data or simply exists as a collection of files that can be downloaded or requested. None of them provide a public interface through which programmatic queries could be directed to obtain the data. The software allows for the importing of data in excel or csv format.

6. CAPACITY BUILDING AND TRAINING

This section of the report highlights the actions, taken between the project's inception till July 2023, to improve student and departmental officials' knowledge and understanding of the Groundwater Resource Directed Measures. The purpose of this program was to give participants the knowledge, abilities, and awareness of updates needed to manage groundwater resources sustainably. The attendance register for the training provided during this period is included in Appendix A.

Activities conducted.

- ✓ Workshops/Seminars
- ✓ Field Visits and Practical Demonstrations
- ✓ Case Studies and Presentations
- ✓ Group Discussions and Knowledge Exchange
- ✓ Development of Educational Materials

6.1 Postgraduate Students: University of the Western Cape

The training of students from the University of the Western Cape [UWC] started with understanding the GRDM manual 2011 with the identification of sections that had shortcomings of the methodology that required redress and improvement. This was achieved through several seminars and training sessions to provide students with a thorough understanding of GRDM. These workshops resulted in the need to address the gaps identified in the GRDM methodology and software version due to the new knowledge that has become available regarding groundwater systems. Such improved knowledge and understanding were not accounted for in the 2013 GRDM methodology. The key parameters and required improvement on the new GRDM methodology were explained to the students.

UWC students participated in the process of upgrading the methodology from literature review to field visits and practical demonstrations for data collection to data analysis to reporting writing. Field trips to the groundwater monitoring sites and hands-on demonstrations were done to help students retain the theoretical concepts they gained in the workshops. Participants gained knowledge of various monitoring strategies, groundwater measurement tools, and approaches to data interpretation. Some students did their MSc and PhD studies on the GRDM project respectively while others were trainees as they participated in the project. The gap analysis from the literature review and stakeholder engagement meetings was explained to UWC students throughout the project period. Below are UWC students who participated in the project.

List of postgraduate students from UWC

Abongile Xaza	PhD Student
Anna Aphia Umunezero	MSc Student
Sandiso Zulu	MSc Student
Paula Finini	PhD Student
Apfeswaho Tshaamano	MSc Student
Rhophiwa Magodi	MSc Student
Kasifa Kakai	PhD Student
Jessie Kanyerere-Amaechi	PhD Student
Clinton Andries	PhD Student
Erin Plato	MSc Student
Anelkha Nicholls	MSc Student
Carlton Aron	MSc Student

About 5 field trips occurred to visit one of the case study areas, the Upper Berg Catchment during the months of April, June, August, and September 2022. The first visit to the site was for field reconnaissance to understand how the gauged system is structured and to identify sites possible to meet the objectives of the GRDM project. The sites with boreholes were visited with spatial coordinates recorded for further intensive desktop study to facilitate geological mapping for aquifer delineation for water resource classification. To address the methodology update on groundwater contribution to baseflow, river cross-sections were developed with three locations below the dam (modified flows) and two locations before the dam (natural flows with no anthropogenic activities) being selected. The depth and width of the Upper Berg River were measured at all site locations using a measuring tape. We traveled from the confluence of the Franschhoek and Berg rivers below the dam to the river before the dam, we mapped the geology of the river for cross-section analysis work. In-situ physicochemical parameters were measured, and water samples were collected from boreholes, rainfall stations, and rivers following sampling procedures for water chemistry analysis. The purpose of the field trip was to collect data for updating the GRDM method. The UWC students were trained on data collection and analysis including report writing.

Photo: UWC Research team in UWC board room: workshop



Photo: UWC Research team in Upper Berg Catchment: data collection

6.2 Postgraduate Students: North-West University

Students from the North-West University (NWU) were trained on the updated Software version for the GRDM as a pilot case by their Lecturer, Dr. Rainier Denis. Such a pilot provided some key Question-and-Answer Sessions for the modification of the updated Software version. Such a piloting session at NWU provided a user-friendly version of the training session when such a version was brought to UWC to train the DWS staff members from the head office and regional office and UWC staff and UWC students as well.

6.3 Training Workshop for DWS Staff members from Head Office [Pretoria Office]

The training workshop on GRDM updated methods and software was held at the University of the Western Cape from the 3rd to the 7th of July 2023. The training workshop was attended by 7 members from the DWS head office as listed in table 24:

Table 24: Staff members from DWS Head office (Pretoria Office)

Name	Surname	Organization
Kwazikwakhe	Majola	DWS Head Office

Adora	Okonkwo	DWS Head Office
Stanley	Zama	DWS Head Office
Philani	Khoza	DWS Head Office
Henry	Maluleke	DWS Head Office
Tichatonga	Gonah	DWS Head Office
Lerato	Molokomme	DWS Head Office

On the first day of the workshop, a presentation on the GRDM theory and methodology was provided. The training program and training materials were provided on a flash disk for participants. Dr Sumaya Clarke, the GRDM project leader gave an introductory presentation. She welcomed all the participants and described the GRDM project which builds on the existing GRDM methodology and the software. The project focuses only on the aspects that have been identified as needing improvements and further explains deliverables that have been made and those yet to be made. Areas that needed improvement were identified. She briefly explained the Terms of Reference (ToR) for the project, the update on the review of relevant literature, and the public stakeholder workshops that were conducted. Prof. Kanyerere, the technical leader on the GRDM Methodology, presented the progress on the update of the GDRM methodology. The gaps needing an upgrade on the GRDM method were identified from the reviewed literature and such gaps were agreed upon by the users and potential users of the GRDM methodology and software. The presentation during the training workshop was to provide progress on such gaps and the workshop focused on the following:

1. Key parameters: Recharge, groundwater contribution to baseflow, groundwater-dependent population, and groundwater quality parameters

2. Water Resource Classification (Aquifer Delineation)

3. Reserve Determination (Quantify and quality)

4. Setting Resource Quality Objectives

5. Testing the updated GRDM software

6. GRDM implementation

After Prof Kanyerere gave the presentation in the morning sessions, in the afternoon session, postgraduate students from the University of the Western Cape (UWC) were given opportunities to demonstrate on how they have been working on the GRDM Project on different case study areas. They were expected to present their research and suggest viable answers. Participants were given case studies presentations pertaining to parameters identified for update within the methodology. The presentations were as follows: Mr. Sandiso Zulu, MSc student, demonstrated on how he carried out aquifer delineation in the Upper Berg River Catchment (G10A) and in Heuningnes Catchment (G50). Several examples were given as he provided a step-by-step demonstration of aquifer delineation. Mr. Abongile Xaza, a PhD student, demonstrated how Concentration Duration Curves were used to setting RQOs in the Upper Berg and Heuningnes Catchments. He also demonstrated how to set the quality component of groundwater reserves. The third student was Annah Umunezero, an MSc student. She demonstrated the equation on how she separated groundwater contribution from baseflow. Her explanation was clear and showed that the actual method to compute the value exists and that it is practical or feasible to extract groundwater contribution from the baseflow. The feasibility of the method applied in this parameter promoted active involvement and knowledge sharing. The participants' ability to think critically and solve problems was encouraged by this activity.

