

# FRAMEWORK FOR NATURAL AND ANTHROPOGENIC CHANGES TO THE URBAN VADOSE ZONE

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# Framework for Natural and Anthropogenic Changes to the Urban Vadose Zone

Report  
to the Water Research Commission

by

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WRC report no. TT 954/1/26

ISBN 978-0-6392-0701-8

May 2026



This is the final report for WRC project no. C2020/2021-00581.

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## EXECUTIVE SUMMARY

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### Rationale

The project was initiated to build on previous projects and focuses on the changes that occur due to nature and the influences of humanity on the water cycle and ground profile. The project team set out to do case studies that play a pivotal role in the developed areas in terms of the mechanical and hydrological properties of the ground and water that are both subject to change in terms of their properties. Water is affected both in terms of its flow and quality, and these both get affected through urbanisation.

Non-revenue water is that water that has been treated and distributed, but that is lost to leakages. Non-revenue water levels are very high in many of South Africa's cities and they turn the vadose zone into areas of focused recharge of the groundwater system. Population growth and urbanisation worsen these and make the negative impacts worse.

Different contaminants are presented that include those derived from coal mining and those derived from petroleum storage and spillage. Water influences on buildings and other land uses such as cemeteries are shown as examples where leaking water can result in failure of buildings and sinkholes.

The literature covers important aspects about urban water and urban groundwater that is required to pre-empt the outcomes and findings of this project's research. This is followed by soil and rock and the water that flows through it that forms part of the original land that is changed through anthropogenic activities. Unsaturated flow is covered specifically, seeing that development occurs predominantly in the vadose zone, and that is often changed locally to phreatic zones.

### Aims

The following were the aims of the project:

1. Compile a generic conceptual urban subsurface water cycle emphasising potential fluxes and interactions superimposed on the natural hydrological cycle, and addressing possible adverse consequences of altered fluxes due to climate change or anthropogenic influence.
2. Contribute to the mechanism and quantification of recharge in complex and developed terrain, incorporating the retardation (and concentration?) of natural recharge processes from hard surfaces and the contribution of anthropogenic recharge (e.g., leaking pipes), and superimposing these on typical hydrostratigraphical settings.
3. Estimate the current status of stability, and predict the long-term behaviour of slopes and ground, mainly due to precipitation and climate change, to develop a deeper understanding of these phenomena in the semi-arid urban environment.
4. Synthesise findings to describe very complex hydrostratigraphical settings affected by for instance climate change, population growth, altered hydrological cycles, and land use change, while providing input into disaster management plans and contributing to the overall limited extent of subject matter related to the intermediate vadose zone.

### Methodology

Various methods were employed to address different aspects of the movement and storage of water through rock and soil. The description of materials and the sampling of water and soil are addressed together with the required laboratory testing.

The methods also include field methods like tracer tests and infrared thermography that were used to determine the flow rates and direction of water in fractured rock. These are two tracers that provide combined input into this difficult problem, and that can be used together to improve the quality and accuracy of the results.

Radon can be used to determine whether the source of water is geogenic (derived from, for instance, U in rock) or not, and therefore assists in the linking of surface water with groundwater. Stable isotopes of H and O were also used to relate the rainwater, groundwater and surface water with each other. General water chemistry that includes microbiology and some metals was used predominantly for surface water in different catchments originating in part in Pretoria and Johannesburg, respectively.

Mineralogy and chemistry were determined with XRD, XRF, SEM and thin sections after following the normal path of hand specimen identification.

X-ray computed tomography was used to identify, through non-destructive imaging, the relict pore structure and geometry, and this provided important input to characterise the pore space orientation and size distribution, and the persistence of the relict rock structure and infill material of undisturbed samples.

Soils were tested in the laboratory to ascertain the behaviour of the undisturbed orientated soils on which building will happen, as well as the parameters required for foundations that included grading, hydrometer analyses, and the Atterberg Limits (liquid limit, plastic limit, shrinkage limit).

The Aquaread AP-5000 was used in the field to measure the following parameters: temperature, pH, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), salinity (SAL), oxidation-reduction potential (ORP), nitrate ( $\text{NO}_3^-$ ), nitrite ( $\text{NO}_2^-$ ) and ammonium ( $\text{NH}_4^+$ ).

## **Case Studies**

The case studies all contribute to different aspects related to the development of new data and outcomes. Two case studies focused on water quality. Water quality was investigated for both surface water and groundwater in the greater Timbavati catchment area, and the use of radon and isotopes assisted in understanding what is happening in the area. General water quality was also analysed over a few sampling runs that provided information about the changes in water quality.

Urban surface water quality was investigated for the tributaries of the rivers and streams flowing into the Hartbeespoort and Roodeplaat dams. The Colbyn wetland inflow and outflow water in the Hartbeesspruit were also sampled to determine the change in water quality across the wetland, and after the wetland beyond the highway and into the industrial area of East Lynn.

Undisturbed and disturbed soil samples were retrieved in the area from Polokwane past Magoesbaskloof to Graskop and Dullstroom. These samples comprised two in-situ (i.e., not eroded or transported) weathering products referred to as completely weathered and residual rock derived from gneiss, gabbro, dolomite, and other rock types. The incorporation of residual dolomite and wad (Mn-rich soil) is because large parts of Gauteng (Tshwane and Ekurhuleni) are underlain by dolomites and face problems with these soils and contains sampling in the Highveld in 2019.

The weathering rims of different rocks were analysed by different methods, including hand specimen description, thin sections and scanning electron microprobe (SEM), and the interpretations relate to changes in colour and texture of the rocks.

A blasted fractured rock quarry was investigated using artificial tracers and infrared thermography. These methods both indicate the movement of water through the rock with different outcomes. These are both used to infer the complex and anthropogenically altered vadose zone in fractured rock systems.

## Results and Discussion

The results from the case studies are used as evidence for the effectiveness of certain methods that are proposed in the outcomes as potential methods to be used. The case studies are also used as examples that build on the literature and methods to validate the relevance of the content in the first part of this book. Case studies make theory real-life and give the opportunity to understand the consequences of anthropogenic changes to the already sensitive vadose zone.

Water quality deteriorates from groundwater to surface water, and even more so further downstream with more impacts from industry and development. The coliforms in water can be transmitted through dermal and oral infection, meaning that anyone in close proximity of polluted water can get infected. Contamination in cities alters the surface water quality, as is found in the Jukskei River and other parts of the catchments. These values are mostly in the tens of thousands (>10 000) counts per 100 ml. The only significant difference between the water before (sample H1) and after (sample H2) the Colbyn Wetland is in the coliforms, meaning that the inhabitants (legal and unlawful) of the suburb and their pets and rubbish contribute to that. This is evident in most of the surface water samples.

Fractured rock can be delineated with infrared thermography that shows fractures and features more clearly than normal view. The results of this study showed that it was possible to identify and record the variations in surface temperatures that resulted from weathering on quartzitic sandstones. Visual inspections conducted in the field verified the interpretations provided, indicating that infrared thermography has good promise as a rapid weathering diagnostic tool.

Adding from the tracer testing, groundwater flow pathways are influenced by heterogeneous subsurface structures in the open pit quarry, and groundwater movement at the quarry is driven by structural features, seasonal rainfall variations, and surface water interactions. It includes the dynamics of environmental tracers (e.g., isotopes) and artificial tracers (e.g., dyes) to reveal natural processes and specific flow paths. Further, the contact between dolerite/diabase and Daspoort quartzite influences flow velocity and drainage towards the pit via fractures. The quarry's double-porosity system features flowing channels and stagnant zones, affecting solute transport, especially during the wet season.

Blasting activities impact hydraulic behaviour by altering fracture morphology. Groundwater flow is governed by the fractured Daspoort Formation, with NW-SE oriented fractures aiding flow under pressure gradients. The aquifer, with borehole yields of 0.5 to 2.0 L/s, relies on fractures for groundwater storage and transmission. Water levels, generally 10-30 m below the surface, fluctuate seasonally.

Regarding the weathered and residual soil studies, most of the macro pores are ineffective and exist in the relict structure when less weathered, with an increase in primary porosity as weathering continues, whereby increasing the total porosity. The secondary porosity decreases with an increase in weathering as the relict structures are destroyed and tends to zero in the residual soil.

The volumetric strain is expected to narrow the existing relict joints and fractures. The volume change also opens up fissures, which are identifiable by the XRCT scans as semi-continuous openings with very little to zero pedogenic deposits or infill. The pedogenic deposits exist along relict structures as staining and coatings on infill, indicating that water flow mainly occurs along these relict openings when the rock is less weathered. The flow happens through the primary pores as well as secondary pores, making completely weathered rock a dual-porosity system. Pedological classifications in engineering can be beneficial for determining the flow of water through the unsaturated zone.

It is expected for the Soil Water Retention Curve to change with a change in void ratio and density; however, the change in the air entry value (AEV) and suction levels between 1 kPa and 1000 kPa indicate the remoulding process destroys critical porosity characteristics for the material to retain high suctions at a given moisture

content. Field observations show the importance of recognising structure in this type of soil where no visible water is seen in the material until the structure is broken down. Thereafter, free water is present in the palm of the hand and the remaining soil texture will be in a liquefied state. This behaviour could indicate the critical role wad has in the formation of sinkholes. If wad near the throat of a receptacle experiences an external force, environmental change or continuous weathering, and the structure is lost, the material will liquify and move into the receptacle, either forming a void or initiating a sinkhole depending on the blanketing material.

The Timbavati and rock quarry both utilised isotopes, and the prior also used Rn, to understand the occurrence and origin of water. The Timbavati study looked at surface water and groundwater, finding that uranium concentrations in the groundwater samples were below the detection limit of 0.015 mg/L of the analysis performed by the lab. It was therefore not possible to see if there was a trend with regards to radon and uranium concentrations, and there were also no clear relationships between pH, DO, EC, TDS, SAL, ORP and radon concentrations. Surface water samples are enriched in heavier isotopes compared to the groundwater samples, likely due to seasonal variation, with surface water sample values varying by 33,5‰  $\delta D$  and 6,2‰  $\delta^{18}O$ .  $\delta D$  and  $\delta^{18}O$  values continued to increase as the dry season progressed, with the heaviest compositions occurring towards the end of the dry season. The heavy isotope compositions of the surface water samples are likely a sign of enrichment due to evaporation.

For the weathering rims, both the quartz diorite and the granite and shale samples had iron-oxide staining. The shale was the only one without quartz, and only the quartz diorite samples had biotite. The exposure of the average size of grains on surfaces are as follows:

- Quartz-diorite: quartz 422.50  $\mu m$  exposed 547.67  $\mu m$  unexposed; biotite/actinolite exposed 676.00  $\mu m$  unexposed 931.00  $\mu m$  2012  $\mu m$  (Cluster)
- Granite: quartz exposed  $\pm 600 \mu m$  unexposed  $\pm 1000 \mu m$
- Shale: none.

## Outcomes

The final outcomes are related to the combination and collation of different methods and techniques to optimally plan for investigation. Methods have been described, motivated and tested during the project, and now they are provided as options for investigation. Aligning methods based on this will minimise the need to motivate for different methods and to end up choosing the most effective after trial and error.

Recharge of water can increase or decrease depending on the relevant aspects forming part of the development or anthropogenic change. Densification happens due to residential development, and this is associated with new infrastructure such as high-rise buildings, factories, fuel storage facilities, roads and railways, tunnels and pipelines, and housing. Recharge can be increased here, with deteriorating water quality being possible together with the increasing quantity of underground water.

Water flows through basements and cuttings, and enters the subsurface through losing streams or canals and leaking buried pipes. This water can move through primary intergranular aquifers into fractured rock aquifers, and carry with it all surface and shallow subsurface sources of pollution. Where the water goes, the contamination follows, and when it is inorganic, it can surface in the subsurface indefinitely.

The following are examples of factors affecting anthropogenic and urban:

1. Leaking underground pipelines (filled with water, sewage, or any other contaminants).
2. Golf course irrigation exceeds annual rainfall significantly.
3. Flooded basements and excavations can collect water and allow seepage outwards.
4. Canals that divert water from sealed surfaces or pipes can leak or discharge at a specific locality.
5. Blasting in quarries or any other place will induce more fracturing in the rock and thereby induce more water flow.

6. Sealed surfaces like pavements and roads will cause water to flow onto the edges to recharge locally.

Anthropogenic recharge increases with development going from greenfields to brownfields, rural to urban, natural and agricultural to buildings with elevated structures, precipitation and irrigation to leaking pipelines, and constant unchanging to intermittent and intense events. Together with this, imminent water quality impacts include petroleum storage facilities, mine activities, waste disposal, and pollution of streams and rivers.

Scientific data form the baseline, and this is followed by the non-scientific data. The former requires experienced professionals to do the field work using best practice documentation, and then to interpret and present water-related outcomes, and finally to provide mitigation, monitoring, and managing output to reduce or prevent additional water ingress.

Non-scientific data are then those professionals designing and signing off on the combined scientific outcomes with cognisance of the fiscal and legal matters and the after-project management that includes water management.

A set of methods is provided that start with standard methodology that is common to almost all work that is related to preparation and initial fieldwork. It then splits into different methods for solids like rock and soil, and fluids like water and air. Here, both need to be described properly and all observations should be recorded.

Physical laboratory parameters and techniques entail determining the composition of the solids in terms of chemistry and mineralogy, and for the fluids, the quality and contamination.

Field techniques are all the methods where properties are determined instead of or together with laboratory samples. For rocks and soil, that entails the use of the geological hammer, penetration and strength testing, and other equipment. For fluids and notably water includes tracer tests and infrared thermography, infiltration and percolation tests (vadose zone tests), borehole tests, and water quality probes.

The same professional person should conduct all the work to ensure professional and technical soundness. This includes the description of materials and the sampling of water and soil.

Water quality data using field and laboratory techniques are worthwhile and valuable. Land uses are the main impacts, and informal settlements and blasting release contaminants to the environment. The main contaminants of concern are N, metals, and microbiology, all of which have very adverse consequences. Isotopes and radon were used to investigate these.

Methods used together provide better outcomes. Engineering geological and hydrogeological methods combined provide information and data that can be used for a wider array of people. The different methods address matters of water seepage in rock mass that may affect stability, and the advection and flow velocity of water through the system.

## ACKNOWLEDGEMENTS

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The project team and authors wish to thank the Reference Group members for their contributions to the project, which included the continuous input and peer review during the project to improve the quality of these project outcomes that include this book and the accompanying case studies book.

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## BOOK COVER CREDITS

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The book covers were taken from the case studies of the three PhD students:

1. For the book (TT954/1/26), the cover shows the quarry used in the case studies of Dr Mampho Maoyi and Dr Yazeed van Wyk. The photograph was taken by Mampho Maoyi in 2023.
2. For the case studies book (TT 954/2/26), the cover shows the weathered granitic profile around Magoebaskloof of Dr Duan Swart. The photograph was taken by Duan Swart in 2020.

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## GLOSSARY

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- Borehole** is a hole that is bored into the ground typically for sampling geological materials and/or water.
- Completely weathered rock** is rock that is weathered to the point that the structures are still present, but some minerals have changed to secondary minerals.
- Contaminant** is any substance of which the concentration is above normal
- Direct recharge** is water infiltrating into the soil after arriving as incident precipitation, and this is the preferred route for precipitation falling on vegetated surfaces
- Indirect recharge** normally occurs on vegetated swales, stream channels and/ below shallow ponds following intense rain periods, and water infiltrates following runoff across the land surface
- Infiltration flooding** causes water saturation of the soils around the house that can infiltrate into basements or foundation walls.
- Overland flow** refers to stormwater and snowmelt that are diverted from urban areas, and flooding can occur that can enter basements through different openings (from Sandink 2009).
- Pedogenesis** refers to the authigenic enrichment of some compound in a parent material to form pedocretes (ferricrete, calcrete, silcrete, laterite)
- Petroleum** is a group of hydrocarbons that include, for instance, petrol (gas), paraffin (jet fuel), and diesel
- Pollutant** is any substance of which the concentration has adverse effects; is when contamination reaches a stage where adverse effects occur
- Porosity** is the ratio of the volume of voids to the total volume
- Residual soil** is rock that is weathered to the point that the structures are no longer discernible and most to all of the minerals may have been changed to other minerals.
- Sewage backup** refers to toilets and other home water uses generating sanitary sewage releasing high degrees of contaminants posing human health and environmental risks.
- Void ratio** is the ratio of the volume of voids to the volume of solids
- Well** is synonymous to a borehole in many instances including in relation to monitoring wells. It, however, refers mostly to a hole that is dug for water by other means.

# CHAPTER 1: BACKGROUND AND RATIONALE

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## 1.1 THE WATER CYCLE

The natural water cycle includes the water above and below the land surface, and the interaction between these. The vadose zone is the pathway between surface water and groundwater, and it is also the zone after the entry point from the land surface into the subsurface where water and air interact to allow biota to exist. This very sensitive soil zone or plant root zone is vital in terms of sustaining life. This is the green land that we look at when we drive by and consider, in our professions, green fields in the context of development.

The infiltration of water through these natural systems is governed by the intensity and duration of precipitation events, especially due to rainfall. Lack of infiltration can cause erosion on the surface, notably in areas where plant roots are sparse. Barren ground erodes more easily, and the transport distance is exacerbated by the grade and drainage density. Nature is in an equilibrium as long as it is not adversely affected by humanity. With the global population growth, however, naturally protected environments become sparser. The ocean remains the biggest ecosystem on Earth, and it sequesters large amounts of carbon. It is, however, susceptible to the effects of preferred urbanisation and development along coastlines. All rivers exit into the oceans, and the transport corridor from continent to ocean merges together with all the associated sediment, dissolved constituents, and contaminants.

Streams and rivers form an important part of the developed areas. They should be conserved both for hydrological and ecological importance, seeing that clean running water ensures biodiversity and environmental health. Understanding both the water flow (quantity) and quality is, therefore, necessary to ensure that it is protected through monitoring, management and mitigation of its use and the influences on it. Also, understanding surface water means that one can understand whether surface water occurs as influent or effluent systems, and on how thick the vadose zone is if it is not a direct groundwater baseflow or shallower interflow through perching or ponding.

## 1.2 PROJECT AIMS

The following were the aims of the project:

1. Compile a generic conceptual urban subsurface water cycle emphasising potential fluxes and interactions superimposed on the natural hydrological cycle, and addressing possible adverse consequences of altered fluxes due to climate change or anthropogenic influence.
2. Contribute to the mechanism and quantification of recharge in complex and developed terrain, incorporating the retardation (and concentration?) of natural recharge processes from hard surfaces and the contribution of anthropogenic recharge (e.g., leaking pipes), and superimposing these on typical hydrostratigraphical settings.
3. Estimate the current status of stability, and predict the long-term behaviour of slopes and ground, mainly due to precipitation and climate change, in order to develop a deeper understanding of these phenomena in the semi-arid urban environment.
4. Synthesise findings to describe very complex hydrostratigraphical settings affected by, for instance, climate change, population growth, altered hydrological cycles, and land use change, while providing input into disaster management plans and contributing to the overall limited extent of subject matter related to the intermediate vadose zone.

### 1.3 PRESENTATION AND USE

In terms of the latter, the following projects have been undertaken in preparation for the culmination of knowledge to be combined for highly complex, heterogeneous, anisotropic and altered systems:

- Dippenaar MA, Jones BR, Van Rooy JL, Maoyi M, Swart D (2022) *The Vadose Zone: from Theory to Practise*. TT 869/21. Water Research Commission. Pretoria. ISBN 978-0-6392-0313-3
- Dippenaar MA, Swart D, Van Rooy JL, Diamond RE (2019) *The Karst Vadose Zone: Influence on Recharge, Vulnerability and Surface Stability*. TT 779/19. Water Research Commission. Pretoria. ISBN 978-0-6392-0080-4
- Dippenaar MA, Olivier J, Lorentz S, Ubomba-Jaswa E, Abia ALK, Diamond RE (2018) *Environmental Risk Assessment, Monitoring and Management of Cemeteries*. 2449/18/1. Water Research Commission. Pretoria. ISBN 978-1-4312-0978-1
- Jones BR, Van Rooy JL, Dippenaar MA, Roux JI (2016) *Advances in the Understanding of Variably Saturated Fracture Flow*. 2326/16/1. Water Research Commission. Pretoria. ISBN 978-1-4312-0794-7.
- Dippenaar MA, Van Rooy JL, Breedts N, Huisamen A., Muravha SE, Mahlangu S, Mulders JA (2014) *Vadose Zone Hydrology: Concepts and Techniques*. Water Research Commission. ISBN 978-1-4312-0507-3.