These presentations resulted in an interactive session that encouraged participants to discuss their suggestions concerning the similarities and differences in the workplace, how the updated method would be implemented and provided valuable insights into real-world scenarios and best practices. The participants agreed with the updated methodology regarding the key parameters, aquifer delineation, reserve determination for quantity and quality; the use of Concentration Duration Curves, and the use of background conditions and the methods to extract or separate groundwater contribution to baseflow.

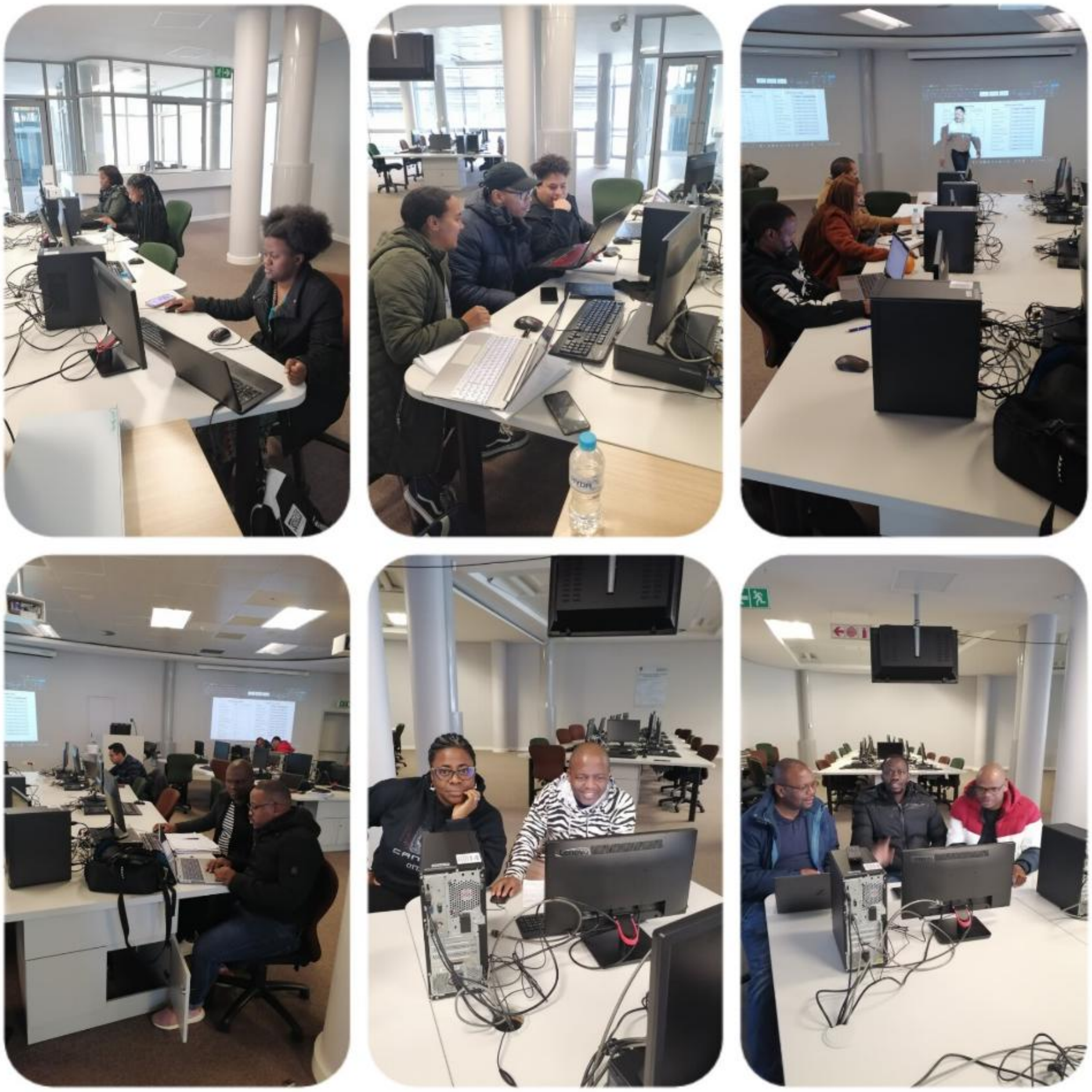


Photo: DWS Staff members from Head Office during the training workshop

On day two, officials from the Department of Water and Sanitation (DWS) head office and UWC research team members attended a one-day field-based training in the Upper Berg Catchment, one of the case study areas for the GRDM project. The UWC team led the field trip to show the sites where data were collected for the project. An explanation was provided at each site visited during the field trip. The processes that were followed for aquifer delineation, recharge estimation, estimating groundwater-dependent population, collecting data for Concentration Duration Curves, and groundwater contribution to baseflow were demonstrated in the field. Delegates for the training workshop were given the opportunity to observe various features in the case study sites such as catchment demarcation, anthropogenic activities, boreholes, and rainfall measurement stations among others.

Photo: UWC Research Team and DWS Staff members conducting field-based training

On day three, the training workshop was based on the GRDM software. It was presented by Dr. Rainier Dennis from North-West University. The focus was to showcase the new features of the upgraded software. The first session was on database management of the software. The second part was on the actual software, the water balance model, the wellfield model in the software, and the third part was on model calibration for aquifer delineation. Based on the information provided by the software facilitator, participants felt that they needed more time to familiarize themselves with several features of the updated software. There was no time to elaborate on the technical aspects of the software and the practical experience of the participants. There was a need for further collaboration and for more interactive sessions between the software team, method team, and users/practitioners on the updated methods and software for more piloting in other catchments and upscaling at the regional levels.

Despite the limited time for more hands-on sessions on the updated software, the training workshop at the University of the Western Cape provided a starting point for more training. During the training workshop, participants were actively engaging in practical classroom activities. Hands-on training sessions and the field visit on the case studies enabled participants to see the application of the methods and how data collected from the case study was used in the software. Participants were able to see what data are required for the software. Participants were able to see the required data, data source, and database for the GRDM software in a practical way and how to resolve challenges faced in the office regarding GRDM components.

The troubleshooting challenges regarding installing the software on some computers during the practical sessions initiated a discussion on the need for support mechanisms when such challenges arise in the future. It was suggested that Mr. Abongile Xaza be set aside as an IT assistant to be working with Dr. Denis for 1-2 years to ensure that technical support is provided to users of the updated GRDM method and software. Such an arrangement would come with a small student bursary supported by DWS to Mr. Abongile Xaza for 2 years as Postdoc scholar. Table 25 list the participants of the training workshop

Table 25: Workshop attendees

Name	**Surname**	**Organization**
Kwazikwakhe	Majola	DWS Head Office
Adora	Okonkwo	DWS Head Office
Stanley	Zama	DWS Head Office
Philani	Khoza	DWS Head Office
Henry	Maluleke	DWS Head Office
Tichatonga	Gonah	DWS Head Office
Lerato	Molokomme	DWS Head Office
Thokozani	Kanyerere	University of the Western Cape
Sumaya	Clarke	University of the Western Cape
Erin	Plato	University of the Western Cape
Abongile	Xaza	University of the Western Cape
Annah	Umunezero	University of the Western Cape
Sandiso	Zulu	University of the Western Cape
Rofhiuwa	Magodi	University of the Western Cape
Paula	Finini	University of the Western Cape

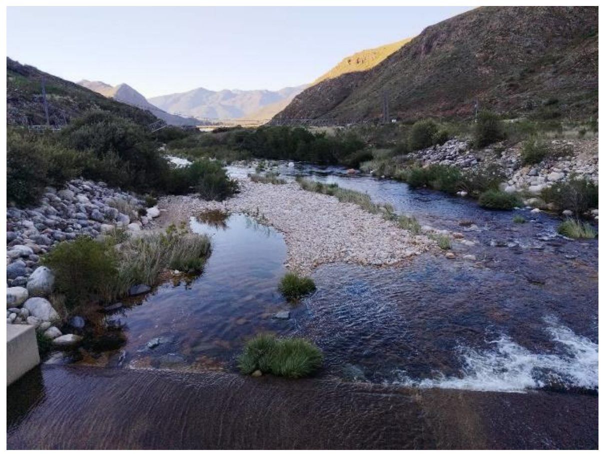
6.4 Training Workshop for DWS Western Cape Regional Office

Although the training was not for DWS staff members from the regional office, DWS from the Bellville Office were invited mainly because the G10A and G50 Catchments that were used as case studies were in their province. Their participation provided a good reflective discussion on the implementation aspects of the updated GRDM method and software. Four DWS Staff members participated in the training as follows: Kezia Smith Van Niekerk, Ashton Van Niekerk, Christo Louw, and T. Bengeza. The discussion on data collection on parameters for GRDM research, the implementation of the methods, and the interpretation of results from the methods and software regarding reserve determination and RQOs in line with water monitoring and water allocation especially for draft license applications were very informative.

6.5 Online Feedback Workshop to Stakeholders

The first online workshop was on gap analysis where potential users and users of the GRDM method and software were invited to discuss the challenges with GRDM and suggest solutions to such challenges. That workshop was carried out successfully. The research was carried out to address such challenges. The results were shared among the research team and DWS staff members from the head office as users of the method and software. The DWS staff members from the head office approved the updated method and software recommended refinement of such method and software and provided guidance on how to scale up such methodology. The next step is now to arrange for a wider stakeholder engagement for the first audience that was invited to report back to such an audience on the findings regarding the updated method and software of the GRDM. Such a workshop will inform wider uptake of the updated method and software in all 9 DWS regional offices by users in the government and non-governmental sectors respectively. Before such a wider stakeholder engagement workshop, reference group members meeting by WRC will be organized where results and progress on the updated methods and software will be presented, discussed, and agreed upon.

Appendix: Field pictures



7. GRDM IMPLEMENTATION

7.1 Consideration of the Delineated Aquifers for Water Allocation and Monitoring

Setting RQOs indicates the completion of the technical component in the GRDM process, however the process is not only technical, but it must also consider other factors such as efficiency, social and economic factors. The process must be iterative to allow for consideration of the outcome of the catchment visioning process and linkages to other components of the hydrological cycle that may have emerged during the GRDM assessment. Once the GRDM assessment is in place, allocation and monitoring requirements of the water resource must be considered.

7.2 Consideration of the Reserve for Water Allocation and Monitoring

Determining how to allocate requires the consideration of certain factors, including the source of the water. Allocation of groundwater should be based on delineated aquifers and not necessarily the entire catchment because of the following reasons: the aquifer is the storage and source of water, not the entire catchment. The aquifer might not occupy the whole catchment. A catchment can have more than one aquifer; hence it is possible for groundwater users in the same catchment to be using water from different aquifers.

7.3 Consideration of RQOs for Water Allocation and Monitoring

Monitoring is required to ensure that the Reserve and Resource Quality Objectives are both realistic and are adhered to. Information obtained from post-GRDM assessment monitoring will be used in the review of the assessment. Monitoring forms an essential part of what must be a seamless process of managing the country's water resources. Groundwater monitoring has the simple goal of quantifying the behaviour and response of groundwater systems to various controls and stressors (recharge, discharge, abstraction, etc.). The response of groundwater systems is usually seen by variation in groundwater levels, a change in groundwater quality, or both. Analysis and interpretation of monitoring data and information enables the groundwater environment to be better understood and is therefore vital for sound and responsible groundwater resource management. All three levels of groundwater monitoring (national, regional, and local) are required by the GRDM assessment process.

However, monitoring at a regional level provides a synthesis of groundwater resource status and trends at a scale more appropriate for implementing meaningful resource management measures, standards and regulations. Local level monitoring encompasses the collection of specified site-focused and use-related groundwater data by, among others, the water user. This is the level at which the CMA should assess compliance with licensing conditions. This is the reason why allocation and monitoring should be based on determined reserve. Once the GRDM assessment has been completed, monitoring requirements need to be considered. The GRDM assessment team must, as part of RQOs, give guidance on the type of monitoring required, while ensuring that monitoring remains both realistic and affordable. The design of any monitoring programme needs to consider the following:

- Methods, location, and frequency of monitoring
- Capture and reporting of data
- Implementation and management of monitoring
- Cost of monitoring

7.4 Consideration for Training (Tailor-Made Courses)

It is Important that specialists are aware of management activities relating to the implementation and GRDM. Giving effect to the RQOs includes the catchment visioning process and publishing the Reserve for public review and comment. The issue of equity and efficiency must be addressed. Information supplied by the groundwater specialist during the GRDM process should be used during the water allocation and licensing processes. "It is a requirement that any Reserve set by the Minister be published for comment and review and once finalized, be published in the Government Gazette" WRC (2013). To give effect to the Reserve of a significant water resource, a strategy needs to be developed to achieve the Class, Reserve and RQOs set for that resource. Ultimately, this will be the responsibility of a catchment management agency.

However, until CMAs are established, this function will continue to be the responsibility of DWS regional offices. Development of a catchment management strategy is a long-term participative process involving stakeholders in the catchment. The strategy needs to consider the National Water Resource Strategy and address compliance with a specified Reserve. In catchments where current levels of water use prevent compliance with the Reserve in the short term, the catchment management strategy needs to include a phased approach that will result in compliance being achieved over a period. RQOs are crucial for the quality and flow of water resources (volume, velocity, and distribution across time). RQOs are numerical and narrative descriptions of requirements that must be fulfilled to fulfil the required management scenario for the resource classification.

8. GRDM TRAINING MANUALS (BRIEFS)

8.1 Manual for GRDM Classification (Step 1)

Delineate the units of analysis and describe the status quo of the water resources

It is recommended that the ongoing process to update the GRDM methodology considers the delineation of aquifer borders as an update to the current methodology, thereby improving the approach. The existing methodology, according to Dennis (per com), does account for aquifer boundaries and double aquifer layer system, but users/ customers are not aware and hence they are not using the software's capability. Therefore, the task here is to strengthen the capacity-building component by increasing awareness of all the features of the program and approach among the users and potential users including the stakeholders. The present GRDM project focuses on aquifer delineation and aquifer overlaying for an aquifer-oriented perspective. Step one shows how to overlay quaternary catchment on delineated groundwater units. Establishing how to scale up and down between aquifer and quaternary catchment delineation is one strategy that could be used.