These have gradually increased knowledge on the behaviour of the shallow subsurface under highly variable moisture contents. During these projects, intergranular, fractured, and karstic media were considered, as well as the complexity resulting when multiple of these coexist. Under further anthropogenic change with altered moisture budgets and potential water quality changes, the last projects addressed altering permeabilities of the shallow subsurface through changing land use (e.g., cemeteries; permeable pavements).

This report is divided into two parts. The first part contains the necessary literature to build upon previous projects. The second part presents the findings and results of the current study, demonstrating the impacts of these changes on the shallow subsurface.

### 1.4 EXPECTED OUTCOMES

Case studies will be used to address the project aims, and they will focus on the complex and anthropogenic effects. Case studies will be presented concisely and focused to ensure that they, like this book, can be easily comprehended and used by a wide variety of professions and decision-makers.

The main outcomes are to provide and contribute to novel methodology, classification, and understanding of these urban altered systems. These outcomes will be implemented in the decision-making process to ensure that local and international parties can use this to monitor, manage, and mitigate the risks associated with urbanisation and human impacts on the natural environment.

It is hoped that this document will be user-friendly and relevant to various entities that include professionals from different disciplines, government officials from various departments, educators and researchers mostly in the tertiary environments, environmental practitioners, and the general public that are involved in these matters.

International terminology is standardised with a number of terms and concepts. A borehole is a hole bored or drilled in any orientation, typically using rotary percussion drilling or means to remove core from the bedrock. These are drilled and can be backfilled following inspection (e.g., to identify the variable behaviour of soluble rock like limestone and dolomite), or they can be equipped for the purposes of using or monitoring. A well here

is used specifically in context of boreholes that are used for monitoring, and those that are combined in wellfields. In normal context a well refers to an open hole with water inside that can be hand-dug or opened by other means.

## CHAPTER 2: SOLID AND FLUID PRINCIPLES

The literature will be completed based on the existing case studies. No theory and results from preceding reports and books will be repeated. This should be considered a sequel to Dippenaar et al. (2022) titled *The Vadose Zone: From Theory to Practise* (WRC report no. TT 869/21).

### 2.1 WATER CYCLE INTERACTIONS

The distribution and movement of water from precipitation to land surface and through the crust is shown in Figure 2-1. Classical water budgets are considered as follows:

- Precipitation (P) is all (100%) of the input into a catchment, and in South Africa this is predominantly in the form of rain that falls onto the land surface, surface water bodies, ocean, and all manmade infrastructure.
- Evapotranspiration (ET) includes evaporation (E) and transpiration (T) because the two cannot be separated in measurements and therefore this loss includes all water returning to the atmosphere from liquid form to gas form.
- Runoff (R) is the surficial transport of water by means of streams, rivers, and manmade canals, removing the precipitation downstream from the original source of precipitation into other catchments.
- Infiltration (I) is all the water that enters the subsurface and moves into the vadose zone that has passed the influence of transpiration (plant root) and is therefore able to move further into the vadose zone.
- Change in storage ( $\Delta S$ ) refers to all the water moving through the intermediate vadose zone and contributing to fluctuations in the groundwater level or piezometric heads and moving through the system as interflow, throughflow and baseflow.

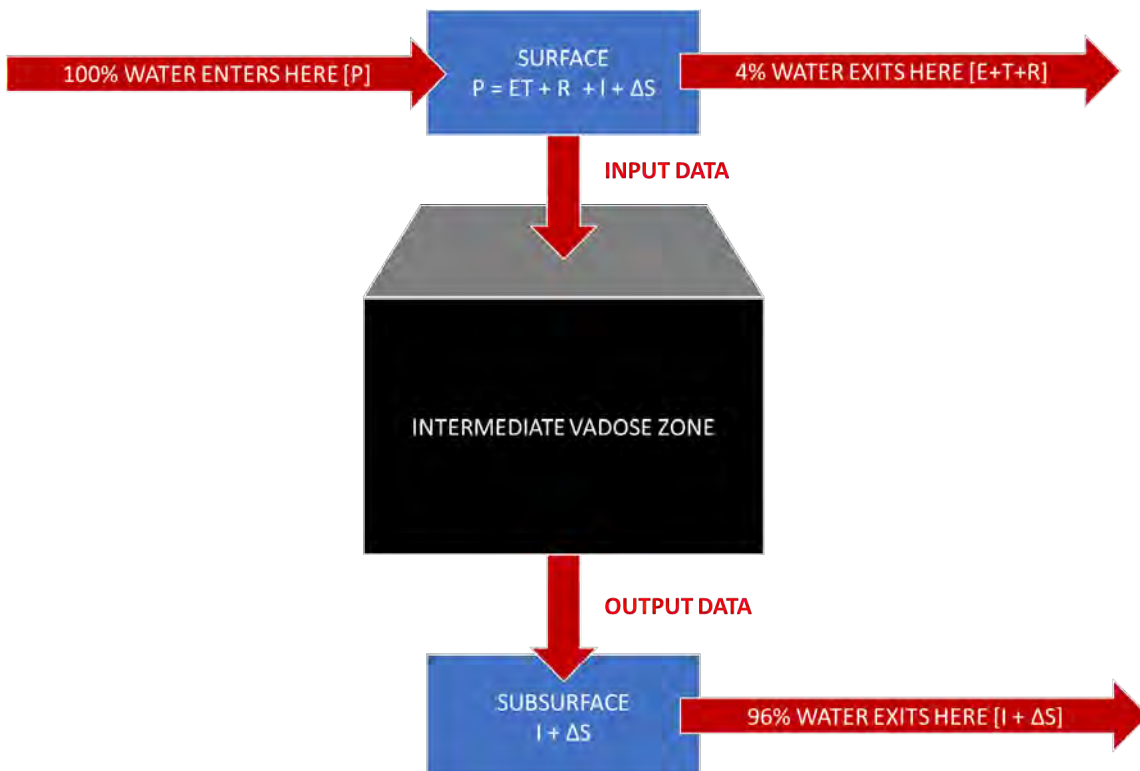


Figure 2-1 The intermediate vadose zone is a black box of knowing what enters from infiltration and what exits as groundwater recharge (Dippenaar 2023).

## 2.2 ROCK WEATHERING AND SOIL FORMATION

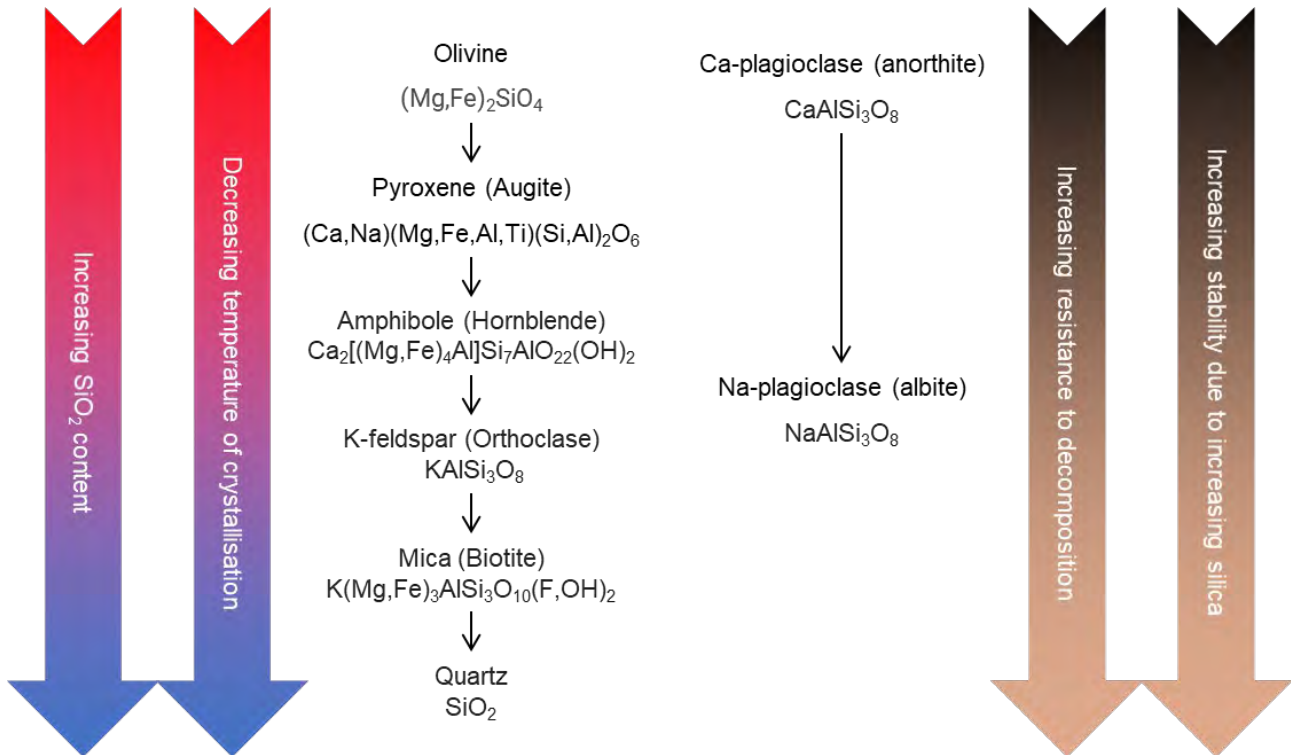
### 2.2.1 Formation of residuum and completely weathered rock

The basic weathering profile is best described by soil scientists' concept of the soil pedon. The weathering profile is divided into defined horizons based on the extent and type of pedogenic processes which generally exist parallel to the soil surface (Shaw 1927). The upper portion of the soil profile is known as the solum and includes all horizons altered or formed from pedogenic processes. The solum lies on top of the C horizon, which is designated as the transition layer between the solum and fresh bedrock and includes completely weathered bedrock and residual soil. Kellogg (1930) defined the C horizon as *parent material that has been unaltered by soil-building forces*. However, for the bedrock to weather and alter via various chemical reactions, rainwater must infiltrate and percolate through the surface soils and flow into and through the bedrock. This percolated water will most certainly have solids and solutes, picked up in the atmosphere and surface soils, which will essentially alter the parent bedrock through illuviation and other pedogenic processes. For this reason, defining the upper boundary of the completely weathered bedrock from chemical observations alone may be challenging. The idea of a D horizon exists, and it represents the lower, completely unaltered, weathered bedrock, while the C horizon includes the upper, slightly influenced by pedological formations and alterations in volume (Kellogg 1936; Schaetzl and Anderson 2005). Geologists and geotechnical engineers tend to focus on the macro structure characteristics during logging and will often refer to the C and D horizons as a singular completely weathered rock horizon.

The residuum, which includes highly and completely weathered rock and residual soil, forms by weathering via physical, chemical and biological processes (Blight and Leong 2012). Initially, physical processes mechanically disintegrate bedrock, which increases the rock mass permeability and rock surface area to allow for increased flow and interaction with slightly acidic rainwater or percolated water. Chemical weathering alters rock minerals through hydration, hydrolysis (silicate weathering), carbonation, dissolution, cation exchange and oxidation, forming clay minerals with lower energy states (Mitchell and Soga 2005). Rock minerals are not equally susceptible to chemical breakdown and mineralogic change. Typically, the minerals that form at the highest temperature, meaning the first minerals to form during cooling of magma and forming igneous rocks, are the least stable at low temperature at the ground surface (Bowen 1929; Goldich 1938). The resultant secondary minerals present in the completely weathered rock and residual soils are further influenced by the intensity to which the weathering has occurred.

Some common minerals making up common metamorphic rocks, including gneiss (various felsic pseudo-granitic compositions), and plagioclase, have a series of minerals and these include only the end-members. The igneous minerals crystallised according to Bowen's Reaction series, and that same series was used to compile Goldich's weathering series, seeing that pure quartz ( $\text{SiO}_2$ ) is the last mineral prone to any decomposition (chemical weathering  $\text{SiO}_2$ ), which is evident by it being by far the most common mineral in both beach sands and aeolian (desert) sands. This is shown in Figure 2-2.

The quantity of weathered material adjacent to joints does, in fact, not need to be significantly large to have a major influence on the geotechnical properties of a rock or rock mass (Hack 2020). Weathering of rock masses is mainly focused along fractures and other discontinuities present within the rock mass, predominantly due to fluid flow. Discontinuities present in rock masses have a significant influence on the engineering behaviour of a rock mass (Bell, 1992b), thus resulting in the necessity to study and understand the changes caused by weathering along these discontinuities (Ismail et al., 2019).



**Figure 2-2 Bowen's reaction series crystallising minerals (common examples are given in brackets), with Goldich's weathering sequences on the right.**

Initially, physical processes mechanically alter the bedrock, which increases the rock mass permeability and rock surface area to allow for increased flow and interaction with slightly acidic rainwater or percolating water. Chemical weathering alters rock minerals through hydration, hydrolysis (silicate weathering), carbonation, dissolution, cation exchange and oxidation, forming clay minerals with lower energy states (Mitchell and Soga, 2005). For many of the secondary minerals to form, certain ions that are liberated out of the primary mineral crystal structure need to be removed from the profile, either through leaching or taken up by plants. For this reason, well-developed weathering bedrock profiles are commonly free-draining and located on the upper to mid-slopes of a conventional valley cross-section.

The resultant macrostructure, porosity distribution and chemical constituents are dependent on the parent rock characteristics, long-term climate conditions and trends, local vegetation and bioturbation, and regional topography. All the factors contribute to the type and intensity of weathering that occurs. However, deeply weathered, chemically altered profiles can only occur in humid, tropical to subtropical climates with high rainfall.

Saprolite, which includes the highly weathered and completely weathered rock, is a mixture of secondary clays, hydroxides formed during physical and chemical weathering, and primary rock-forming minerals which have survived the chemical decomposition thus far. The presence of the relict rock structure and unique mineral occurrences can have an unexpected impact on the hydromechanical behaviour of the material (Wesley 1990; Swart et al. 2019). This behaviour does not usually conform to simple index classifications which are based on well-sorted and highly weathered, transported soils.

Examples of rare minerals that are frequently found in weathering products, namely wad, from Mn-rich dolomite are (Swart et al. 2019):

- Birnessite:  $(\text{Na,Mg,Ca,Mn}^{2+})\text{Mn}_7\text{O}_{14}$
- Lithiophorite:  $(\text{Al, Li})\text{MnO}_2(\text{OH})_2$
- Todorokite:  $(\text{Na, Ca, K, Ba, Mn}^{2+})_2\text{Mn}_5\text{O}_{12} \cdot 3\text{H}_2\text{O}$
- Plagioclase albite end member is predominant:  $\text{NaAlSi}_3\text{O}_8$
- Plagioclase anorthosite end member is absent to minor:  $\text{CaAl}_2\text{Si}_2\text{O}_8$

- Orthoclase and microcline:  $KAlSi_3O_8$
- Quartz and chert:  $SiO_2$
- Biotite:  $K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$ .

The more mafic igneous compositions that include gabbro and norite include the following minerals:

- Olivine:  $(Mg, Fe)2SiO_4$
- Clinopyroxene:  $Ca(Mg,Fe)Si_2O_6$
- Orthopyroxene  $(Mg,Fe,Ca)(Mg,Fe,Al)(Si,Al)_2O_6$
- Plagioclase anorthosite end member is abundant:  $CaAl_2Si_2O_8$
- Plagioclase albite end member is absent to minor:  $NaAlSi_3O_8$ .

The weathering of silicate minerals results in the addition of cations and silica to the water chemistry. The weathering reactions of albite, anorthite, microcline and biotite to kaolinite are per Equation 1 to Equation 4 (Appelo & Postma, 2005).

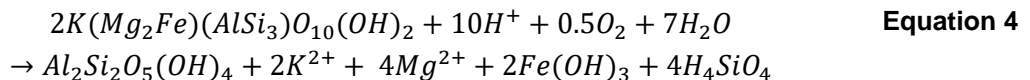
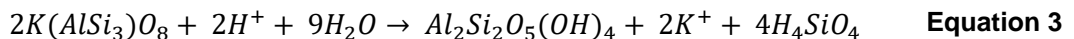
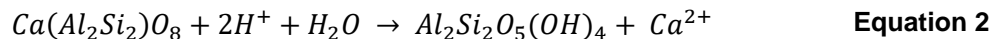
Some common minerals making up common metamorphic rocks, including gneiss (various felsic pseudo-granitic compositions), and plagioclase, have a series of minerals, and these include only the end-members:

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- Orthoclase and microcline:  $KAlSi_3O_8$
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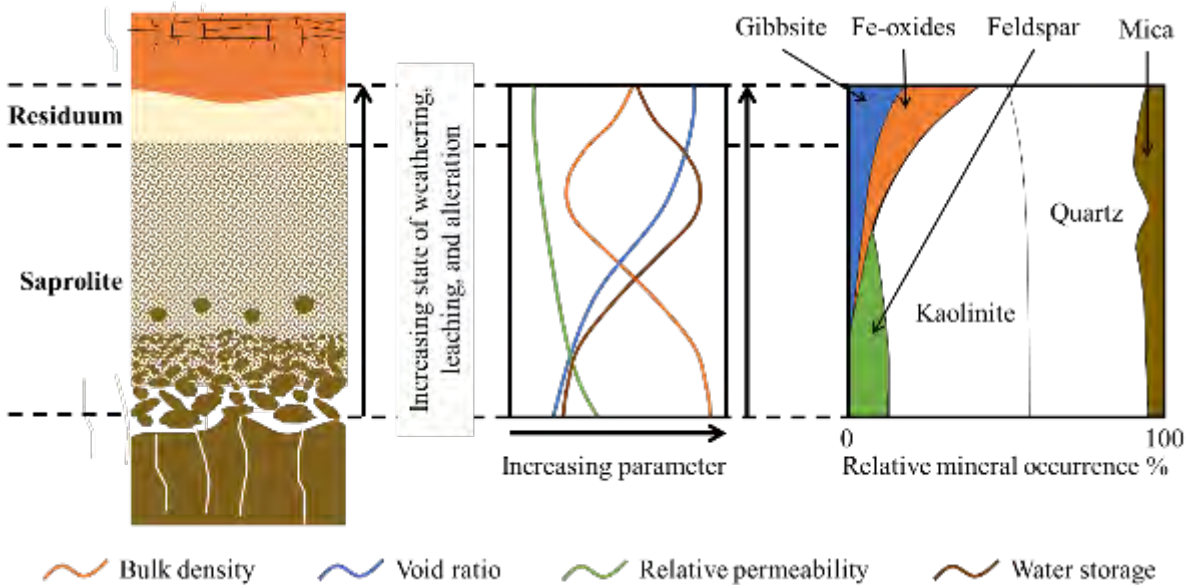


### 2.2.2 Weathering Profile

The basic weathering profile is best described by a soil scientist's concept of the soil pedon. The weathering profile is divided in defined horizons based on the extent and type of pedogenic processes which generally exist parallel to the soil surface (Shaw, 1927). The upper portion of the soil profile is known as the solum and includes all horizons altered or formed from pedogenic processes (Kellogg, 1930). The solum lies on top of

the C horizon, which is designated as the transition layer between the solum and bedrock (Schaetzl & Anderson, 2005). Geologists and geotechnical engineers will often refer to the C and D horizons as completely weathered rock or extremely weak rock.

Like most natural material in geology, the behaviour of a material is dependent on its formation and stress history. Weathering is most intense at the surface and along joints and decreases with an increase in depth and reduction in jointing. This will usually result in a typical sequence of mineral occurrences with depth, as shown in Figure 2-3. The mineral which forms at a certain depth within a profile is dependent on the composition of the pore water, mineralogy of the parent rock, intensity of leaching and prevailing Eh-pH conditions at that depth (Summerfield, 2013).



**Figure 2-3 The structural and chemical profiles formed in weathered intermediate igneous saprolite.**

Rock minerals are not equally susceptible to chemical breakdown and mineralogic change. Typically, the minerals that form at the highest temperature, meaning the first minerals to form during cooling of magma forming igneous rocks, are the least stable at low temperatures at the Earth's surface. An example of this is olivine-rich and calcium-rich plagioclase, which are the highest-temperature forming minerals on Bowen's reaction series (Bowen, 1929). Similarly, the mineral to form at the lowest temperature, which is quartz, is the most stable on the Earth's surface in the series. This is shown by Goldich's (1938) mineral stability series.

This vertical distribution in chemical compositions and degree of weathering will form various structural profiles, as presented in Figure 2-3. Chemical loss and volumetric strain result in a general increase in void ratio and decrease in bulk density as weathering increases (Hencher 2012; Hayes et al. 2019; Riebe et al. 2021). The stiffness provided by the surviving relict rock structure and high porosity allows the completely weathered rock to achieve a large water storage capacity relative to the rest of the materials in the weathering profile (Kresic, 2023). Consequently, this completely weathered rock zone influences groundwater recharge and return flow, impacting the quantity and quality of surface and sub-surface waters (National Research Council, 2001; Dippenaar et al., 2022). The volumetric strain during weathering will generally increase the volume of the completely weathered rock, whereby narrowing and warping relict joints and fractures. Any open flow paths will clog due to infill forming through illuviation or sidewall erosion. These processes will decrease the relative permeability as weathering increases.

## 2.3 UNSATURATED FLOW IN FRACTURED ROCK

The subsurface flow of fluids through rock formations is an interdisciplinary subject closely linked with various scientific and engineering domains. These encompass hydrogeology, rock mechanics, geotechnical engineering, and earth resources engineering (Berkowitz, 2002; Neuman, 2005; Meakin and Tartakovsky, 2009; Chen et al., 2014a; Lei et al., 2017). The formation and alteration of fractures within rocks are influenced by numerous factors, including lithostatic, tectonic, and thermal stresses, elevated fluid pressures, and fluid-induced erosion (Brown, 1995; Chen et al., 2018a; Frash et al., 2019; McBeck et al., 2019; Yang et al., 2019a). Consequently, fractures are pervasive in subsurface rock formations, manifesting across various spatial scales, from the microscopic to the continental (National Research Council, 1996). A fundamental grasp of the mechanisms governing unsaturated flow in fractured rocks across altered scales serves as an essential prerequisite for forecasting and managing seepage-related issues, as well as ensuring the safety and stability of various geotechnical applications. Fractures within the vadose zone play a pivotal role in expediting the transport of contaminants into groundwater systems, creating preferential flow pathways that significantly reduce contaminant residence times in comparison to conventional models of uniform fracture flow (Su et al., 2001).

The complexities of vadose zone flow and transport within fractured rock stem from nonlinear and hysteresis-driven processes, driven by intricate fracture-matrix interactions and hydraulic property disparities between fractures and the matrix (Nimmo, 2009). The spatial distribution of fluid flow in the vadose zone hinges on the interplay between gravitational forces, which induce downward water movement, and capillary forces, which retain water within pores. Capillary forces inversely correlate with pore size, and the inherent heterogeneity of rock pore structures governs the distribution and motion of water in partially saturated formations. Various modelling approaches have been developed for unsaturated fractured rock systems (Bear et al., 2012; National Research Council, 1996), revealing that a significant portion of unsaturated-zone transport occurs exclusively through a limited fraction of the medium, characterised by preferential flow modes such as macropore, fingered, and funnelled flow (Nimmo, 2009).

The equivalent-medium approach quantifies preferential flow by approximating the effective hydraulic properties of a complex medium, including preferential pathways, with those of a hypothetical homogeneous granular porous medium. This simplification allows us to apply existing theories and models for diffuse flow. For macropores behaving like tubes, the cubic law representation is often used, treating macropores as parallel plates. Fractures can significantly impact fluid flow in geological systems, providing preferential pathways. In a Danish quarry, infrared thermography (IRT) and fracture analysis were employed to assess preferential flow in hydraulically active fractured cretaceous chalk. The fracture system consisted of horizontal and four sets of vertical fractures. Staining with  $\text{Fe}^{3+}$  and Mn was primarily observed in fractures with strikes of approximately  $25^\circ$  and  $175^\circ$ , indicating that these extensional and shear fractures were the main groundwater-controlling pathways. This conclusion was supported by IRT surveys of quarry walls and injection well test data using temperature contrasts between groundwater ( $\approx 8^\circ\text{C}$ ) and wall surface temperatures on cold winter and hot summer mornings.

### 2.3.1 Characteristics of partially saturated media

In fractured rock formations, fractures can be considered as either conduits or barriers to groundwater flow (Bear et al., 2012). In the saturated zone, water tends to move rapidly along fractures. However, for a fractured unit situated in the vadose zone above the water table, the fractures (with apertures larger relative to the size of the pores in the matrix) should be dry, and the bulk of the groundwater movement should be through interconnected pores in the matrix. Under such conditions, as water moves from one matrix block to another, the drained portions of the fractures will essentially reduce the effective area for water flow from one matrix block to another matrix block (Wang and Narasimhan, 1985). It is well established in the field of soil physics that in partially saturated porous media, the fluid pressure in the water phase is less than atmospheric pressure

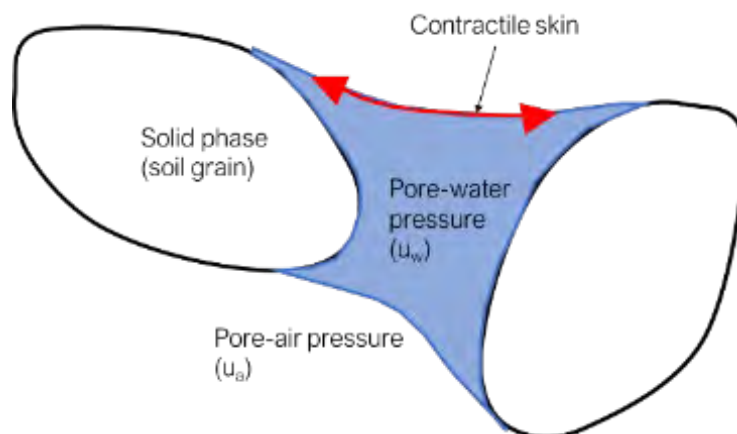
and that the fluid saturation in the porous medium is a strong function of the water phase pressure. The relation between fluid pressure and saturation is governed by surface tension between the liquid and the solid phases and by the effective capillary radii of the pores. Indeed, it is accepted knowledge that as the water phase pressure in the porous medium is decreased below atmospheric pressure, the largest pores will desaturate first, followed by the desaturation of successively smaller pores.

Within a fracture that is partially saturated, the presence of a relatively continuous air phase will produce an almost infinite resistance to liquid flow in a direction parallel to the fracture. Therefore, as the fracture begins to desaturate, its effective hydraulic conductivity will decline abruptly by several orders of magnitude. It is thus reasonable to expect that during fracture desaturation the effective hydraulic conductivity of the fractures will rapidly become smaller than that of the porous matrix, which needs fairly large capillary pressures to initiate desaturation (Wang and Narasimhan, 1992). An interesting consequence of this dramatic reduction in fracture permeability is that water will tend to flow across fractures from one matrix block to another instead of flowing along the fractures.

## 2.4 UNSATURATED FLOW IN SOIL

### 2.4.1 Matric suction

Saturated soil mechanics is a two-phase system that deals with soil that has one fluid phase, generally water, with positive pore-water pressures, and one solid phase, the soil matrix. The Principle of Effective Stress, as presented by Terzaghi (1943), is used to describe forces transmitted through the soil skeleton in fully saturated soils only. The fundamental difference between saturated and unsaturated soil mechanics is the presence of air pore spaces and the contractile skin (Fredlund and Morgenstern, 1977; Fredlund et al., 2012). Terzaghi (1943) emphasised the significant role of the air-water interface in the understanding of unsaturated soil behaviour. The four phases forming unsaturated soils and the relationship between them are shown in Figure 2-4.

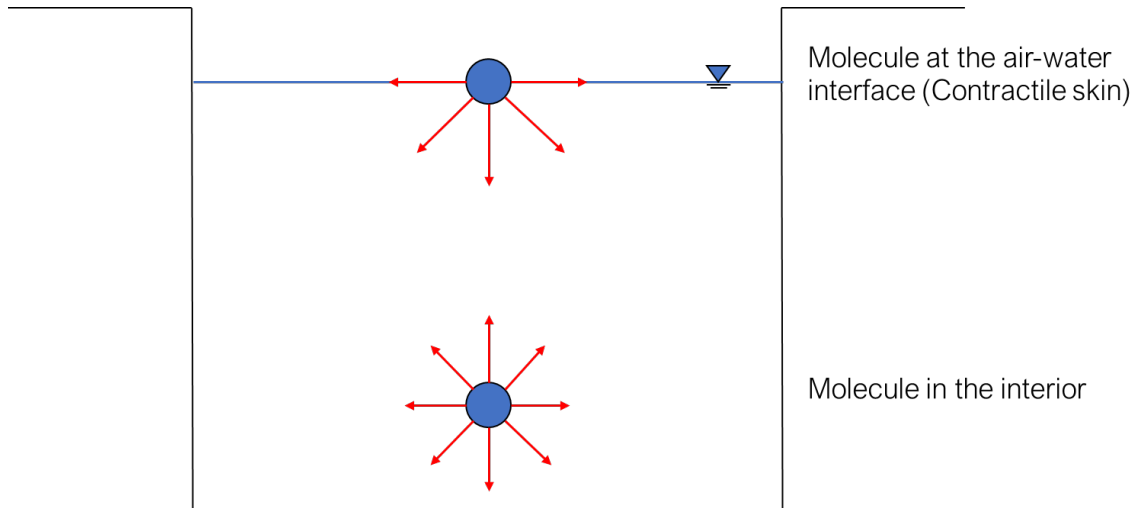


**Figure 2-4 Components of unsaturated soils.**

The contractile skin at the air-water interface acts as a thin membrane interwoven throughout the voids of the soil. The presence of this thin partition can cause an unsaturated soil to change volume, water content and shear strength when the stress state changes in the contractile skin. Surface tension acts along the air-water interface and matric suction acts across the interface due to the pressure differences ( $u_a - u_w$ ) (Figure 2-4) (Fredlund et al. 2012).

Surface tension is tangential to the contractile skin and is measured as a tensile force per unit length of contractile skin (i.e., units of N/m) (Fredlund et al., 2012). Surface tension manifests from intermolecular forces

acting on the molecules in the contractile skin. These forces are different from the forces experienced by molecules in the interior. The molecules in the interior of a fluid experience both attractive and repulsive forces of equal magnitude in all directions. The intermolecular forces act to stabilise the system through interaction between near neighbouring molecules that results in a reduction of their potential energy. These interactions give rise to cohesion among molecules in a fluid and adhesion or adsorption between molecules of that liquid and any bounding solid surface. A water molecule in the contractile skin experiences unbalanced forces toward the interior of the water mass, as shown in Figure 2-5.



**Figure 2-5 Intermolecular forces acting on contractile skin at the air-water interface (adapted from Fredlund et al., 2012).**

#### 2.4.2 Movement of moisture in unsaturated soil

The theories of fluid flow through moisture are primarily based on saturated material occurring in the phreatic zone. Darcy's Law is still applicable for flow of moisture through unsaturated material in the vadose zone. The hydrology of the vadose zone has been intensely investigated, with authors describing various flow mechanisms in a soil region where pore pressures are lower than atmospheric and the system is governed by forces of capillarity and gravity (Lu & Likos, 2004; Fredlund et al., 2012; Dippenaar et al 2022).

The behaviour of water flow through unsaturated soil can be summed up by: *water can only flow where there is water*. In a saturated medium, effective porosity is the portion of total porosity that can transmit water. In a partially saturated medium, the available pore space contributing to flow is reduced as the moisture content is reduced.

Hydraulic conductivity in unsaturated soils is dependent on the fluid properties, the material attributes (pore structure and geometry), and the relative degree of saturation present in the pore openings. The variability of flow in unsaturated soils is also a function of the initial water content prior to an alteration of moisture conditions in the system. In other words, unsaturated hydraulic conductivity exhibits hysteresis. The SWRC exhibits hysteresis, and since the hydraulic conductivity is a function of matric suction, it will follow the same trend (Lu & Likos, 2004). The hydraulic conductivity is greater along the primary drying curve compared to along the primary wetting curve at the same degree of saturation.

The permeability of a completely weathered igneous rock is generally low and similar to a silt or clay within the matrix, and it is low but variable along the relict rock structure. The secondary/structural porosity, namely fractures that persist from the original rock structure and fissures which formed during weathering, are usually the preferred flow paths for moisture movement (Talib et al. 2015). However, this flow will not behave as an

open fracture in competent rock and will depend on the porosity distribution, geometry and connectivity. Completely weathered rock is expected to be a dual porosity system with a high matrix/primary porosity and a low to high secondary porosity (Van der Hoven et al., 2003). The presence of double porosity within the weathering profile becomes increasingly important to recognise at lower moisture contents as the flow through finer pores in the matrix may dominate over the larger pores existing in the secondary/structural porosity.

## CHAPTER 3: URBANISATION AND URBAN WATER

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Urban space is defined differently, with terminology being inconsistent in different countries. In the following countries it is based on populations (inhabitants) and population densities in locations as follows (UN Demographic Yearbook (unless noted otherwise) all in McGrane 2016):

- Australia: populations > 1 000; densities > 200 people/km<sup>2</sup> (Australian Bureau of Statistics)
- Canada: population ≥ 1 000; densities ≥ 400 people/km<sup>2</sup>
- Greenland: population ≥ 200
- India: population ≥ 5 000 (≥ 75% employed in non-agricultural industry); density ≥ 400 people/km<sup>2</sup> (Census of India 2011)
- Ivory Coast: population > 10 000 (4 000 employed in non-agricultural industry)
- Japan: population ≥ 50 000; ≥ 60% houses in the main built-up area
- Peru: populated centres ≥ 100 dwellings
- Republic of Ireland: suburbs (in cities and towns) with ≥ 1 500 dwellings
- Spain: population ≥ 2 000
- Turkey: population of settlement places ≥ 20 001
- United Kingdom: England: population ≥ 10 000 (ONS 2004)
- United Kingdom: Northern Ireland: Derry and Belfast are the only urban areas differentiated from large towns (NSRA 2005)
- United Kingdom: Scotland: population ≥ 3 000 (simplest definition) (Scottish Government 2012)
- United Kingdom: Wales: population ≥ 10 000 (ONS 2004)
- Venezuela: population ≥ 1 000
- Zambia: population ≥ 5 000; majority dependent on non-agricultural activities.

Two of the countries in the provided examples are not dependent on populations or population densities (UN Demographic Yearbook in McGrane 2016):

- Brazil: urban and suburban zones within the administrative centres of districts and municipalities
- South Africa: places with some form of local authority.

Challenges related to the urban water cycle include a few aspects. Precipitation forecasting prediction should be quantified in terms of the impact that urban areas have on climate dynamics. Evapotranspiration rates due to urbanisation require an empirical method to determine the urban water balance, seeing that evapotranspiration is used more as a part of managing stormwater fluxes. Infiltration rates. Infiltration rates across pervious and impervious urban areas are poorly understood and the assumptions are invalid. The engineered water cycle is poorly determined and leaky infrastructure can lead to up to 40% of urban recharge. Pervious and impervious areas have interconnected dynamics that cause a complex, poorly understood response to the rainfall-runoff transformation. Various contaminants that are harmful to aquatic ecosystems and humans are sourced from urban surfaces, where spatial and temporal patterns of the contaminant fluxes into the urban rivers should be understood. Different pollutants can be distinguished by associating different pollutants with specific land uses (McGrane 2016).

### 3.1 GLOBAL POPULATION

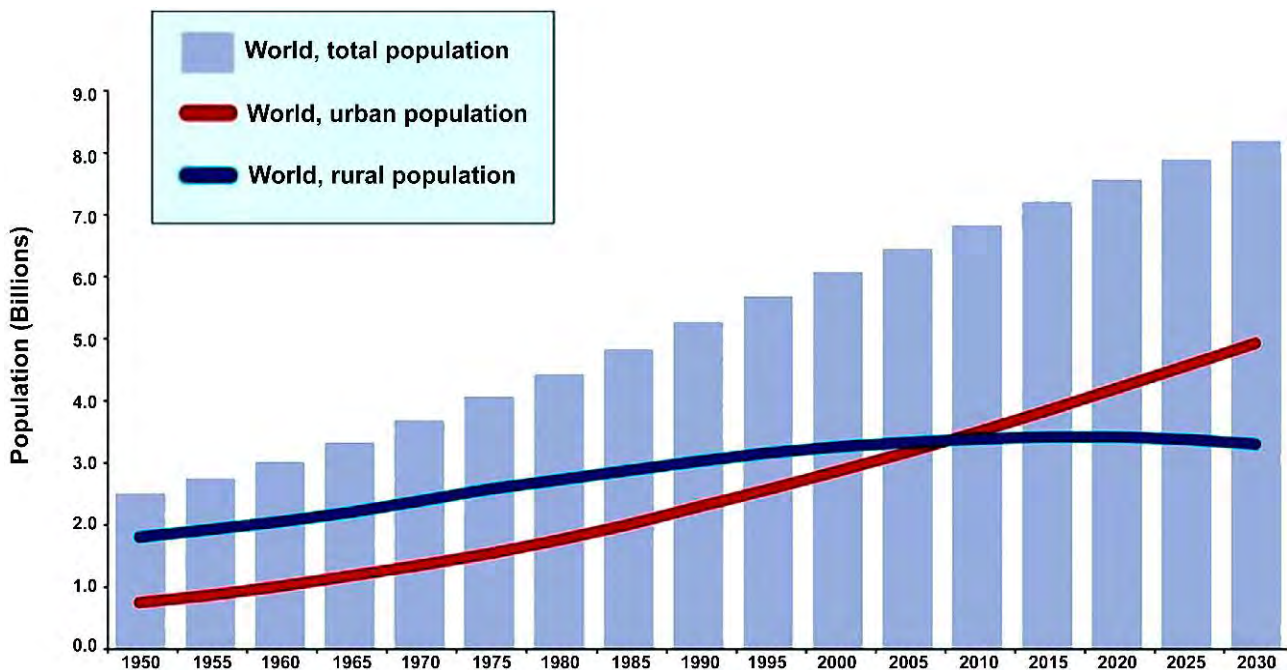
The world population is growing and the predominant growth is in urban areas, with over 50% of the world's population living in urban areas in 2010 and anticipated to reach around 60% by 2023, with a global population of about 8.2 billion. Given the birth rate that exceeds the death rate, the growth rate is increasing. In addition, there is a significant increase in migration of rural inhabitants to cities because they are either (Howard 2023):

- (1) Compelled to move due to environmental crises and political conflicts (World Water Assessment Programme 2009), or

(2) Moving with the hope to find work, alleviate poverty, and to improve living conditions.

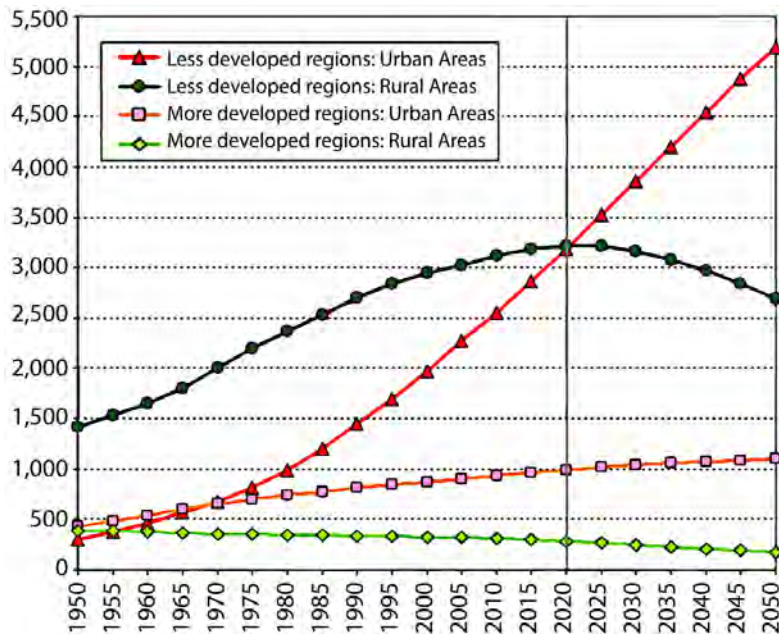
Urbanisation is rapidly increasing worldwide. The impact of this urbanisation on the natural environment mostly relates to the utilisation or degradation of Earth and water resources through construction, abstraction, and influences on its integrity and quality. South Africa is not special in this regard, and the environmental cost of our urbanisation is further exacerbated by our largest urban nodes situated on regional water divides (e.g. Gauteng), in semi-arid regions (e.g. Cape Town; Polokwane; Mangaung), or surrounded by large-scale industry and mining operations, with substantial historical and present-day environmental impacts (e.g. Gauteng; eThekweni; Cape Town). There are also concentrated informal settlements on the urban edge and peri-urban environments without any water reticulation services, contributing directly to polluted runoff and indirect recharge.

Figure 3-1 and Figure 3-2 show these changes and growth in global population for the urban and rural population, and developed and undeveloped urban and rural developments respectively.