How to do Step 1

The present GRDM study proposes to use aquifer-quaternary overlay catchment as units of analysis and proposes that all assessments, estimates, determinations, and status quo assessments of groundwater including RQOs must be done from the aquifer perspective or at aquifer scale rather than catchment scale. Below are the steps that need to be followed for the aquifer-quaternary overlay unit of analysis for GRDM. Delineated aquifers must be the unit of analysis.

Part A in step 1 is to source quaternary catchments shapefile

How to do this task: Acquire quaternary catchments from the following link http://www.sasdi.net/metaview.aspx?uuid=d83ff9c0965b1a2d4a1457b80677ce1f

Select the catchment(s) of interest by using the following query: "QUATERNARY" = 'G10A' in GIS environment. The output of this activity is the image below in Figure 42 and 43.

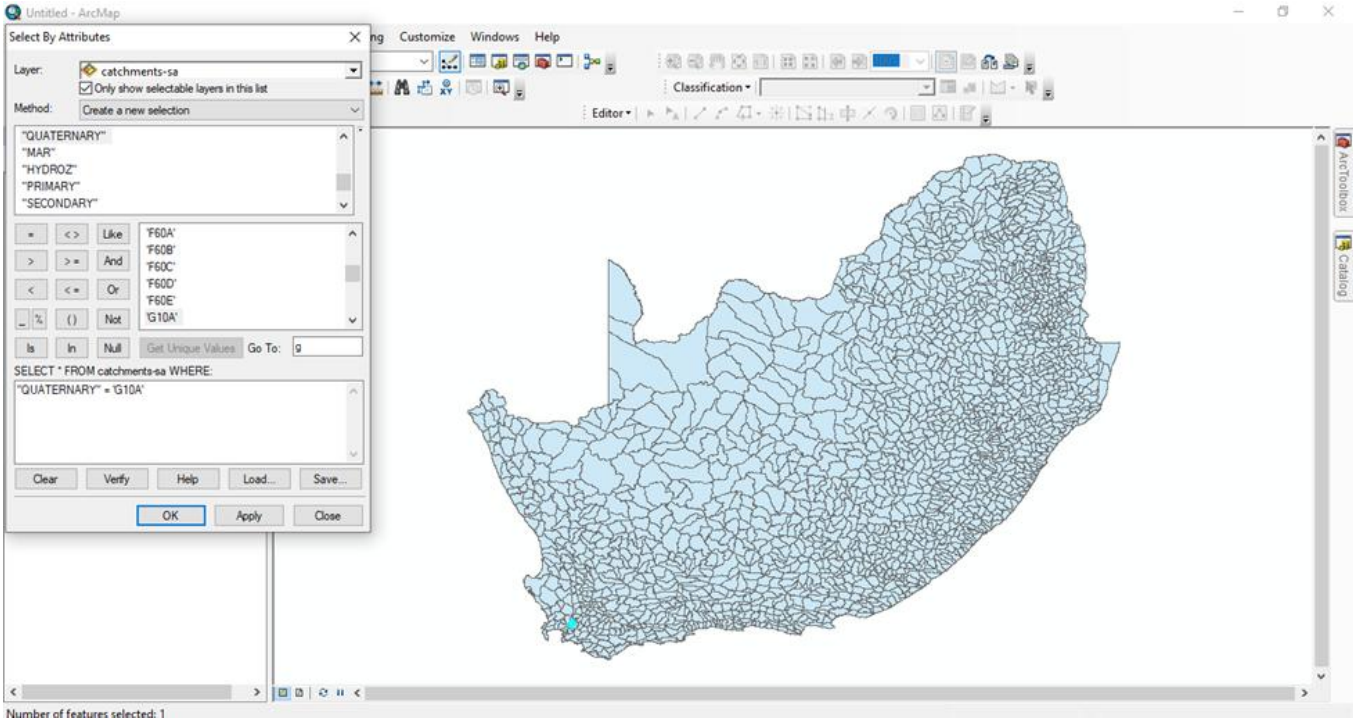


Figure 42:Delineated study area

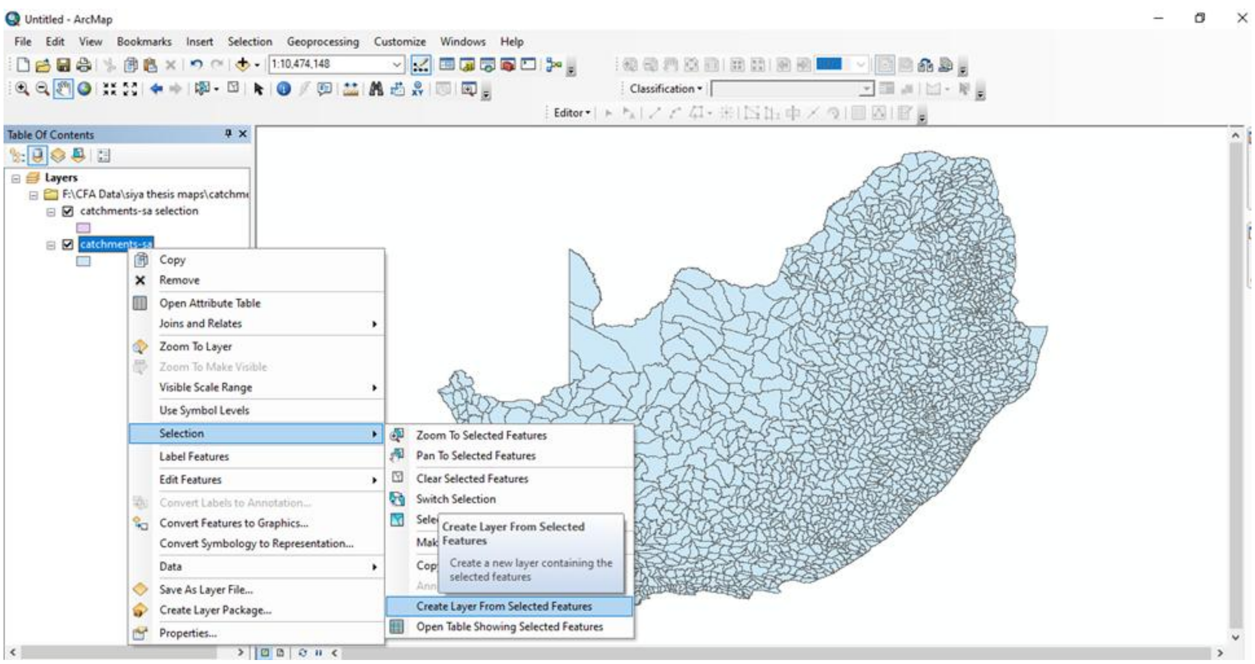


Figure 43: then create layer from selected features as shown in fig 44.