**Figure 3-1 The urban and rural world population from 1950 to 2030 (modified from the United Nations, 2006 in Howard 2023).**

Development of any kind affects the properties of the ground and the movement of water through the hydrological cycle. As development advances, becoming deeper, denser, and higher, the consequences become visible over larger spatial scales and over longer time periods. This implies that one has to plan for mitigation measures further away from these developments, as well as longer in the future. Mining, industrialisation, and urbanisation all form part of this, where the effects on notably the hydrological cycle become more permanent and adverse, coupled with the impacts of, for instance, more erratic and intense rainfall cycles.



**Figure 3-2 Urban and rural population change for more and less developed regions in the world (from United Nations, 2006 in Howard 2023).**

### 3.2 URBAN WATER CYCLE

Urbanisation is known to alter urban water cycles distinctly in terms of its quantity (through imports, leakages, construction altering flow paths) and quality (through contamination and reticulation of chlorinated water). This is well described (e.g. Attard et al. 2015; Lerner 2002; Vásquez-Suñe et al. 2005). Apart from the obvious influences on the phreatic zone (aquifer), changes in moisture content and water quality of the vadose (unsaturated) zone are becoming increasingly important in planning urban development. In addition, changes in climatic weather patterns influence rainfall intensity and seasonal distribution.

Surface water (streams and rivers) and groundwater (aquifers) have some very important differences that should be considered. Surface water is represented by long linear features with replenishment solely from upstream sources, and the resource usage is limited to being near river channels or requiring transport with pipelines. Rivers have limited storage and are prone to drought, with limited opportunity to manipulate the storage in the river’s natural confinement. There is an immediate downstream impact due to abstraction and a small impact on upstream riparian zones. Groundwater, on the other hand, comprises bulk 3-dimensional systems with replenishment from any or all possible directions. Aquifers bring the resource to the borehole’s length and show a slow response to replenishment. There is very large natural storage in aquifers, allowing net gain to be drawn over long time periods and a good resilience against drought. There is a significant opportunity to manipulate the storage in the aquifer body and abstraction impacts in all directions, manifesting slowly over years to decades. There is an equal impact on the upstream and the downstream riparian zones (Puri & Naser 2002 in Howard 2023).

In urban areas, large volumes of water are imported from other catchments (e.g. Lesotho Highlands to Gauteng), or groundwater contributes in part to the water supply mix. This affects local water cycles substantially through the import and subsequent discharge of enormous volumes of treated wastewater from urban settings into catchments previously not required to tolerate said flows. Coupled with this, non-revenue water losses of roughly 25% contribute to anthropogenic urban recharge of hundreds of millions of litres of chlorinated water in urban centres.

The statistics and distribution for South Africa are shown in Figure 3-3. Stormwater is increasingly being required to be attenuated on site, also contributing to anthropogenic urban recharge, or alternatively affecting urban runoff through overloading stormwater systems or diverting natural flow to manmade channels. Urban expansion into previously mined areas adds to the complexities of the urban water cycle. It should be noted that all the large red areas are sparsely populated compared to the cities and contain large areas of agriculture, and therefore those large amounts of water losses are insignificant compared to the water losses in the larger municipalities.

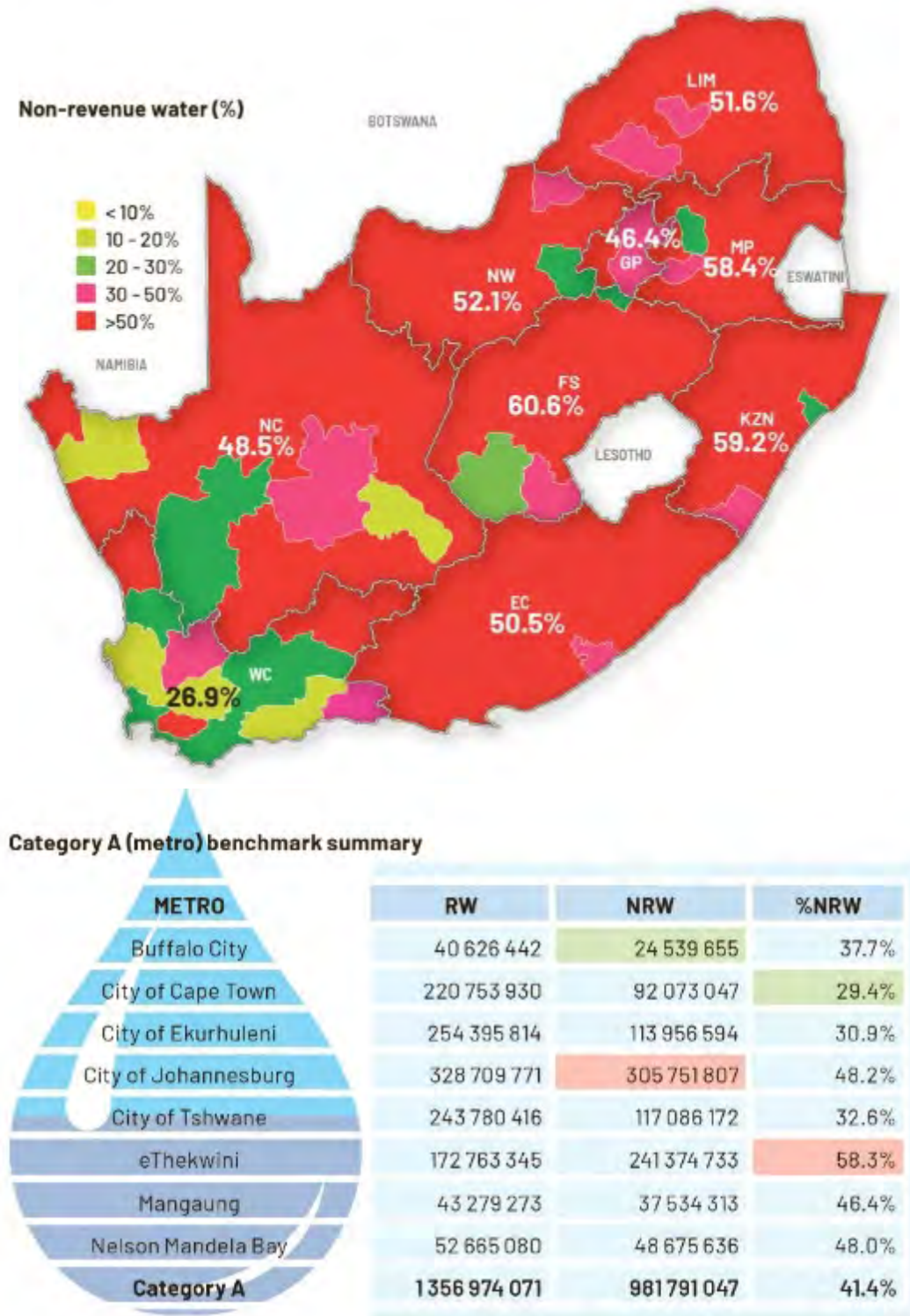


Figure 3-3 Non-revenue water (water losses) in South Africa (Daily Maverick 2024).

This highlights questions around the addition of substantial volumes of water of different quality to urban centres, and how this water is discharged into other catchments or anthropogenically released into the subsurface. Whereas stormwater systems can be designed, on-site attenuation of water is becoming increasingly important through advancing infiltration of runoff. The impacts of urban infiltration in terms of quality and quantity are rarely quantified.

Groundwater is preferred over surface water (e.g., dams, lakes, reservoirs, streams, rivers) because it is usually protected against contamination from the surface or shallow subsurface, rarely affected by climate change and drought, and can be brought with only one borehole at a time online to contribute to the city's increasing demands (with minimal upfront expenses) for private, municipal, and industrial use (adapted from Howard 2023). The role of groundwater in the development of a city is shown in Figure 3-4 (Howard, 2023).

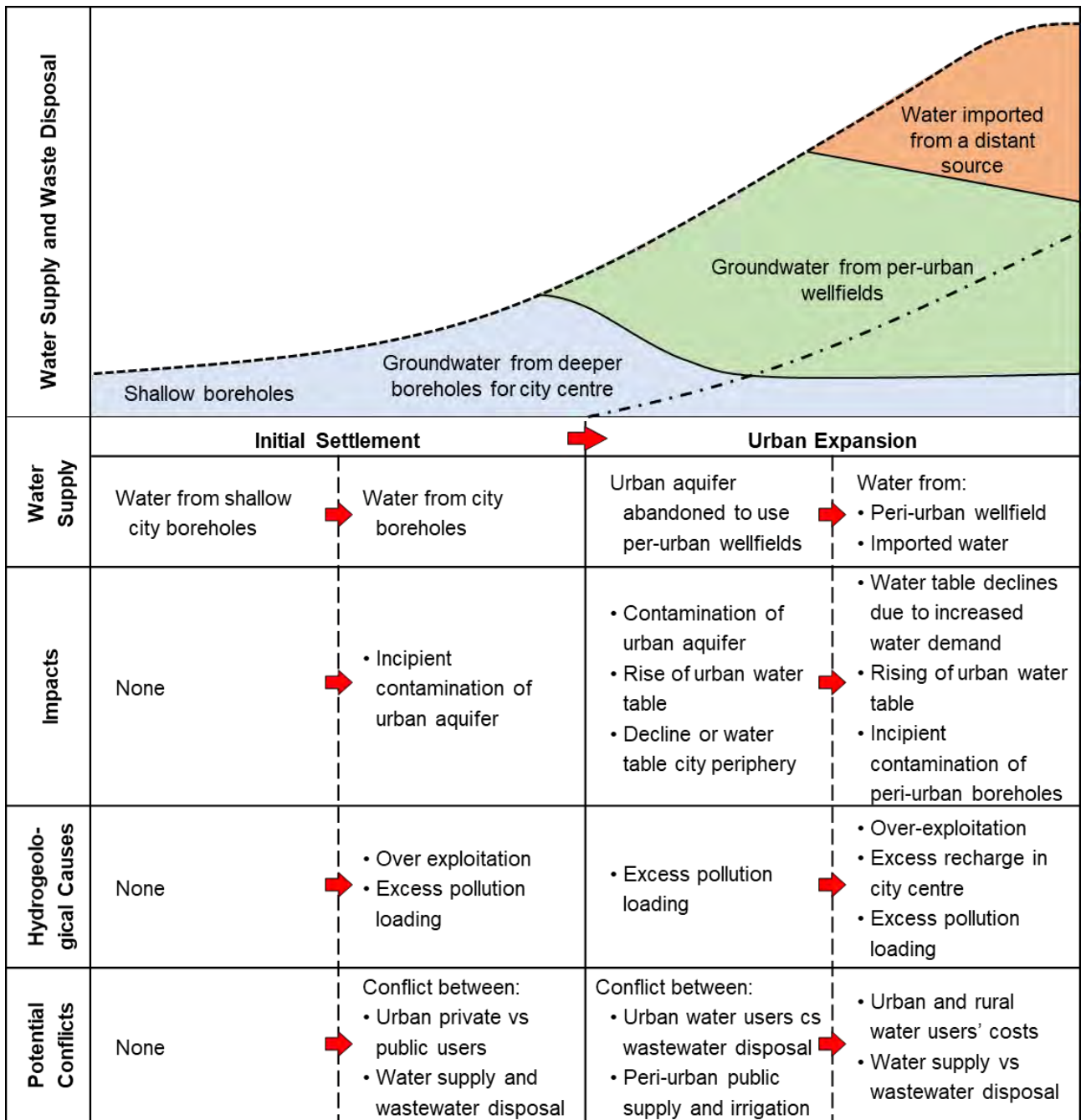
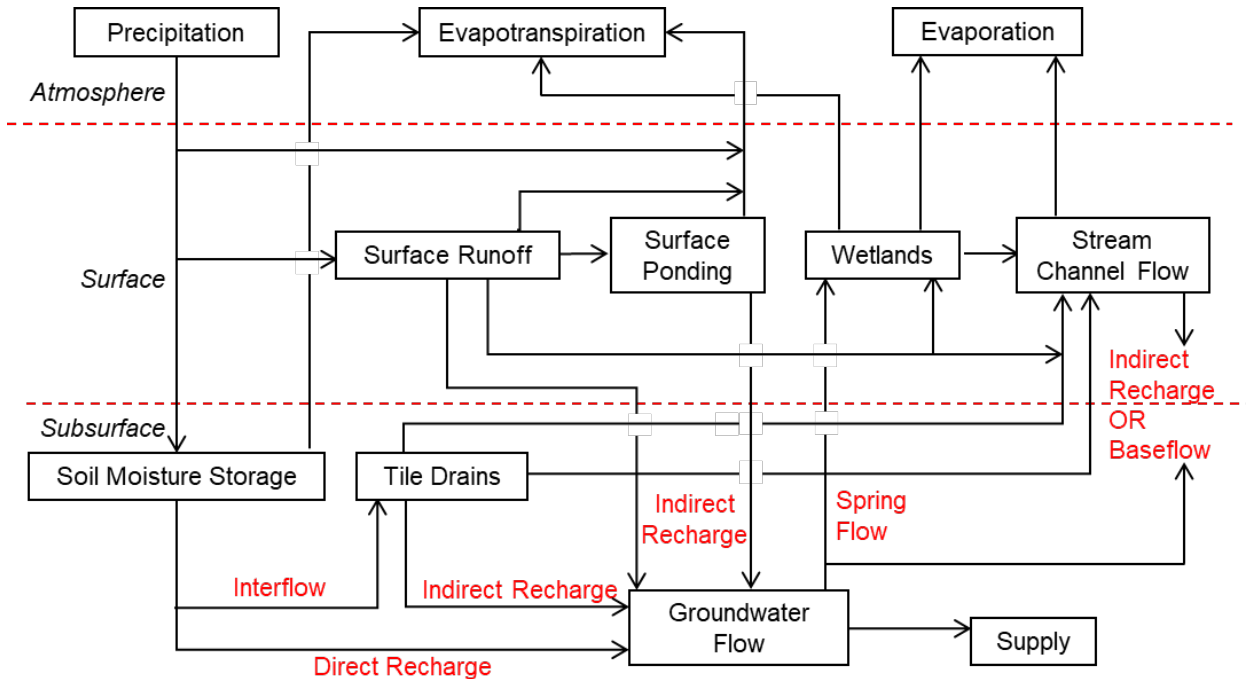


Figure 3-4 The role of groundwater in the evolution of a city (adapted and modified from Howard 2023)

The preferred water flow paths in urban areas are shown in Figure 3-5 and has two flow paths (Howard, 1997; 2023):

- Direct Recharge (Pathway 1) is the water infiltrating into the soil after arriving as incident precipitation, and this is the preferred route for precipitation falling on vegetated surfaces.
- Indirect Recharge (Pathway 2) normally occurs on vegetated swales, stream channels, and/ below shallow ponds following intense rain periods, and water infiltrates following runoff across the land surface.



**Figure 3-5 Preferred water flow paths in urban areas (adapted and modified from Howard, 1997).**

For direct recharge, the following happens per annum (Howard, 1997; 2023):

- Pre-urbanisation: for precipitation of 850 mm, evapotranspiration is 550 mm, surface runoff is 50 mm, and direct recharge is 250 mm.
- For annual precipitation of 875 mm, evapotranspiration is 375 mm, runoff to storm drains is 375 mm, and direct recharge is 125 mm.

Permeable pavements (Van Vuuren et al. 2022), water-sensitive design, and other urban interventions such as beneficial use of water abstracted from underground excavations such as basements and tunnels (Seyler et al, 2018), can all contribute to better urban water management. The same applies to industrial and mining developments, where the hydrological cycle is changed in space and over time in terms of both the flux and quality. Investigating certain fundamental questions related to these spatial and temporal variations in the hydrological cycle, coupled with altering the ground profile, can inform about the response of the hydrological cycle to certain developments during the life cycle.

This highlights the importance of hydrostratigraphy (the spatial distribution of strata with variable hydraulic properties; Diamond et al., 2019) and the overlay of a natural and anthropogenically altered water cycle on a natural and anthropogenically altered ground profile. In urban areas, karsts (soluble rocks with cavities) and impervious surfaces affect hydrogeology by altering the media, while changes in discharge through leaks, irrigation, and removal or abstraction affect hydrogeology in terms of fluxes. These changes have direct

implications beyond water availability and quality, influencing the likelihood of sinkhole formation and the resilience of urban environments to floods and droughts.

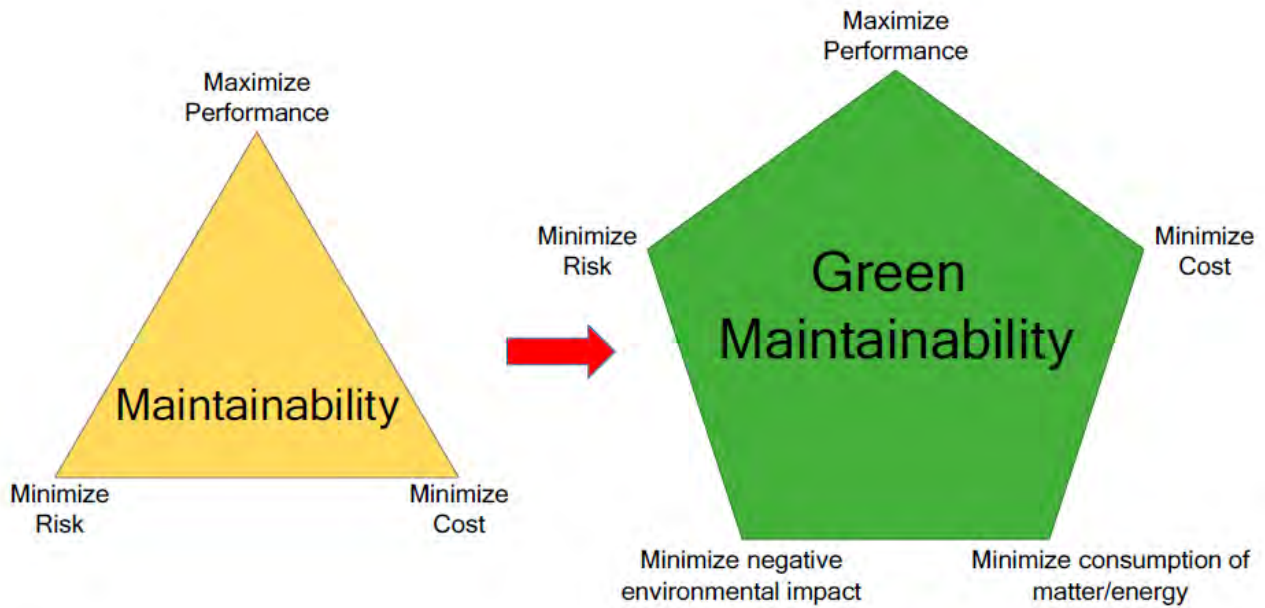
The role and importance of geologists and specifically hydrogeologists include the following (South African, from Dippenaar 2025):

1. The complexities of sites based on the materials making up the vadose and phreatic zones should be understood.
2. Groundwater should take precedence in all water-related decision-making because it is much more abundant and uncertain.
3. Groundwater monitoring is the basis of groundwater management, and aquifer classifications should be done broadly to be understood by everyone.
4. Qualified experienced hydrogeologists should do all the groundwater-related fieldwork to ensure that everything is scientifically sound and ethical.
5. Scientific data come first and foremost, and similar sites and conditions cannot be based on previous site investigations.

Extreme precipitation events in recent years cause many destruction events of structures and building because of water problems that include flooding and washout of basements and soil beds of roads. These disasters were mostly due to the strength decrease of sandy soils and sand-clays that pass from capillary water saturation into the flooded state (Smplyanitskii 2018).

A flooded soil is a soil that is water-saturated with water-filled pores, meaning that the capillary menisci are absent. Flooding of sands and light sand-clays causes the capillary water to be replaced by self-weight water, suspending the soil in it. Capillary forces disappear, and the mineral particles are pressed together in the transitions into the flooded or air-dry state. Flooding of a sandy soil causes the capillary menisci of the water to disappear as the soil strength decreases. For potentially landsliding slopes, more detailed engineering geological (geotechnical) investigations should be conducted on the texture and hydraulic conductivity (water-permeability) of soils up to the depth where sliding surfaces can possibly develop. This is to analyse the balance between water's surface drainage and its infiltration into the soil (Smplyanitskii 2018).