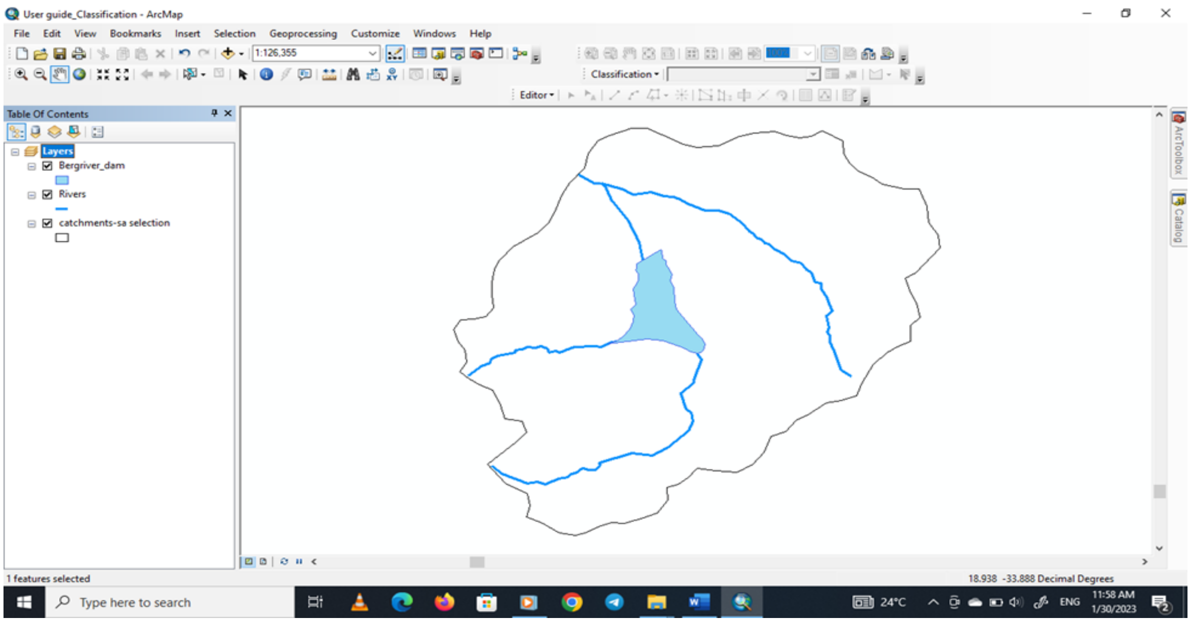


Figure 44: Created layer.

Part B in step 1 is to delineate aquifer types within the study catchment(s)

How to do this task: Acquire the groundwater yield shapefile from the GRA2 project as seen in figure 45 and then create a layer

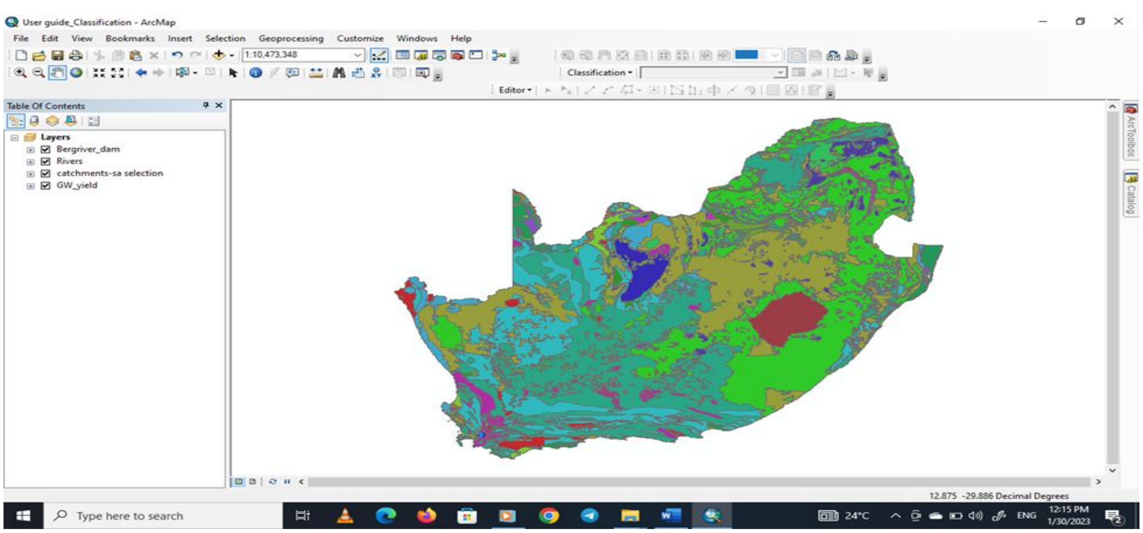


Figure 45: Groundwater yield map of South Africa

Then clip the catchment of interest as seen in figure 46

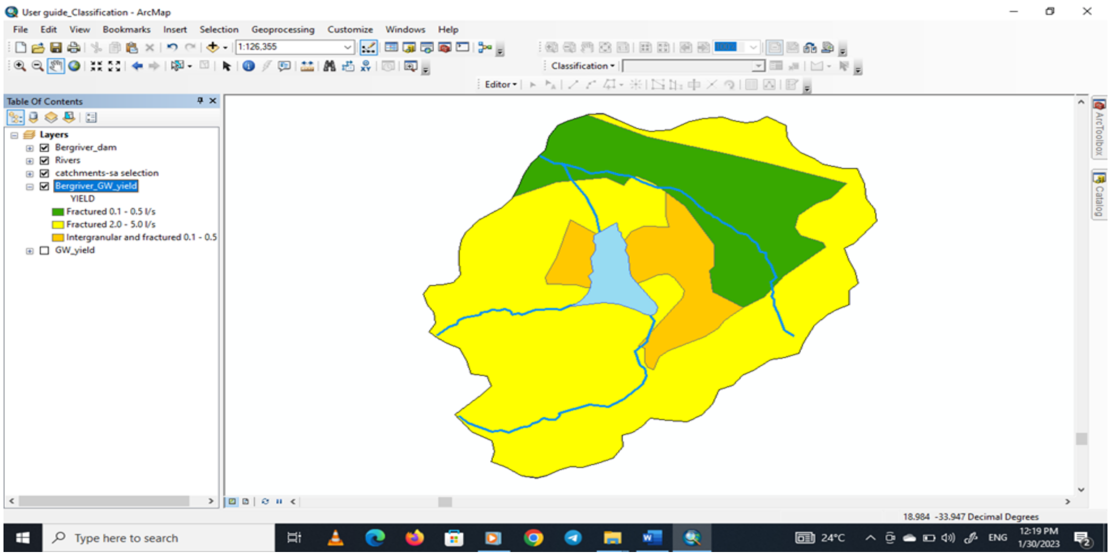


Figure 46:Groundwater yield in the Berg River catchment

Part C in step 1 is to overlay the quaternary catchment with the groundwater resource units

Task: Overlay the groundwater resource units over the quaternary catchments (Figure 47)