*"Maintainability* is defined as the ability to achieve the optimum performance throughout the lifespan of a facility within the minimum life cost." When combining considerations of sustainable design accompanied with efficient usage of resources and emphasising environmental consciousness and practices, it is termed *Green Maintainability* as shown in Figure 3-6. The lack of considerations during both the design and construction stages resulted in building defects accounting for billions of dollars throughout the building's lifecycle. Potentially unsafe conditions of buildings can negatively affect the users' lives and health (Chew 2021).



**Figure 3-6 Definitions of Maintainability and Green Maintainability (Chew 2021).**

Surface water is prone to pollution that can be transmitted rapidly downstream in the order of metres per second, possibly leaving the upstream unaffected. In groundwater, the pollutant is transported based on the local hydraulics, and the movement of pollutants is very slow, in the order of metres per annum, and an operating borehole may cause upward migration of the pollutant towards itself. Remediation following the pollution event is much easier and cheaper for surface water than groundwater, and in groundwater full remediation is rarely achieved (Puri & Naser 2002 in Howard 2023).

The sustainability of urban aquifers is based on efforts to control the activities that may threaten groundwater quality. Groundwater resource protection is important to do to maximise fresh groundwater availability and minimise groundwater degradation's extent. Standards of practice for groundwater protection aim to reduce groundwater degradation, and these are highly prescriptive while being easy to comply with and easily enforceable. Groundwater degradation is an inevitable consequence due to numerous activities. These activities place the responsibility on the entities that propose activities that can affect the groundwater quality to meet and maintain that target over time (Howard, 2023).

Wellhead protection areas should be delineated to allow, exclude, or strictly control certain high-risk activities, including (modified from Howard, 2023):

- Industrial sites
- Transport and storage of dangerous chemicals
- Buildings creating extensive impermeable areas
- Highways and roads
- Intensive agriculture (crop and livestock)
- Petroleum storage facilities
- Excavations such as pits and quarries
- Waste and waste water disposal sites.

From Howard (2023): "Urban development can radically change the water cycle and introduce new water balance components, many of which are not well quantified. From a groundwater perspective, urgent data needs for most cities include:

- Monthly or annual estimates of water withdrawals (municipal use, industrial use, private use, and groundwater removed for construction dewatering)

- Sewer exfiltration and infiltration rates
- Exfiltration and infiltration rates for rail and vehicle tunnels
- Leakage rates from pressurized water supply networks
- Water level and streamflow monitoring to assess inequities in the water balance and provide essential input to urban groundwater modelling
- Stormwater infiltration rates, especially where stormwater is managed by releasing excess surface water to the shallow subsurface, often with the assistance of purportedly green infrastructure.”

## CHAPTER 4: URBAN WATER-RELATED PROBLEMS

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### 4.1 SURFACE WATER FLOODING AND BUILDINGS

Flooding can occur due to a variety of causes that will differ between areas with different climate, topography, and population. This means that flooding can be due to natural precipitation events, those induced by the development of humanity, and a combination of these two. Development includes spatial change in terms of the materials, vegetation and topography, and vertical changes in terms of high-rise infrastructure and excavations into the subsurface and slopes for a variety of reasons. Buildings can be built with concrete that is made up of cement and sand that is often used together with steel and brick.

Surface water reaches the land surface through precipitation, the most general form being rainfall since it happens in liquid phase and that its intensity is variable. This reaches surface water and can then form drainage features such as streams and rivers that have different energies related to flow velocity and channel morphology, and also in terms of its quality that can result in pollution.

Water can enter buildings during a flood through various processes and parts of the construction. The natural permeability of masonry and mortar joints can be highly notable in the mortar. The brickwork can contribute, together with cracks in the outer walls, as well as the flaws, vents, and airbricks that form part of the walls. Gaps and cracks exist in the connections of the frames and the walls around doors and windows, as well as the thresholds (the gap below the door) that are lowered to the ground to ensure level access. There are also gaps around the wall outlets and other voids for all services (e.g., water, electricity, telephone, and drains). Walls that form terraced or semi-detached buildings are affected during flooding of the neighbouring property. The damp proofing may be inadequate, and sanitary appliances (toilets, baths, showers, basins) can cause backup from flooded drainage systems (Garvin et al. 2005).

Leaking pipes cause a downslope flux of water that can cause damage or failure to infrastructure. An example of this is shown in Figure 4-1 where the building on the Witwatersrand Supergroup sedimentary rocks failed due to water moving into the cut-and-fill and back of the building. This is exacerbated by more intense rainfall during the time that this failure occurred. This damage is irreversible and irreparable to the point that the building will be required to construct proper drainage to ensure that water is removed. Subsurface pipes and drains are discussed further together with §4.3.2 seeing that it is linked to subsurface openings, such as basements (based on Dippenaar et al. 2022).



**Figure 4-1 Cracking and failing of walls and retaining wall due to leaking pipeline upstream (photograph by Dippenaar).**

## 4.2 URBAN IRRIGATION

Urban irrigation has a cooling effect that is enhanced during heat extremes, with a maximum temperature decrease that can exceed 1°C. However, this cooling effect is highly sensitive to the environment. The irrigation cooling is sensitive to urban vegetation coverage, air temperature, and drought conditions. The heat extremes will increase the sensitivity of the irrigation cooling due to these environmental variables. A climate assessment and water cost analysis are required to prevent mitigation measures in the wrong places in a city that can end up being costly and ineffective (Gao et al. 2020).

Irrigation differs between businesses, residences with many families, and homeowners' associations. The drivers of water demand for large landscape irrigation in urban environments can assist in making informed decisions about optimal conservation and future supplies. Alternative supply sources such as recycled water can be incorporated by utilities to combat changes in supply and the realities of demand. They have a deep understanding of the behaviour of different customers under various policy and climate regimes, which is important to ensure optimal infrastructure planning and investment (Quesnel and Ajami 2019).

Based on a study, the following recommendations are proposed for both water resource and infrastructure managers, and water users (Schurtz et al. 2022):

- The optimum location-specific irrigation depth should be determined for best plant health.
- The optimum value should be communicated to customers while explaining why overwatering is inadvisable and unnecessary.
- Water conservation and landscape programmes should be focused on proper application of fertilizers and other non-water factors that support healthy gardens and lawns.
- Land-use policies should be adjusted to avoid production of small, irregular, and/or disconnected landscaped areas, notably on individual land parcels, and where green space is required in high-density developments, encouraging large and contiguous landscaped areas.
- Excessive use will be discouraged by metering outdoor water use, and established water rates with aggressive tiers.

### 4.2.1 Cropland irrigation

Urban and peri-urban agriculture can have irrigated or rainfed cropland in Mha (million hectares) as shown in Table 4-1. According to statistics, around 2014, South and East Asia had 49% of urban croplands and 56% of non-urban irrigated areas globally. Regions with irrigated cropland of larger area can have higher proportions of urban extent areas that are used for irrigated croplands (Figure 4-2). More arid countries like Namibia and Saudi Arabia have little to no rainfed urban croplands, and wetter countries like Rwanda and Cambodia have a greater proportion of urban land areas that are allocated to the rainfed croplands, as shown in Figure 4-3.

**Table 4-1 Distribution of global croplands – irrigated and rainfed (Thebo et al. 2014)**

	<b>Irrigated croplands</b>	<b>Rainfed croplands</b>	<b>Maximum croplands</b>
Urban croplands	23.6 Mha	43.8 Mha	67.4 Mha
Non-urban croplands	190.6 Mha	881.1 Mha	1078.7 Mha
Total croplands	214.2 Mha	931.9 Mha	–

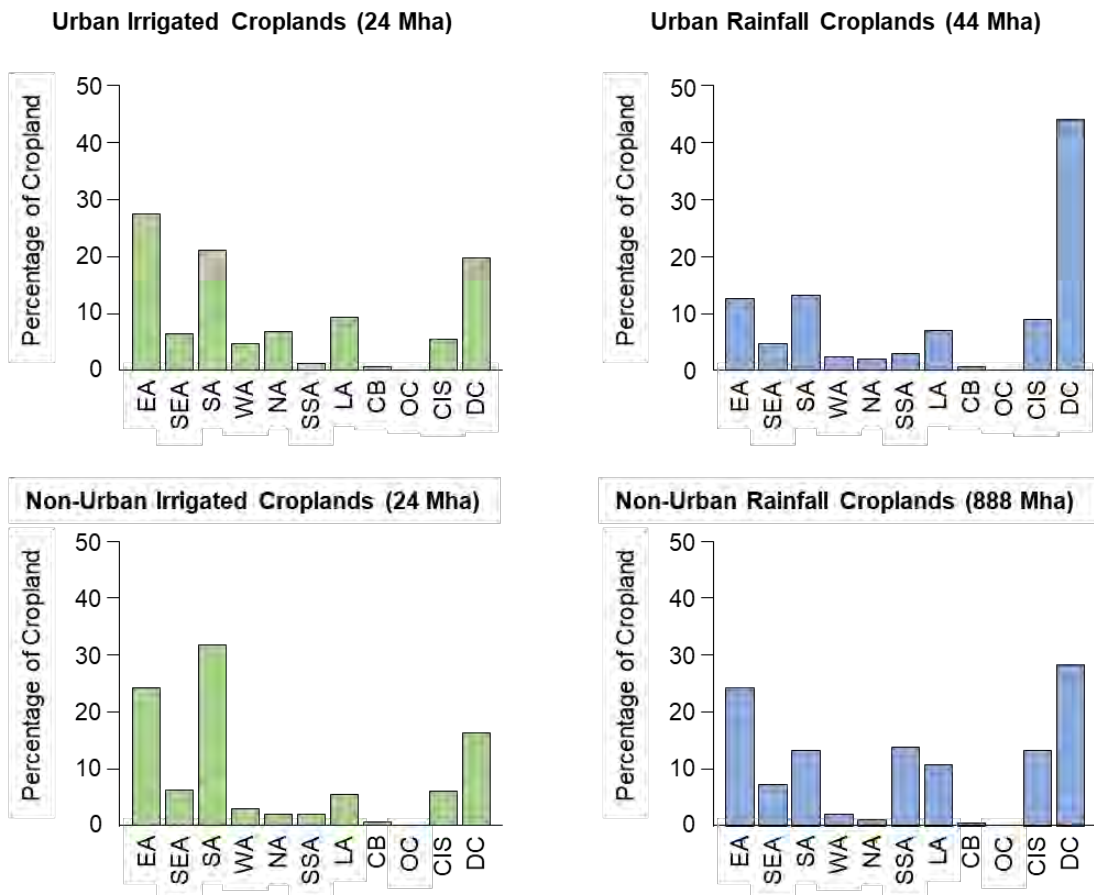
The following aspects underpin the need to understand the extent and drivers of both urban and peri-urban agriculture more deeply across many scales (Thebo et al. 2014):

- Growing uncertainty in the availability of water resources
- Urban populations expanding rapidly
- Urban food demand increases
- Rising incidences of the rural-urban interaction occurring along the peri-urban interface.

Intelligent irrigation solutions are based on a cost-effective and energy-efficient sensor network that is wireless and that can monitor ambient temperature, soil water content, humidity, applied water volume, and electrical conductivity of the irrigation water (Kechtgary and Deljoo 2012; Coates et al. 2013).

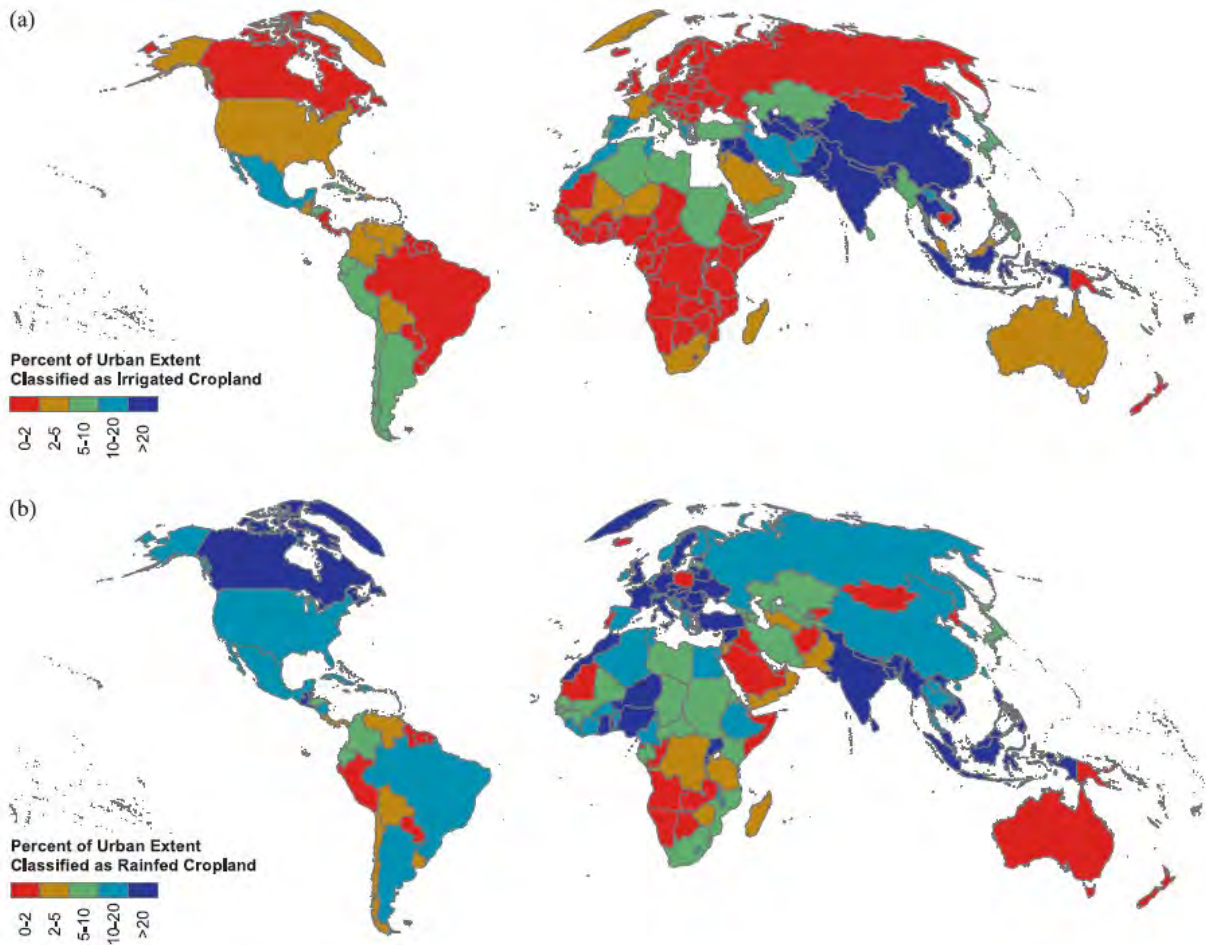
The semi-arid areas of the world and the United States necessitate a cost-benefit analysis before the implementation of an intelligent urban irrigation system. In semi-arid areas, the same cost-benefit analysis will assist in determining whether the installation is worthwhile. In sub-humid climates, intelligent irrigation systems should be considered, seeing that water saving may be more than the additional costs of the system (Mason et al. 2019).

A holistic approach was developed to ensure better understanding of the large landscape customers with recycled and potable water connections, and different climatic regimes can change water use behaviour, meaning that the water sector should understand the reactions of different customer subsections. There is a link between drought awareness and water use behaviour that is important information to be incorporated in future supply infrastructure planning and investigation. Policy regimes are related to the yearly irrigation trends, but distinct political actions and events did not explain week-to-week changes. Geospatial clusters were identified for high and low conservation rates that can be used by water managers and utilities to identify locations in the service areas that can benefit from targeting conservation programming. Behaviours of customers under different customers with different water types under various policy and climate regimes should be understood well to ensure optimal infrastructure planning and investment (Quesnel and Ajami, 2018).



Regional groupings and abbreviations: East Asia (EA), Southeast Asia (SEA), South Asia (SA), West Asia (WA), North Africa (NA), Sub-Saharan Africa (SSA), Latin America (LA); Caribbean (CB); Oceania (OC); Commonwealth of Independent States (CIS); Developed Countries (DC)

**Figure 4-2 Urban and non-urban irrigated and rainfed croplands by region (modified and adapted by Thebo et al. 2014).**



**Figure 4-3** Percentage of urban land area classified as (a) irrigated or (b) rainfed croplands by country (Thebo et al. 2014).

#### 4.2.2 Golf course irrigation

Many developed areas have irrigation related to, for instance, golf courses, agriculture, and sports fields, and of these the golf courses are the most intensive. Soil texture plays an important role and classification is based on the well-known textural triangle compiled by the Irrigation Association that generalises soils into percentages of *clay*, *silt*, and *sand*, and that uses the term *loam* for specific mixes (Barrett et al. 2003).

The soil's intake rate is the infiltration rate that measures the rate of water intake of the soil in mm/minute (inches per hour). This is high in a dry, bare soil that slows down until reached a consistent rate over time. The intake rate is easily obtainable because the intake rate is much higher than the precipitation rate due to the sprinkler system. The soil's intake rate is decreased by turf cover, compaction during construction, the low-pressure sprinklers, thatch build-up, and long-term use of effluent water depending on the water quality (Barrett et al. 2003).

The turf grass efficacy is based on the water use and relative drought tolerance of different plants. This is based on their classification into cool-season and warm-season categories with particular behavioural characteristics that are influenced by soil type, shade, air temperature, soil temperature, water quality, mowing heights, and other cultural practices. The guide to estimate relative plant water use requirements is shown in Table 5-5 (Barrett et al. 2003).

**Table 4-2 Relative drought tolerance (Barrett et al. 2003)**

Season	Turfgrass	Drought Tolerance
Cool	Bluegrass	Low to medium
Cool	Annual bluegrass	Low
Cool	Fescue	High
Cool	Ryegrass	Medium
Cool	Creeping bentgrass	Low
Warm	Bermudagrass	High
Warm	Zoysia	High
Warm	Carpetgrass	Medium
Warm	St. Augustine grass	Medium
Warm	Buffalograss	High

Different pumps can be used in a golf course pump system, that is different types and orientations of centrifugal pumps. In the beginning stages of irrigation systems, one should do the following (Barrett et al. 2003):

- Obtain licenses (sic. permits) for supply
- Ensure that the water supply is large enough to provide the required water volume.
- Ensure that water quality is acceptable throughout the irrigation season.
- Know that water is a finite resource with increasing competition by other parties, increasing the difficulty for golf course irrigation.

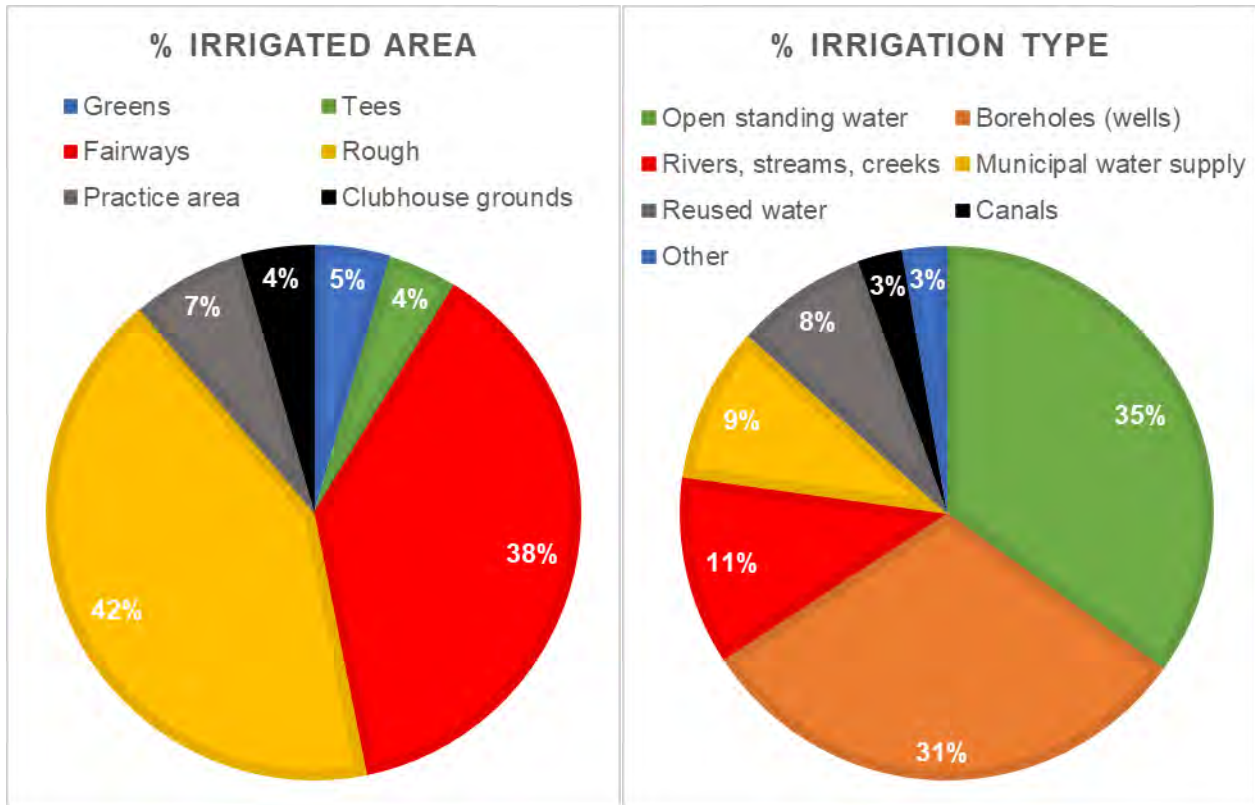
The factors that should be considered include location, elevation, quantity, quality, and power availability. Surface water is most likely the most common source of irrigation water for golf courses, and includes ponds and lakes. Groundwater, on the other hand, includes shallow, deep, and artesian boreholes (wells), and they can be pumped directly into the irrigation system, which includes lakes, ponds (Barrett et al. 2003), and dams.

For boreholes, a hydrogeologist should be consulted, and groundwater is usually of higher quality than surface water. Combined sources generally include groundwater, surface water from streams and rivers, and/or municipal water. Reclaimed water becomes increasingly important given that the use of freshwater sources is under more pressure for other uses than irrigation. Water quality should be addressed, notably as it deteriorates to unacceptable levels during droughts when contaminant concentration increases with lower flows. Chlorides, suspended solids, nitrogen, dissolved solids, manganese, pH, faecal coliforms, and heavy metals (e.g., chromium, manganese) may be of concern in the evaluation of water supply for irrigation (Barrett et al. 2003).

Statistics in the USA provide the water uses by percentage proportion for an average 18-hole golf facility, as shown in Figure 4-4. A survey was done based on the absence of a systematic process to document the changes made by golf courses to make them more compatible with the environment. 18-hole courses make up the vast majority in the USA in 2009 (9 408) followed by 9-hole courses (4 557) and then 27-hole courses (1 487). The main water treatments are as wetting agents (34%) and fertilizer (23%) that are delivered via irrigation systems. Acid-injection systems and sulphur burners are common treatments for water on golf facilities (Throssel et al. 2009).

All water users must use water efficiently, and this includes golf courses, where many use water efficiently, but two areas need improvement based on the survey by Throssel et al. (2009):

1. The use of evapotranspiration estimates together with soil sensors for the scheduling of irrigation
2. The use of audits of irrigation to improve the distribution uniformity of irrigation.



**Figure 4-4 Percentages of irrigated parts of golf areas (left) and the source of irrigation water (right) in the USA (Throssel et al. 2009).**

The study by Mauri et al. (2021) states that golf course irrigation needs differ based on differences between the area in vegetation, soil composition, and terrain, and the soil moisture at each part of the golf course must be monitored to adjust the amount of irrigation per area or sprinkler. Soil moisture estimation using satellite imagery is important to evaluate irrigation efficiency, and it can be applied to urban lawns, golf courses, agriculture, and higher scales in whole river basins. These existing proposed models do, however, have fairly low accuracies, and the indices offered accurate results only for fairways and greens.

Based on a study in the USA, the golf course industry has shown improvements since 2025, but further improvements are needed for the following, with acreages referring to land areas (Gelernter et al. 2015):

1. "Use proven strategies for reducing water use:
  - a. Reduce golf course acreages.
  - b. Adopt recycled water sources where available.
  - c. Adopt tools to improve irrigation efficiency.
  - d. Decrease plant water demand.
2. Adopt a metric for monitoring water use efficiency.
3. Install water meters.
4. Increase golfer education.
5. Work with regulators to identify reasonable water conservation measures."

A shallow root profile requires management of water that places a premium on the uniformity of the applied water, noting that remembering the uniformity and penetration of water is of utmost importance. Surfactants should be used effectively, and soil surfactants should be chosen to provide hydration patterns and penetration characteristics to allow effective management of water repellent soils. There are two questions to answer for this matter (Kurtz 2003):

1. Where the water repellent conditions on the golf course are, and whether the greens, fairways, tees, mounds, or bunker faces are the biggest challenges
2. How the superintendent wants to manage the water repellence challenges.

Golf course irrigation is done before sunrise to limit evaporation so that the water can be absorbed. The wind flow increases as well and hampers the water uniformity through sprinklers. Irrigation should also occur when there are no golfers. Climate and weather are important, seeing that the season may change the irrigation timing and method. Irrigation systems of a golf course are among the most complicated components, with generally confidence well below 100% for only managing and inspection (Golf 2023).

The increased water infiltration of irrigation on golf courses can cause water to move downslope as a perched system. This happened in a new development with housing and a golf course in Johannesburg (South Africa) that is underlain by the Johannesburg Dome granites. The water eroded some ground under the houses that did not have concrete around to protect infiltration and wetting. The damp rose inside the house, meaning that it moved through the floor or other parts of the structure, as shown in Figure 4-5 (based on Dippenaar et al. 2022).



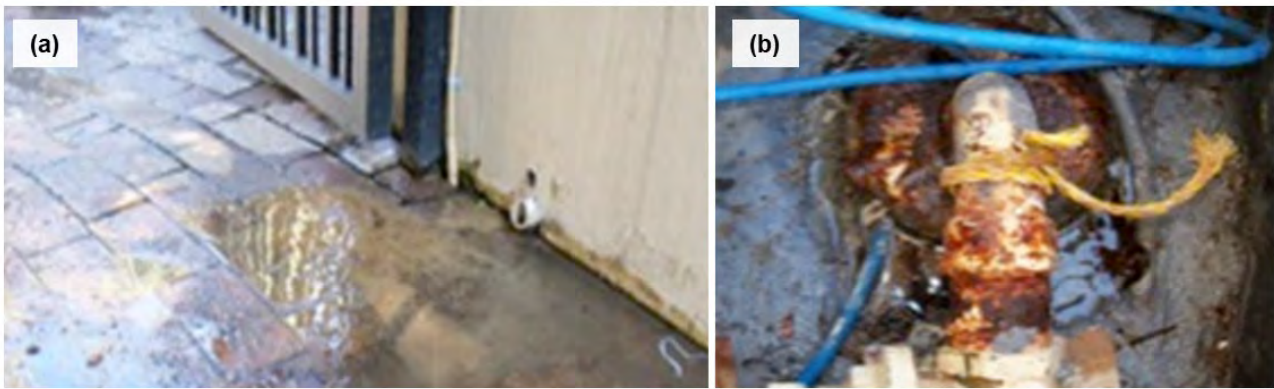
**Figure 4-5** Water from golf course irrigation that caused (a) damp to rise inside the house and (b) erosion of soil under the house (photograph by Dippenaar).

### 4.3 SUBSURFACE WATER AND INFRASTRUCTURE

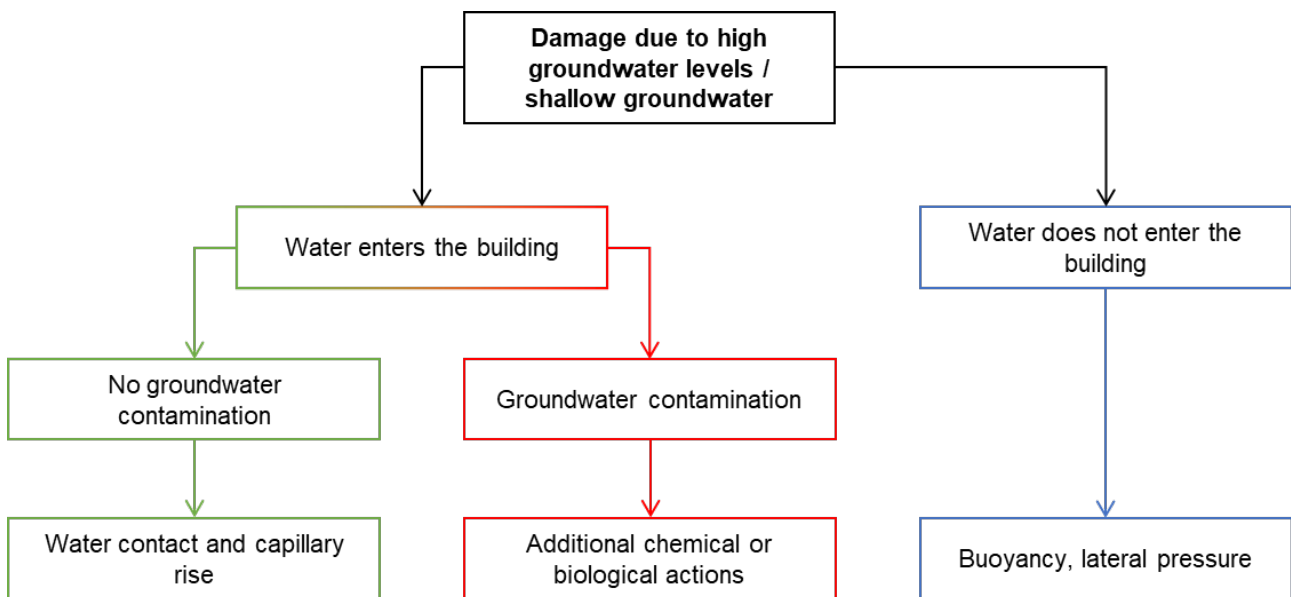
#### 4.3.1 Groundwater and leakage

Whether water enters buildings will dictate whether damage happens, and this is further affected by the presence or absence of contamination. Groundwater can enter buildings through basements with floors and walls that provide access for water, as well as cracks or openings in subsurface pipes

Figure 4-6 shows a leaking borehole that releases water on the surface in the casing and the pavement. This can happen due to (a) shallow groundwater, or (b) the borehole passing through an upper confining layer in the aquifer, pushing up the water due to pressure release. This affects the building and associated infrastructure since this water cannot be removed or limited. The damage caused by shallow groundwater is shown in Figure 4-7.



**Figure 4-6** Leaking boreholes and free water flow showing shallow groundwater (Johannesburg; photograph by Dippenaar).



**Figure 4-7** Damaging processes due to shallow groundwater or high groundwater levels (adapted from Kreibich & Thieken 2008).

The following applies to situations with no groundwater contamination where water entered the building into the basement or cellar (Kreibich & Thieken 2008):

- Examples include wooden floors and panelling with possible damage to the wall paint and all the contents, including the heating systems.
- Mitigation measures include construction without a basement or ensuring waterproofing; building openings should be raised or sealed, in interior fittings should be used for floods.

The following applies for situations with groundwater contamination where water entered the building into the basement or cellar (Kreibich & Thieken 2008):

- Examples include corrosion of the foundation materials and the walls, and contaminants that include faecal germs and oil.
- Mitigation measures include the safe storage of hazardous substances, and flood-proof tanks storage of hydrocarbons.

The following applies for situations with no water entering the building into the basement or cellar (Kreibich & Thieken 2008):

- Examples include demolishing the foundation, and destruction or destabilisation of the building.
- Mitigation measures include artificial flooding to create counter pressures, and improving the building stability through, for instance, anchoring.

Wet Areas comprise different components, and different structural, architectural, and services factors as shown in Table 4-3. The following components can be present for basements and wet areas (Chew 2021):

- Structural components: e.g., floors, slabs, walls, and other load-bearing and non-load-bearing components
- Architectural components, e.g., furnishings, finishes, and other elements contributing to aesthetic liveability and value
- Service components: vertical and horizontal circulation systems, electromechanical connections, sanitary connections.

**Table 4-3 Factors that affect basements and other wet areas (as considered by Chew 2021)**

<b>Factors</b>	<b>Basement</b>	<b>Wet Area</b>
<b>Structural</b>	Corrosion/spalling of concrete Seepage through cracks Seepage through porous concrete Flood control	Seepage through structural joints Leakage through concrete slab Leakage through cracks and porous walls/floors Corrosion and spalling of concrete
<b>Architectural</b>	Proper installation of construction joints Seepage through joints Water ponding Waterproofing Wall finishes Flooring	Efflorescence Biological stains Paints Tile interface with other elements Tile cracks Tile staining Tile joints Floor gradient and screed Waterproofing
<b>Services</b>	Drainage Penetration for services Pumped drainage system Gas installation	Accessibility Penetrations for sanitary fittings Fixture and fittings Gas installation

11 (eleven) factors were found to be significant in causing seepage and/or leakages, including (Chew 2021):

- Design factors:
  - Adoption of an inappropriate waterproofing system
  - Poor drainage design detailing lacking
  - Waterproofing detailing lacking
- Construction factors:
  - Insufficient compaction
  - Improper waterproofing installation
  - Waterproofing damaged during construction
  - Insufficient waterproofing curing
- Maintenance factors:
  - Regular inspection for defect detection lacking
  - Delayed repair of initial defect
  - Deterioration of waterproofing.

### 4.3.2 Basements and cellars

On-site drainage features may fail during heavy rainfall, causing the water level to no longer be able to lower quickly. The buoyancy of the basement increases due to prolonged submersion in water, causing cracking of the floor and leakage, as shown in Figure 4-8. Basement leakage requires controlling the water level in the basement that is upward, and rotational control of this upward water level is related to the basement's usage, structural safety, and cost control (Yue et al. 2024).

*Overland flow* routes are designed and built to help convey stormwater and snowmelt away from urban areas, and often streets, swales, ditches, and parks are designed to remove water from residential areas. All of these structures and strategies can aid in the reduction of basement flooding. Underground stormwater pipes are very costly to build and install, and they are mostly designed to handle hailstorms at a 20% incidence per year once every five years. In older parts of the cities, this gets more frequent, reaching a 50% incidence for once every two years. Overland flooding can occur when stormwater exceeds the capacity of the pipes, and/or the capacity of overland flow routes. This flood water can then enter basements through vents, doors, windows, and other openings, including reverse-sloped driveways (Sandink 2009).

*Infiltration flooding* can cause the soil around a home to become saturated with water. This occurs after steady rain (a few days), when snowmelt occurs, or during extreme rainfall events. The groundwater can infiltrate into the basements through cracks in the basement walls or foundation walls. This is especially bad in older homes where mortar has weakened, and where there is no weeping tile, where the weeping was not maintained, or where poor drainage increases the chance of infiltration flooding (Sandink 2009).

*Sewage backup* is due to toilets, sinks, drains, and other home water uses that generate sanitary sewage that contains a high degree of contaminants that can pose noteworthy risks to human health and the environment. It therefore requires treatment at sewage treatment facilities before being released into the environment. Sanitary sewage laterals, which connect homes and buildings to underground sanitary sewer pipes, collect sanitary sewage (Sandink 2009).



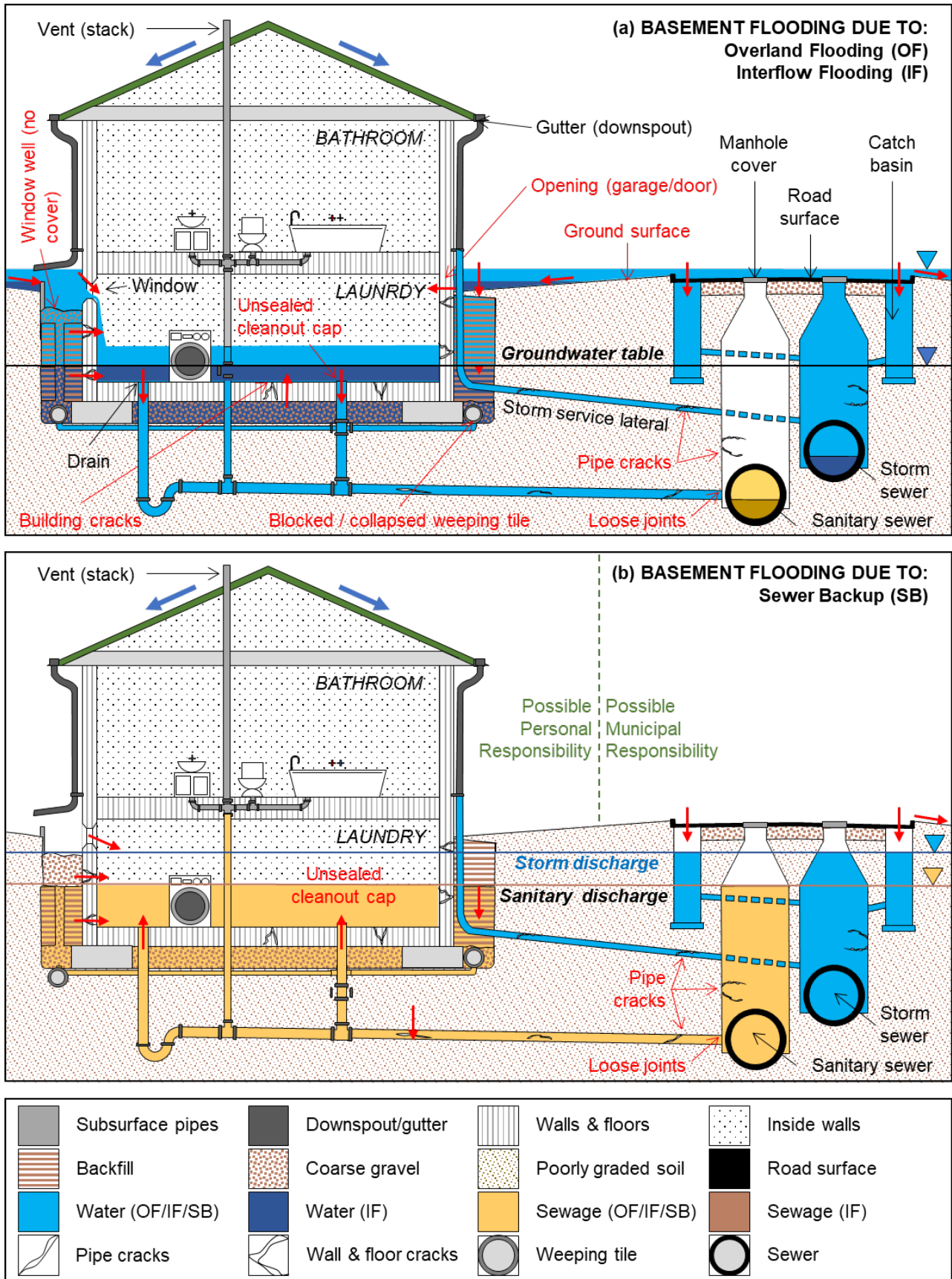
**Figure 4-8** Groundwater level rise around the basement leads to leakage (Yue et al. 2024).

The responsibility between the owner and municipality can vary, but the common and probable boundary is shown in Figure 4-9(b). Figure 4-9 shows a home that has a basement that is likely to flood due to overland flooding, infiltration flooding, and sewer backup, and on the figure the following applies:

- White colours indicate an air-filled situation
- Shades of blue and brown show water and sewage respectively in the different materials and infrastructure.
- Black text and arrows show general components of relevance in the infrastructure and environment.
- Red text and thin red arrows show aspects of influence on the movement of water and/or sewage.
- Thick red arrows show the movement direction of water and/or sewage.
- Horizontal lines transecting the section show different depths, including the groundwater table, the depth of the stormwater discharge sewer, and the depth of the sanitary sewer.