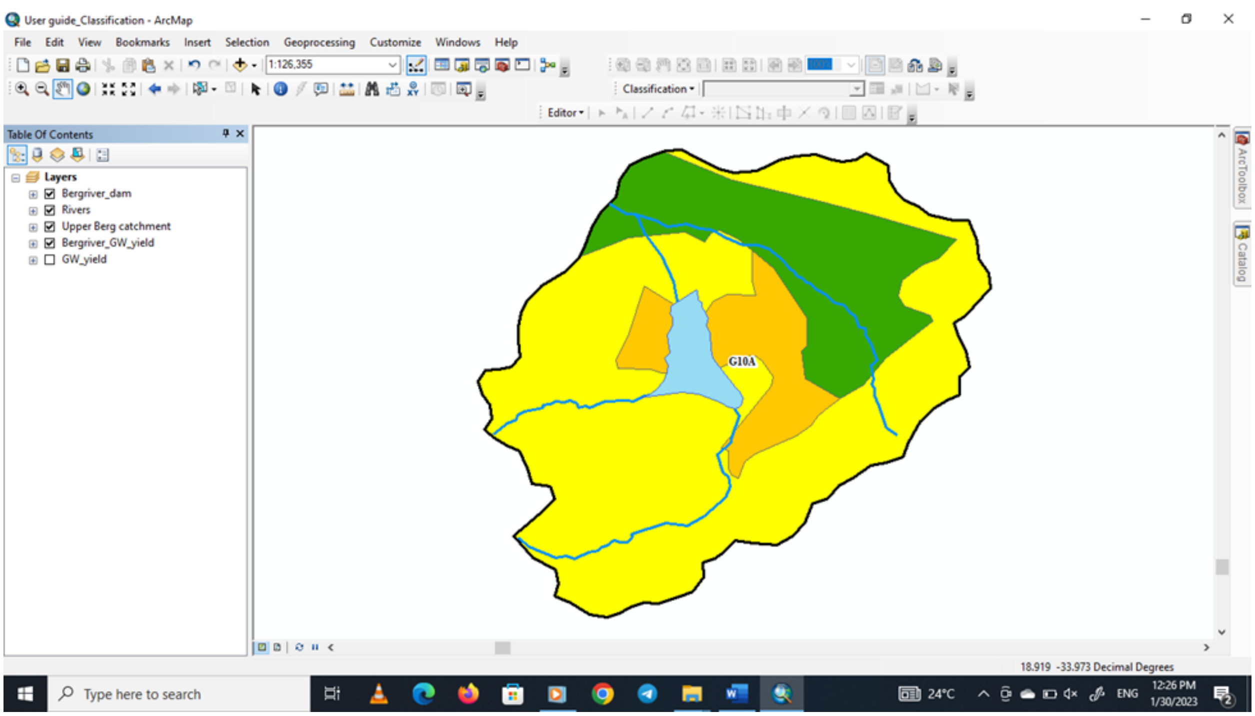


Figure 47: Groundwater resource units overlayed with quaternary catchments

Summary of step 1 is as follows: Access shape files of quaternary catchment; delineate groundwater resource units [Aquifers] and then overlay the two. This overlayed groundwater resources unit becomes the unit of analysis for GRDM activities i.e. classification, reserve, RQOs, monitoring and protection among others. It is proposed that an overlay of the delineated groundwater resource unit and quaternary catchment can now be a resource unit for various assessments for GRDM. A groundwater resource unit [GRU] was delineated by superimposing the quaternary catchment with information from shapefiles and from structural geologists. The identified GRU would be response units that are relatively homogenous in aquifer characteristics among others. The GRU would assist the team in identifying the areas where the system is under the most stress (where added development or impacts would alter the integrity of the system the most) or an area that is close to natural or pristine or not impacted and therefore needs to be used as a baseline or reference condition for reserve determination and setting RQOs. Various assessments would then be carried out within each GRU or if this would require too many. GRUs to be assessed only the critical GRUs would be selected for various assessments. The information from the GRUs would also assist the team in identifying relevant scenarios for the various aspects of the GRDM. Carrying out tasks in step 1 will require the following human resources: Project leader; GIS, Geologist, Hydrogeologist and DWS GRDM personnel.

8.2 Manual for GRDM Reserve (Quantity)

Step-by-step process of baseflow and groundwater Contribution to Baseflow Estimation

Step 1: Acquisition and gathering of data records

- Obtain river flow data from the gauging stations for a given study area and time frame.
- Sources of data may be the Department of Water and Sanitation (www.dwa.gov.za/hydrology) or other National databases or private organizations.

Step 2: Capturing of data records

- After the acquisition of time series river flow data to use in the filtration of quick flow and baseflow, enter this data into a Microsoft Excel © (Excel) spreadsheet as follows:
- Transfer or input the time series river flow data into Excel.
- Create seven columns (Date; Daily flow rate (m^3/s); Surface flow or filtered flow (Q(t)) (m^3/s); Baseflow qb(t) (m^3/s), Baseflow Index (BFI), BFI % and average BFI% as shown in example Figure 48 below)

	A	B	C	D	E	F	G
10	Date	Daily flow rate (m^3/s)	Surface flow (Q(t))(m^3/s)	Base-flow qb(t)	BFI	BFI (%)	Average (BFI) %
11	1/1/2016	0.096	0	0.096	1	100	8.008958425
12	1/2/2016	0.087	0.0801375	0.0068625	0.07887931	7.88793	
13	1/3/2016	0.075	0.068925	0.006075	0.081	8.1	
14	1/4/2016	0.068	0.0626375	0.0053625	0.078860294	7.88603	
15	1/5/2016	0.091	0.0850375	0.0059625	0.065521978	6.5522	
16	1/6/2016	0.08	0.0735875	0.0064125	0.08015625	8.01563	

Figure 48: Example of the organization of data in Excel for baseflow calculations

Step 3: Choose the filter parameter (α / β) to use

- Based on the study site choice and literature review, select the filter parameter to use from the example Figure 49 shown below

β value
0.925
0.950
0.997

Figure 49: Examples of filters parameter used

Step 4: The first quick flow (Filtered Surface water)

- Make the value of the first filtered surface water equal to 0 as the filtered quick flow for the previous sampling of the first daily flow rate is unknown as shown in example (Figure 50) below.

J15

	A	B	C
10	Date	Daily flow rate (m^3/s)	Surface flow (Q(t))(m^3/s)
11	1/1/2016	0.096	0
12	1/2/2016	0.087	0.0801375
13	1/3/2016	0.075	0.068925

Figure 50: Example of Daily flow rate with first filtered surface water equal to zero

Step 5: Filter quick flow from the daily flow

- Insert the baseflow separation algorithm equation you want to use in excel to filter quick flow (Surface water) from the daily flow as indicated in the example in Figure 51.

SUM | =MAX(0,(((C9*B11)+((1+C9)*0.5)*(B12-B11))))

	A	B	C	D	E
7	G1H076				
8	Variable 100.00 Surface Water Level				(1+α)*0.5
9		α	0.925		0.9625
10	**Date**	**Daily flow rate (m^3/s)**	**Surface flow (Q(t))(m^3/s)**	**Base-flow qb(t)**	**BFI**
11	1/1/2016	0.096	0	0.096	
12	1/2/2016	0.087	C9)*0.5)*(B12-B11))))	0.0068625	0.0788793
13	1/3/2016	0.075	0.068925	0.006075	0.08
14	1/4/2016	0.068	0.0626375	0.0053625	0.07886029
15	1/5/2016	0.091	0.0850375	0.0059625	0.06552197
16	1/6/2016	0.08	0.0735875	0.0064125	0.0801562

Figure 51: Example of how the baseflow algorithm is used to calculate Surface water flow

Step 6: Estimate baseflow

- Subtract the filtered surface flow from the daily flow to get the baseflow value as shown in the example Figure 52.

SUM | =B11-C11

	A	B	C	D
10	Date	Daily flow rate (m^3/s)	Surface flow (Q(t))(m^3/s)	Base-flow qb(t)
11	1/1/2016	0.096	0	=B11-C11
12	1/2/2016	0.087	0.0801375	0.0068625
13	1/3/2016	0.075	0.068925	0.006075
14	1/4/2016	0.068	0.0626375	0.0053625
15	1/5/2016	0.091	0.0850375	0.0059625

Figure 52: Determination of the baseflow value by subtracting the filtered surface flow from the daily flow to obtain the baseflow value

Step 7: Calculate the Baseflow index percentage

- Divide the baseflow value by the daily flow to get the BFI then times with 100 to get the BFI% (Figure 53)

SUM | =100*(D12/B12)

	A	B	C	D	E	F	G
10	Date	Daily flow rate (m^3/s)	Surface flow (Q(t))(m^3/s)	Base-flow qb(t)	BFI	BFI (%)	Average (BFI) %
11	1/1/2016	0.096	0	0.096	1	100	8.008958425
12	1/2/2016	0.087	0.0801375	0.0068625	0.07887931	=100*(D12/B12)	
13	1/3/2016	0.075	0.068925	0.006075	0.081	8.1	
14	1/4/2016	0.068	0.0626375	0.0053625	0.078860294	7.88603	
15	1/5/2016	0.091	0.0850375	0.0059625	0.065521978	6.5522	
16	1/6/2016	0.08	0.0735875	0.0064125	0.08015625	8.01563	

Figure 53: Dividing the baseflow value by the daily flow to determine the base flow index as a percentage

Step 8

Hover the mouse cursor over a small square at the lower right-hand corner of each cell with calculated filtered flows, baseflow, BFI and BFI%, Hold and drag the fill handle down the columns to get the values for all the daily flow rates (Figure 54).

Surface flow (Q(t))(m^3/s)	Base-flow qb(t)	BFI
0	0.096	
0.0801375	0.0068625	0.0
0.068925	0.006075	
0.0626375	0.0053625	0.07
0.0850375	0.0059625	0.06
0.0735875		
0.0826625		

Figure 54: Hold and drag the formula down the column to repeat the calculation for the entire data record

Step 9: Calculate the average baseflow Index percentage as shown in Figure 55.

=AVERAGE(F11:F2260)

	C	D	E	F	G
3/s)	Surface flow (Q(t))(m^3/s)	Base-flow qb(t)	BFI	BFI (%)	Average (BFI) %
0.096	0	0.096	1	100	F2260)
0.087	0.0801375	0.0068625	0.07887931	7.88793	
0.075	0.068925	0.006075	0.081	8.1	
0.068	0.0626375	0.0053625	0.078860294	7.88603	
0.091	0.0850375	0.0059625	0.065521978	6.5522	
0.08	0.0735875	0.0064125	0.08015625	8.01563	
0.089	0.0826625	0.0063375	0.071207865	7.12079	
0.074	0.0678875	0.0061125	0.082601351	8.26014	
0.059	0.0540125	0.0049875	0.084533898	8.45339	
0.054	0.0497625	0.0042375	0.078472222	7.84722	
0.053	0.0489875	0.0040125	0.075707547	7.57075	
0.055	0.05095	0.00405	0.073636364	7.36364	

Figure 55: Determination of the average baseflow index

The steps followed when estimating groundwater discharge using the mass balance equation (natural EC tracer)

Step 1: Site characteristics where data are collected

- River flow discharge data from the gauging stations in the area (DWS)
- Measure EC values from groundwater and surface water (the inflow from upstream and at the gauging station) using the YSI multi-parameter probe in the field or secondary data

Step 2: Catchment division

- Divide the catchment into equal segments based on the gauging station locations

Step 3: Estimate the inflow from upstream

- Use the mass balance equation to calculate for inflow from upstream manually or in Excel
- Qin = Q1 $(C1-Cg)/(Cin-Cg)$
- Where the Qg1 and Q1 are the groundwater discharge in the first segment and the discharge at the end of the first segment in m^3 /s; Qin is the inflow from the upstream in m^3/s; Cg and C1 are the tracer values of the groundwater discharge and total discharge at the end of the first segment in µS/cm

Step 4: Estimate groundwater discharge

- To estimate groundwater discharge in the segment, Subtract the estimated inflow from upstream from the river flow discharge at the end of the segment (gauging station).
- Qg1 = Q1 – Qin

8.3 Manual for GRDM Reserve (Quality)

Spatiotemporal assessment of groundwater quality in South Africa exist and such assessment provides a basis of accessing to the database that produced such maps. In 2012 and 2013, CSIR produced maps that showed the tendency or likelihood for contamination to reach specified positions in the groundwater system after introduction at some location above the uppermost aquifer system. The least vulnerable regions that are only vulnerable to conservative pollutants in the long term when continuously discharged or leached were established and mapped including moderately vulnerable regions which are vulnerable to some pollutants but only when continuously discharged or leached. Knowledge and database on most vulnerable aquifer regions which are vulnerable to many pollutants except those strongly absorbed or readily transformed in many pollutants scenarios exist.

Murry et al [2012] and DWA [2013] used the database to produce spatial assessment in the form of susceptibility matrix map which showed the qualitative measures of the relative ease with which a groundwater system can be potentially contaminated by anthropogenic activities and included both aquifer vulnerability and the relative importance of the aquifer in terms of its classification. In addition to the susceptibility matrix map, Dennis et al [2012] from WRC project No.1763/1/11 assessed the quality of groundwater of South Africa for various purposes. For example, areas of groundwater with slightly salty taste, noticeably salty taste, marked salty taste, extremely salty taste and bitter taste were assessed and mapped. In other words, database on groundwater reserve quality exist which needs to be accessed for new analysis or new interpretation on groundwater reserve quality. It is important to emphasize that CSIR [2013] produced maps showing aquifer classification regions of South Africa showing aquifer systems of good water quality, of variable water quality and of moderate to poor water quality. This classification forms the basis for accessing the database which produced such assessment for further assessments on groundwater reserve quality and associated assessments.

8.4 Manual for GRDM RQOs (Quality)

Steps followed when setting RQOs for groundwater resource in a delineated aquifer system

***Step 1:* Acquisition and gathering of data records**

- Before beginning CDC, obtain groundwater quality data from groundwater monitoring sites (boreholes) for a given study area and time frame (time series data vs times).
- Sources of data may be National databases or from private organizations, and water users

***Step 2:* Capturing of data records**

After locating the relevant data for creating the concentration compliance probability curve, the water quality data for the period of record are entered into a Microsoft Excel © (Excel) spreadsheet as follows (Learn to work with Microsoft Excel © (Excel):

- Transfer or input the groundwater quality data into Excel.
- Create three columns (Point ID, Date, and Concentration, and organize the data accordingly (Figure 56).

	A	B	C
1	**ID**	**Date**	**Ca (mg/L)**
2	200000516	2010/04/21	15.598
3	200000516	2010/11/03	12.4
4	200000518	2010/11/03	13.1
5	200000520	2010/04/20	31.76
6	200000520	2010/11/02	37.8
7	200000524	2010/04/20	1.386
8	200000524	2010/11/02	2.27
9	200000528	2010/11/03	14.6
10	200000530	2010/11/03	1.39

Figure 56: Example of initial organization of groundwater quality data

Step 3: **Determine the number of records**

- Compute the total number of data sets in the period of record (Figure 57).