The following reasons are some of those causing the flooding of the basement and proximate subsurface in Figure 4-9 (Sandink 2009):

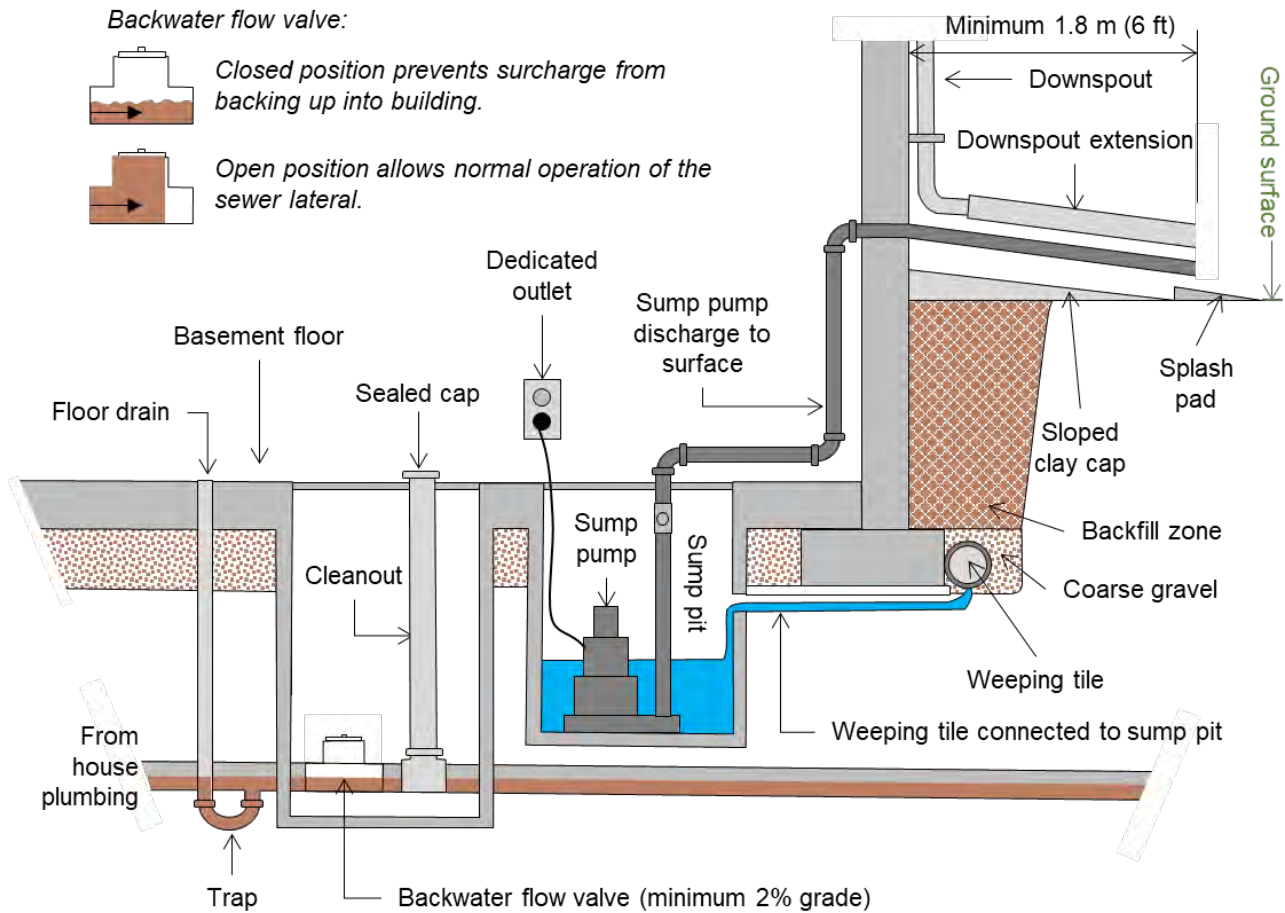
- The basement floor and the foundation wall have unsealed cracks.
- The backfill area next to the foundation wall is not capped.
- The property's soil is not graded well.
- The site slopes towards the house.
- The backfill area next to the foundation wall is not capped.
- There is no cover above the window well.
- The downspouts (gutters) are discharged close to the foundation or are connected to the sewer system of the municipality.
- Weeping tiles were not maintained and are damaged, and are connected to the sanitary sewer laterals that are damaged and are not being maintained.
- The storm sewer lateral was not split and will likely be detached.
- There are no backwater valves.



**Figure 4-9** Depiction of (A) overland flow, infiltration flow, and (B) sewer backup in context of buried infrastructure and a basement (based on Sandink 2009).

Backwater valves are open when sewer addition occurs allowing the gases to vent. When the valve is closed the sewage can no longer get in or out of a building. When these are disconnected a sump-pit with a sump

pump have to be installed to pump the water from the weeping tiles to the surface of the lot, and this may be recommended by the municipal government to be used to the municipal sewer system (Figure 4-10) (Sandink 2009).



**Figure 4-10 Basements valves and their purpose in managing sewage in basements (Sandink 2009).**

#### 4.4 SURFACES

Surfaces refer to anything that covers the subsurface, and this can be natural and anthropogenic media. For natural areas this includes ground cover like transported or in-situ soil, rock outcrop, ground-covering vegetation like grass, and agricultural cropland. Irrigated land includes, for instance, agriculture, gardens, and golf courses (§4.2). These allow infiltration at different rates and localities that affect the environment, and include roads, pavements, and roofs.

#### 4.5 SURFACE WATER AND GROUNDWATER IN URBAN AREAS

##### 4.5.1 Water from dolomites

In South Africa, the Gauteng Province has the highest population. The province houses the capital city, Pretoria, that was founded predominantly due to groundwater from springs. The economic hub of the country, Johannesburg, is also in the province, and was founded after the discovery of gold. The Chuniespoort Group

(for the geologists) form the dolomites, and this overlies the Witwatersrand Supergroup in which the fold is found.

As the rock dissolves in slight acidic water the water gets harder and as the water flow out through the process of dissolution. The dolomites that is made up of  $\text{CaMg}(\text{CO}_3)_2$  dissolve through dissolution while the chert that it is often interlayered with (cryptocrystalline  $\text{SiO}_2$ ) maintains its integrity. This shown in the Sudwala Caves (South Africa) as shown in Figure 4-11(a) comprising dolomite (light grey) interlayered with chert (black;), that has a main entrance for tourists. The springs occur in in the same dolomite that form due to dissolution of the rock as shown in Figure 4-11(b) (more information in Dippenaar 2013).



**Figure 4-11 (a) Grootfontein spring providing Pretoria with drinking water (photograph by Gerrit Burger), (b) and (c) sinkhole falling due to leaking pipe and destroying houses; (d) sinkhole due to leaking irrigation pipe in cemetery (photographs by Dippenaar).**

This continues, enlarging the cavities underground, and when these openings daylight on surface, they are referred to as sinkholes, and they cause substantial damage. Figure 4-11(c1) shows the damage to houses as a consequence of the sinkhole shown Figure 4-11(c2) that formed due to a leaking pipe. Figure 4-11(d) shows a sinkhole that formed in a cemetery due to irrigation.

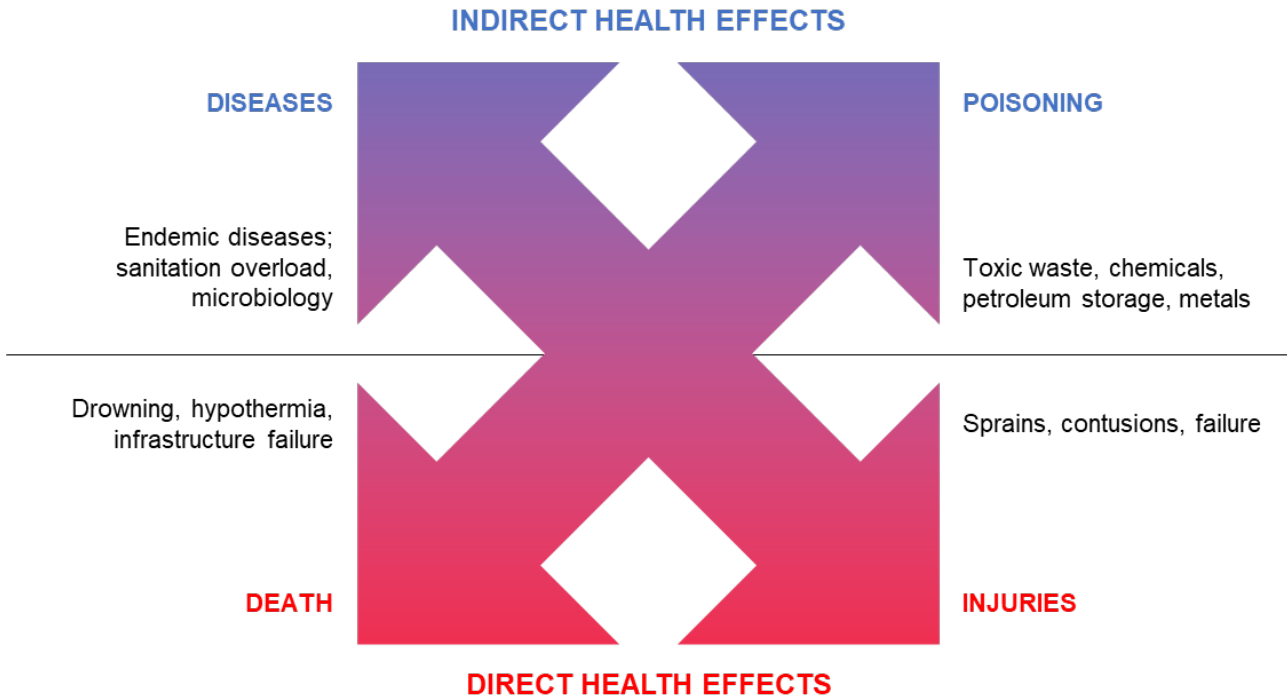
c). These dolomites also provide Pretoria with drinking water from various springs, including Grootfontein as shown in Figure 4-11(d). This means that acid mine drainage (AMD) can decant onto these dolomites.

#### 4.6 URBAN WATER CONTAMINATION

Direct and indirect health effects are provided for urban flooding, but it is still considered relevant die flooding enters buildings, including basements or cellars. In terms of floods, direct effects refer to those occurring during or after the flood, whereas the indirect effects develop after the flood (days or weeks) with long-term effects that can develop over months of years. This is shown in Table 4-4 and Figure 4-12.

**Table 4-4 Direct and indirect health effects from urban flooding (adapted from Garvin et al. 2006)**

Risk Effects	Health Effects
<b>Direct Health Effects</b>	
Stream flow velocity and topography No warning Rapid flood speed onset and deep water from floods Debris carried by rapidly flowing water Existing mobility or health problems Failures of protective structures (toppling/collapse) and dams Standing water Contact with water (pure or polluted) Manhole covers missing	Risk of injury or drowning Risk of respiratory disease, shock, hypothermia, cardiac arrest Risk of wound infections, conjunctivitis, dermatitis, gastrointestinal illness Risk of ear, nose and throat infections Falls that lead to head injury, broken limbs, or cuts and bruises
<b>Indirect Health Effects</b>	
Damage to water supply Damage to sewerage and sewage disposal systems Damage to gas and electrical services Loss of wastewater services Disruption of underground piping Dislodging of petrol storage tanks and external pollution factors like petroleum tanks, farm storage, and land runoff Release of household and other chemicals Heavy rainfall Rodent migration Cryptosporidium in drinking water after the flood Clean-up activities after the flood and reparation	Waterborne infections, e.g. E. coli, hepatitis A Vector-borne diseases Rodent-borne diseases Dermatitis and conjunctivitis Acute or chronic effects of chemical pollution Bites and scratches from animals Electrocution, injuries, lacerations, puncture wounds Vapour inhalation Stress and trauma

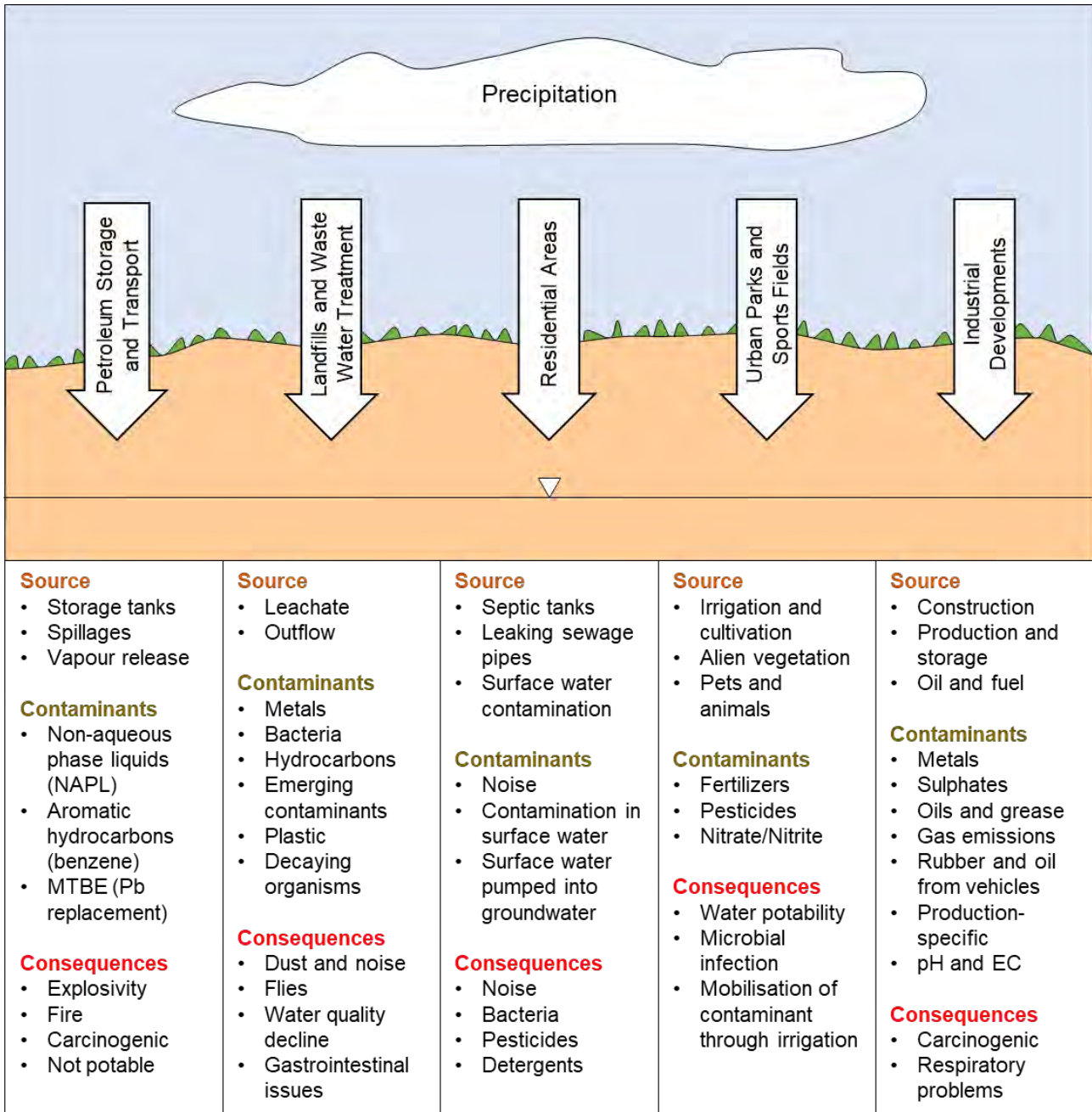


**Figure 4-12** Indirect and direct health effects due to urban flooding (adapted from Garvin et al. 2006).



**Figure 4-13** Pollution of rivers in Johannesburg (South Africa).

Different sources exist in urban environments that are all associated with specific components of infrastructure or services that allow for the release of associated contaminants as shown in Figure 4-14. In urban environments different contaminants contribute to the same system meaning that different contaminants become present in the same environment. The contaminant associated with the different sources are highly variable, but some are common in more of these environments. Consequences vary, and are also different based on the susceptibility of the receptor. Some of these are also not merely additive where the combined effect is equal to the sum of both of the contaminants, but rather synergetic where the two combined are more than their individual contributions.



**Figure 4-14** Examples of urban sources of contamination with examples of the respective contaminants and anticipated consequences.

Pollution sources are abundant and included, for instance, spillages of light non-aqueous phase liquids (LNAPLs) like petrol, paraffin (jet fuel), and diesel as shown in Figure 4-15. These form free flowing plumes on the water table or on surface water, and explosive and toxic aromatic hydrocarbons in vapour phase are associated with it.

Mining in urban areas also pose big problems with contamination. Figure 4-16 shows the problems associated with coal mining that include tension cracks forming sinkholes that is associated with spontaneous combustion of the remaining coal underground. The water is enriched in iron and in some places acid mine drainage occurs.



**Figure 4-15** Petroleum spill in Gauteng (South Africa) (photograph by Matthys Dippenaar 2015).



**Figure 4-16** Spontaneous combustion of coal, sinkholes due to collapse of stopes, and water pollution (Mpumalanga).

Generally in urban areas, cognisance is given to the different types of contaminants that can become pollutants once it is associated with adverse effects. Figure 4-17 shows a building with an underground storage tank that is adjacent to a manmade cutting with a car. Groundwater is used for the building that comes from a primary, intergranular aquifer that is in the soils and that is connected to a fractured aquifer that is used at the area below the cutting. The groundwater flows towards surface water that is connected to the primary aquifer. At the elevated areas sources include the sewerage from the building, the underground thank that includes

petroleum hydrocarbons, the leaks from the vehicle, and any other waste generated from the site. The pathways here is the aromatic hydrocarbons that can be inhaled, the polluted water that can be ingested, the concentrated uptake by the vegetation and animals that can in turn ingest and be ingested, and the dermal contact with any of the fluids.

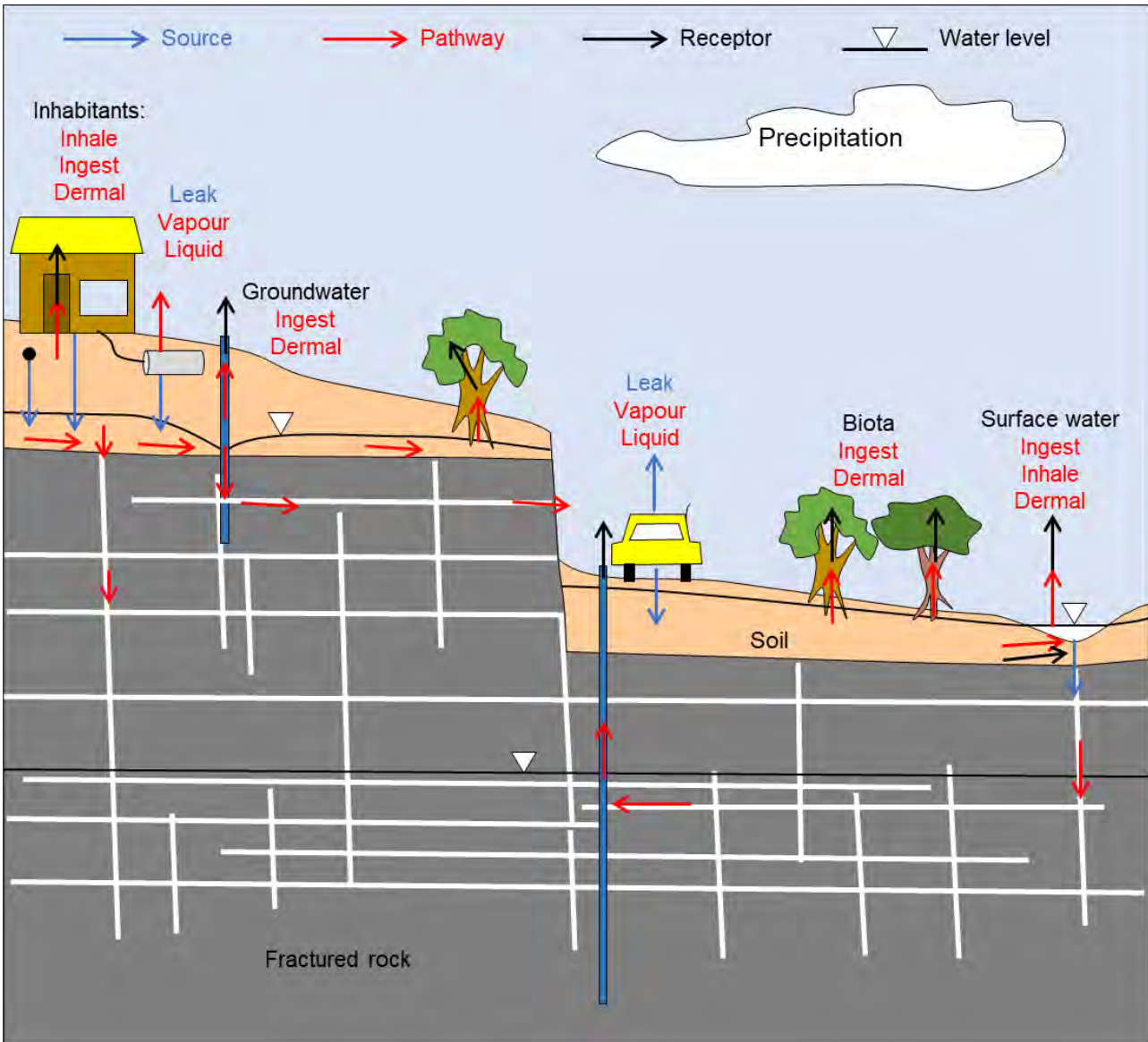


Figure 4-17 Example of a Source-Pathway-Receptor analysis.