	A	B	C
302	200000692	2017/10/27	1.25
303	200000694	2017/05/25	1.25
304	200000694	2017/10/27	1.25
305	200000696	2017/04/25	1.25
306	200000696	2017/10/27	1.25
307	200000698	2017/04/25	1.5
308	200000698	2017/10/27	3.7
309	200000724	2017/10/26	1.25
310	200189652	2017/04/10	1.25
311	200189652	2017/10/04	1.25
312		Total records	310

Figure 57: Example of calculation of data sets covered in the period of record using groundwater quality data

Step 4: **Sorting of the data according to magnitude and assigning of ranks**

- Highlight all the data (excluding column headers) and select the "sort" command to rank data by concentration (mg/l), from smallest to largest (ascending order). Important to note that data is ranked in ascending order for upper limits and in descending order for lower limits.
- Create a new column and assign the concentration value a rank (M), starting with 1 for the smallest concentration value. Use the Excel auto-fill feature to generate a list of rank numbers down to the last concentration row (Figure 58).

	A	B	C	D
1	**ID**	**Date**	**Concentration**	**M**
2	200000516	2010/04/20	0.5	1
3	200000516	2011/04/21	0.5	2
4	200000518	2010/11/02	0.5	3
5	200000520	2010/11/02	0.5	4
6	200000520	2010/04/22	0.5	5
7	200000524	2010/04/22	0.5	6
8	200000524	2011/04/21	0.5	7
9	200000528	2011/10/13	0.5	8
10	200000530	2011/10/13	0.5	9
11	200000532	2012/10/09	0.5	10
12	200000532	2012/10/09	0.5	11
303	200000694	2015/04/20	39.098	302
304	200000694	2014/04/04	41.85	303
305	200000696	2017/10/04	47.2	304
306	200000696	2014/10/14	48.449	305
307	200000698	2012/10/10	51.338	306
308	200000698	2016/10/17	56	307
309	200000724	2012/04/25	56.082	308
310	200189652	2013/10/01	60.245	309
311	200189652	2015/10/12	65.383	310
312		Total records	310	

Figure 58:Example of sorting and ranking in Excel using concentration data

Step 5: **Computing of compliance probability (P)**

- Compute *compliance probability* (P) for concentration in each line of data by using the formula provided below.
- Create a new column and input the formula in the first cell (Figure xxxx). Make sure to select the appropriate cells called for by the formula (M = rank #, n = total records calculated) and use "$" symbols to lock the formulas' reference (absolute reference) to the total records cell.
- Apply the formula to all concentrations and calculate all the compliance probabilities by copying the formula down the column to the last ranked concentration row. (You can copy the formula by hovering the mouse over the lower right corner of the formula's cell until a black cross-hair appears, then drag down the column.)

$$P = [\, M / (n + 1)] \times 100\% \qquad (2)$$

P = the probability that a given concentration will be equalled or below or not exceeded (% of time)

M = assigned rank number

n = the total number of days for period of record

The Excel formula, as shown in Figure 59 is =(F3/(E21917+1))*100.

E2 | fx | =(D2/(C312+1))*100

	A	B	C	D	E
1	ID	Date	Concentration	M	mp
2	200000516	2010/04/20	0.5	1	0.3
3	200000516	2011/04/21	0.5	2	0.6
4	200000518	2010/11/02	0.5	3	1
5	200000520	2010/11/02	0.5	4	1.3
6	200000520	2010/04/22	0.5	5	1.6
7	200000524	2010/04/22	0.5	6	1.9
8	200000524	2011/04/21	0.5	7	2.3
304	200000694	2014/04/04	41.85	303	97
305	200000696	2017/10/04	47.2	304	98
306	200000696	2014/10/14	48.449	305	98
307	200000698	2012/10/10	51.338	306	98
308	200000698	2016/10/17	56	307	99
309	200000724	2012/04/25	56.082	308	99
310	200189652	2013/10/01	60.245	309	99
311	200189652	2015/10/12	65.383	310	100
312		Total records	310		

Figure 59: Example of display showing the calculation of compliance probabilities using groundwater quality data

***Step 6:* Creating the annual concentration compliance graph**

- Plot the compliance probability values calculated in Step 5 against associated concentrations.
- In Excel, highlight the data to be graphed (in the Figure 59 example, columns C and E), then select the "scatter plot" graph option.
- Place compliance probability values on the x-axis and concentrations on the y-axis.
- The graph should look like Figure 60 below:

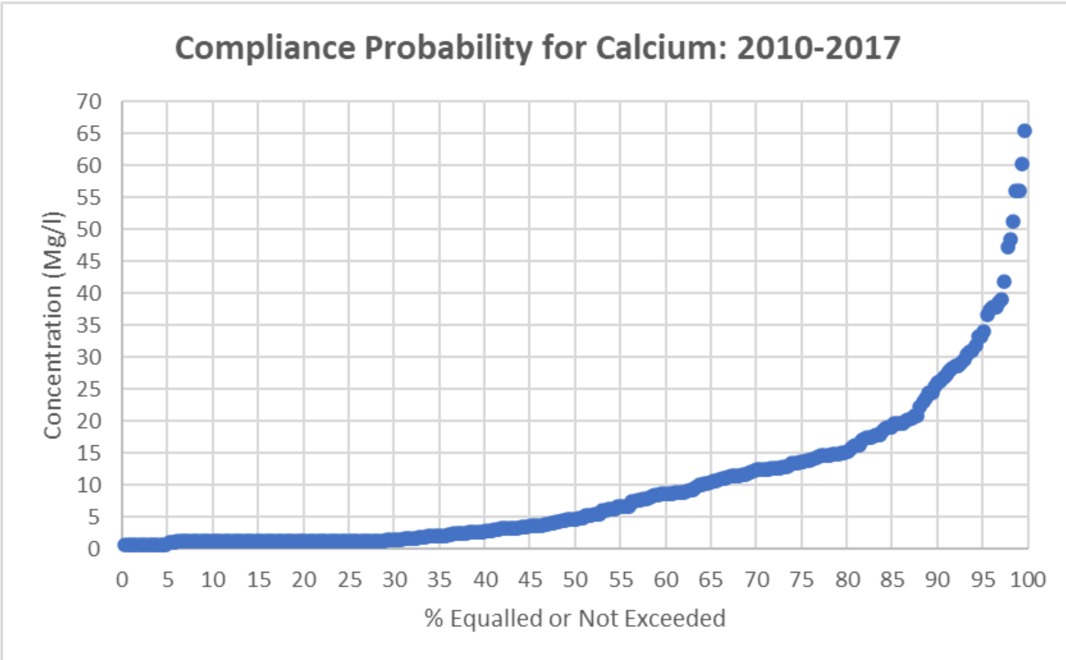


Figure 60: Example of concentration compliance probability curve for Calcium

8.5 Manual for GRDM Software (User Manual)

This will be submitted as a separate report and can be accessed at https://waterscience.co.za/grdm.html

8.6 Manual for GRDM Software (Demonstration Videos)

Videos will be made available on the website https://waterscience.co.za/grdm.html housing the software program.

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