## CHAPTER 5: METHODOLOGY

### 5.1 SOIL AND ROCK

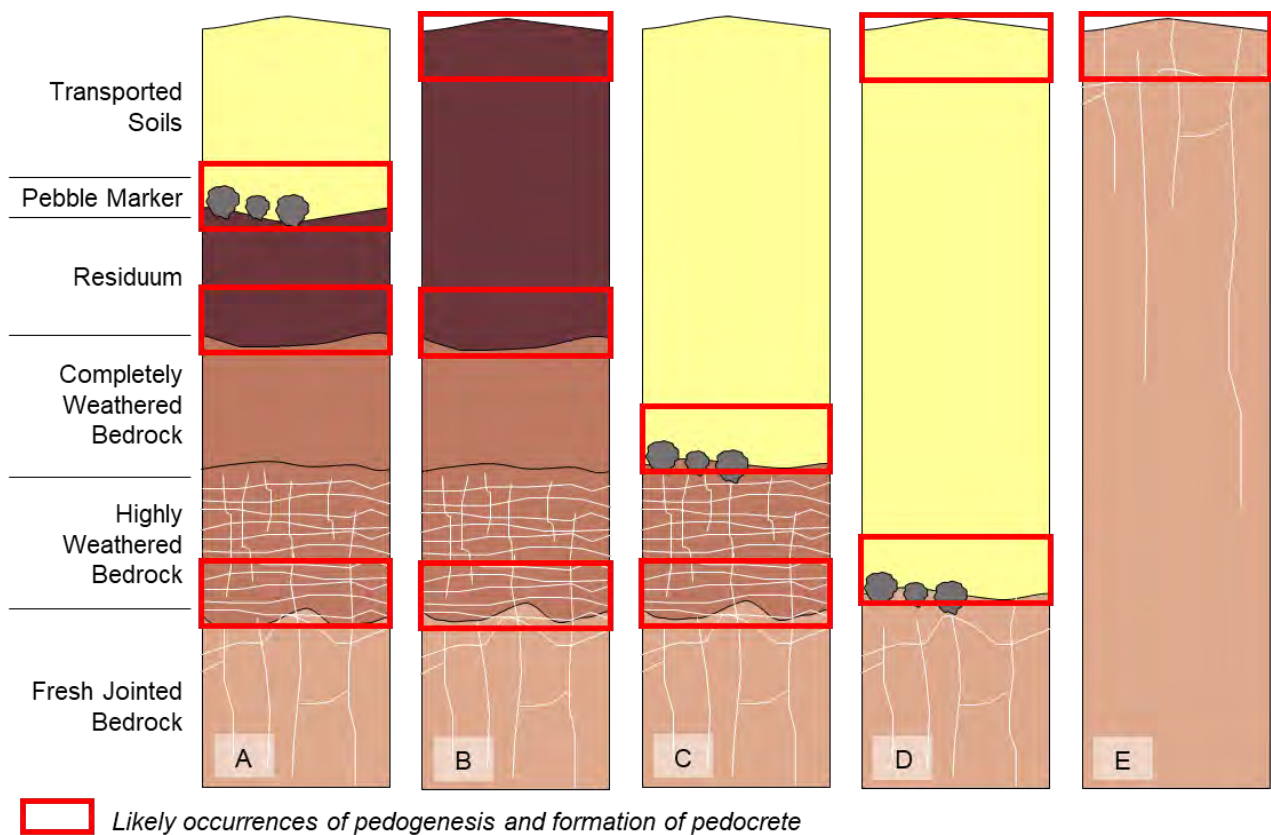
#### 5.1.1 Soil and rock mapping and description

Mapping of outcrops give geologists insight into the composition and structure of the rocks below. It provides very important information on how and to which extent the rocks are fractured or deformed, and provides an opportunity to assess the composition of the different rocks. Materials that are described include rock outcrop, drill core, percussion drilling chips, and soil profiles in natural or excavated openings.

All materials were described according to *Engineering Geological Soil and Rock Description* by Dippenaar et al. (2024) that shows the typical profiles that comprise the following:

- Transported soils that were transported by a variety of transport agents such as gravity, wind, and water, and that is often underlain by a coarser pebble marker indicating the deeper end of the transported soils.
- Residuum is the weathered product of rock to the point that the minerals and structure are no longer discernible, but there has been no movement.
- The rock goes from completely weathered becoming less weathered with depth until it reaches fresh bedrock that may be jointed.

Typical successions are shown in Figure 5-1 with South African examples in Figure 5-2.



**Figure 5-1** Typical successions of earth materials (Dippenaar et al. 2025).

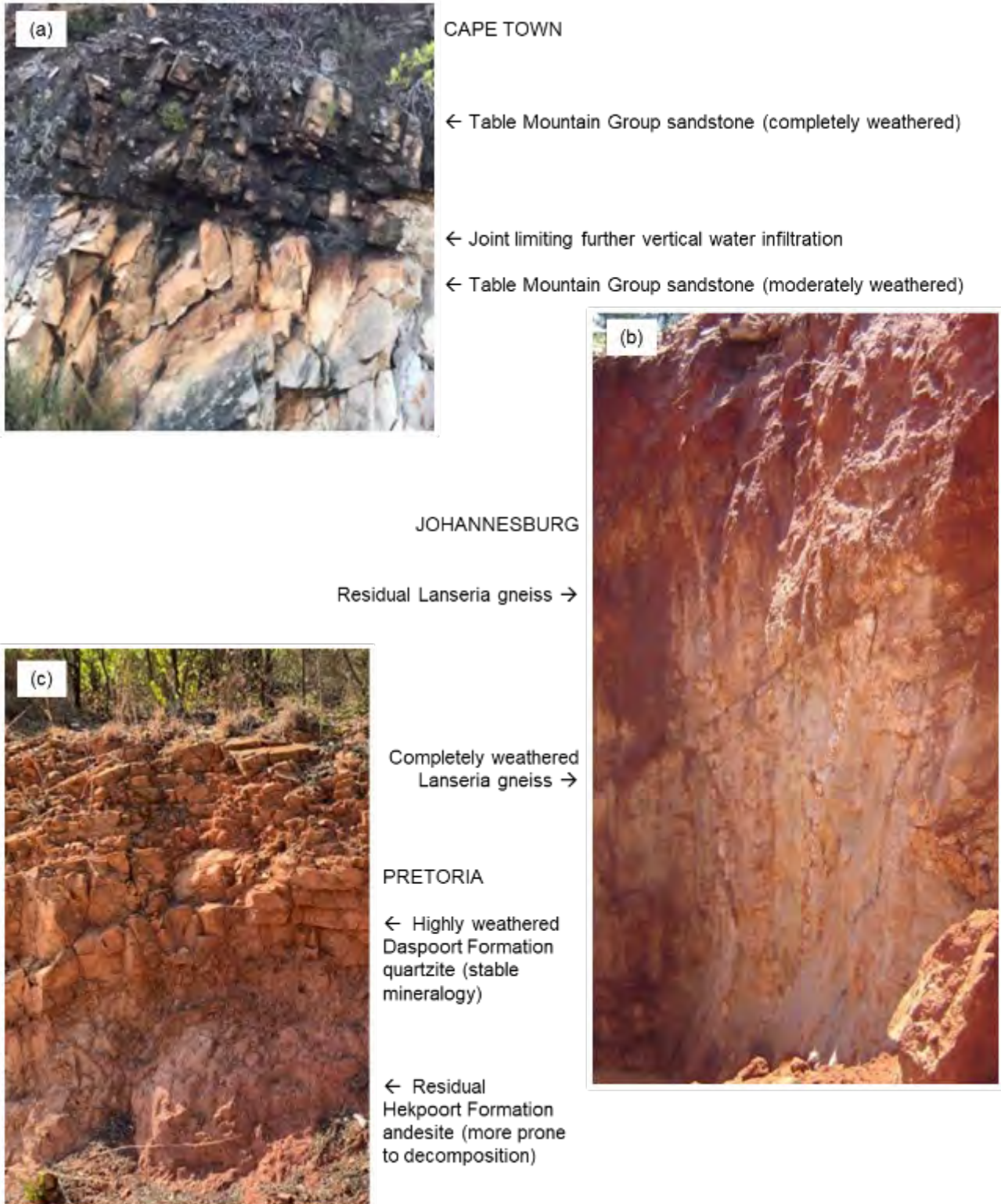


Figure 5-2 Examples of the typical profiles and how geology affects the soils forming.

### 5.1.2 Soil sampling

Disturbed and undisturbed soil samples are retrieved to determine various properties required to understand the behaviour of the material in natural and disturbed states. Samples were sent to accredited laboratories or testing by the project team. Sampling and preservation of undisturbed soil samples are shown in Figure 5-3.



**Figure 5-3 (a) Retrieving an undisturbed sample; (b) example of an undisturbed sample; (c) wrapped and stored undisturbed samples (photographed by Dippenaar 2024).**

### 5.1.3 XRD and XRF

X-ray Fluorescence (XRF) Spectroscopy is used to determine the chemical composition of rocks and soils. The is used in conjunction with X-ray Powder Diffraction (XRD) that is used to determine the minerals present in a rock. These facilities are available in the Stoneman Building on the Hatfield Campus of the University of Pretoria.

### 5.1.4 X-Ray Computed Tomography scan

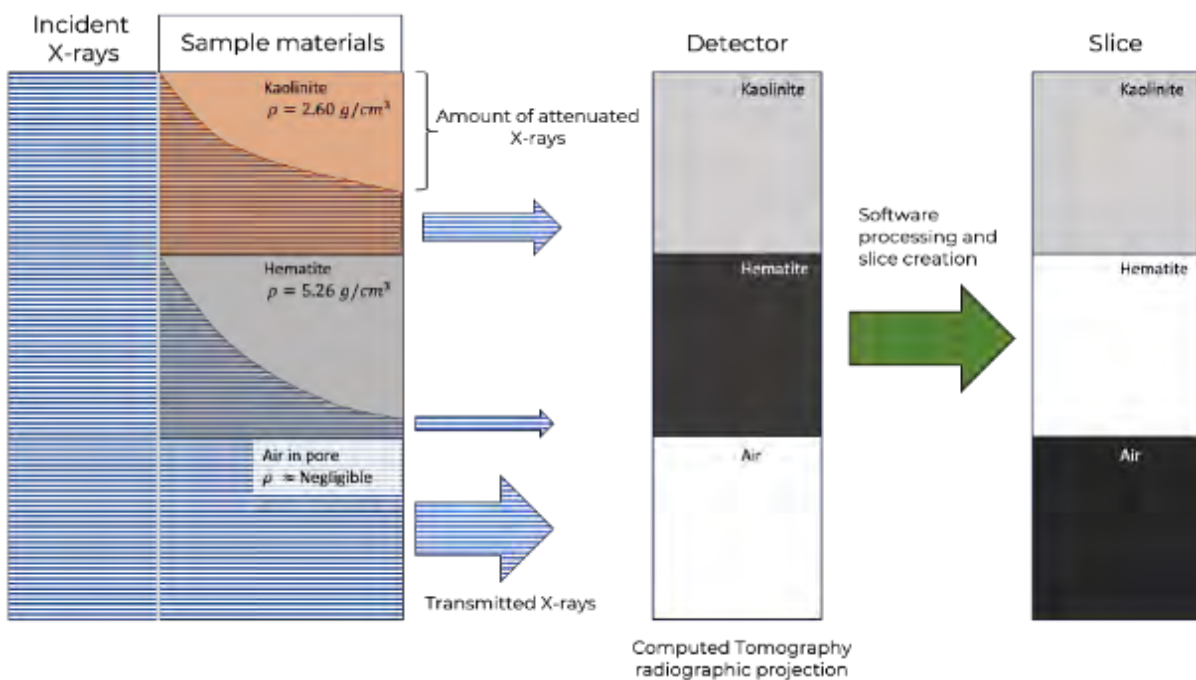
To study the flow of fluids, containing solutes and solids making up the pollutants, in unsaturated soil the effective porosity needs to be modelled. The use of an X-ray Computed Tomography (XRCT) scanner to visually assess the 3D relict rock structure, pore geometry and chemical constitutes present in soils at any moisture content. These parameters provided indices for water flow characteristics through the material and the typical weathering profile created, whereby impacting on the vertical anisotropy and movement of pollutants within the weathered rock horizon before reaching factures in competent rock.

XRCT is a non-invasive, non-destructive, imaging technique developed for the visualisation and quantification of the interior structure of an object in the 3-dimensions (3D). A sample is placed within the scanner and exposed to a beam of X-rays, generated from an X-ray tube, while the sample is rotated a full 360°. The X-rays are absorbed or scattered by, or passed through, the sample materials causing attenuation of the beam. The degree of attenuation is proportional to the atomic number of the material, the photon energy of the incident

beam and the thickness of the material. The degree of X-ray attenuation is acquired by the detector from the numerous 2D radiographic images, often called projections (Sturrock 2022).

The key principle of the XRCT imaging technique is based on the differential attenuation of X-rays as they interact with the minerals and pore spaces within the sample. The ability of differing materials to adsorb and scatter incident photons is referred to as the linear attenuation coefficient (Huda 2012). At a given photon energy and sample thickness, a higher density material (i.e. larger linear attenuation coefficient) will absorb or scatter more X-rays, increasing the attenuation, resulting in a darker appearance on the Computed Tomography (CT) projection (Sturrock 2022).

Using relevant software depending on the application, the CT projection is converted into a slice where the denser materials appear lighter, and air appears darker (Li and Tang 2019; Sturrock 2022). The process of X-ray attenuation in sample materials before photons reach the detector in a XRCT scanner is shown in Figure 5-4.



**Figure 5-4 X-ray attenuation contrast of solid mineral grains compared to open pore spaces in soil.**

The sampling methodology for XRCT samples comprised undisturbed block and tube samples. The tube samples were retrieved by pushing a PVC pipe (30.0 mm x 150.0 mm) into the sidewall of a freshly dug test pit. Undisturbed samples were wrapped and capped appropriately to ensure moisture loss was minimal before being tested in the laboratory.

The tube samples were scanned at X-Sight X-Ray Services by means of their Nikon XT H225 ST system. The scans were conducted at 180 kV and 330 uA where approximately 2985 (no.) images were acquired of each sample while the samples rotated a full 360 degrees. Two-dimensional (2D) and three-dimensional (3D) slices were constructed using the Phoenix Datas acquisition and reconstruction software. The software processing focused on the sample material only and excluded a 2.00 mm space between the sample material and the tube's inner wall and 2.00 mm at the top and bottom portion of the sample. This was done to exclude areas where displacement and density alteration would have occurred at the sample and tube interface during sample retrieval. The density contrast and pore space analyses were performed with use of VOLUME GRAPHICS (VG) STUDIO MAX software.

The purpose of obtaining images using the XRCT scanner was to characterise the pore space orientation and size distribution, and the persistence of the relict rock structure and infill material of undisturbed samples. After the tubes were scanned, the PVC pipes were cut open to assess the macro-relict-rock-structure. Finally, the samples were oven-dried to calculate the natural moisture content and dry density.

### **5.1.5 Oedometer testing**

One-dimensional consolidation testing is widely used and is seen as a fundamental soil behaviour test. The oedometer test applies a series of predetermined loads on to the sample and the deformation response is measured. The consolidation of a soil is dependent on its stress history, density, and porosity (Terzaghi 1943). Humans frequently use the completely weathered rock in a profile as a founding medium and will apply loads that may or may not cause deformation to take place. Furthermore, the completely weathered rock is often ripped and recompacted at the founding level thereby changing the density and porosity. The change in volume will impact the porosity value and therefore flow characteristics of the soil and completely weathered rock profile.

Undisturbed samples were placed in an oedometer to undergo a one-dimensional consolidation test guided by the method stated in the BS 1377-5: 1990 (1998) code. These samples underwent a full consolidation test at the in-situ moisture content before the material was removed and remoulded to destroy any remaining soil structure. The remoulded soil material was placed back into the oedometer cell and compacted to achieve the undisturbed density and similar porosity values and moisture content prior to being retested. The behaviour of the undisturbed and disturbed samples was assessed and compared in this study.

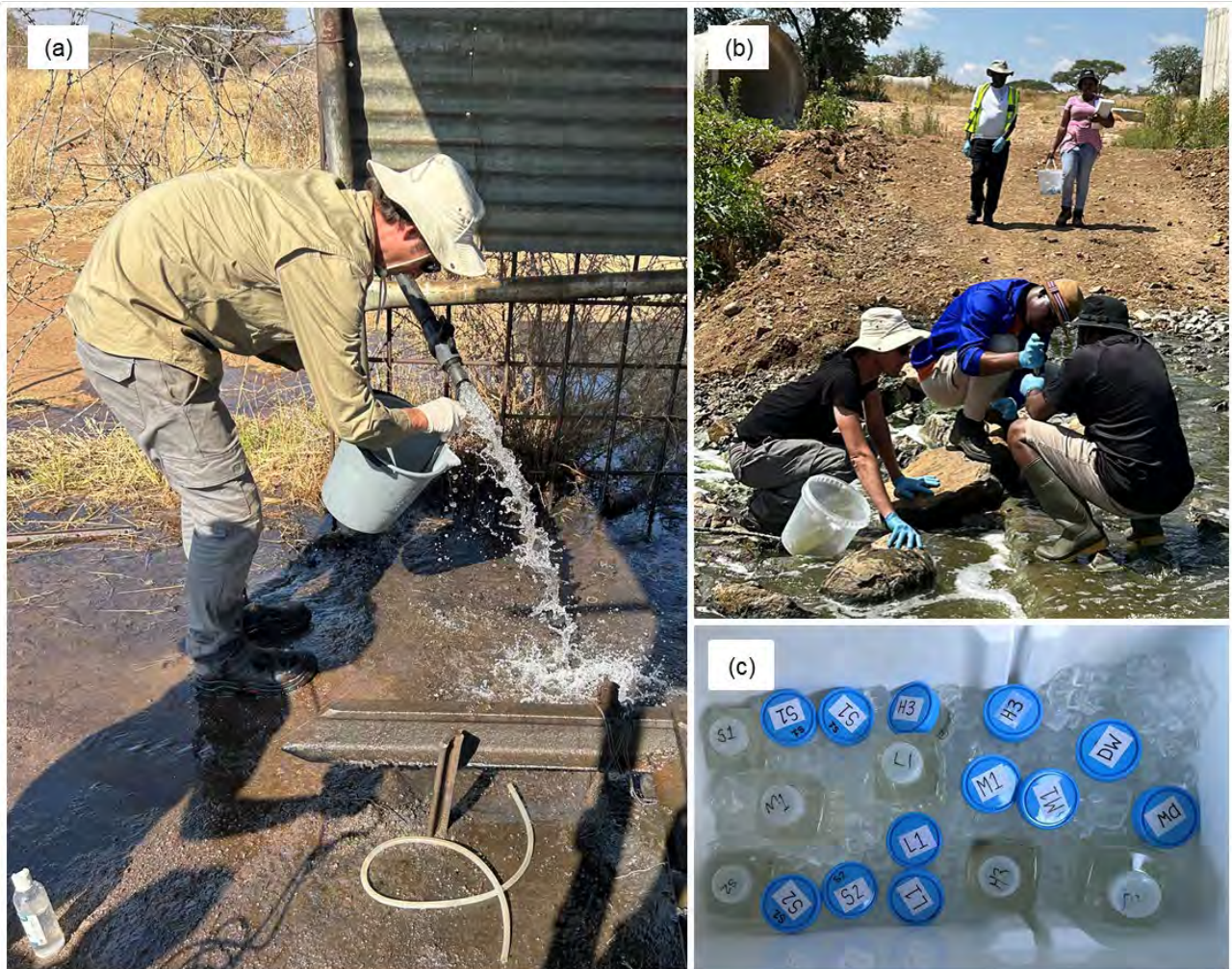
### **5.1.6 Particle size analysis and Atterberg limits**

The soil samples underwent particle size analysis according to SANS 3001 GR1 (2013). The Atterberg limits testing was conducted using the one-point method as stated in SANS 3001 GR10 (2013). In this standard the liquid limit and plasticity limit (PL) are determined using the Casagrande cup and the thread rolling method, respectively. The Atterberg limits testing was duplicated to ensure accurate readings were achieved. The laboratory Unified Soil Classification System (USCS) description was determined as stated in the ASTM D2487 – 17<sup>1</sup> (2020).

## **5.2 WATER**

### **5.2.1 Water sampling**

Water samples are retrieved from surface water that includes rivers, streams, and dams. Groundwater samples are retrieved from boreholes where the water is purged with existing pumps as close as possible to the borehole and before any storage like water tanks. Samples are taken in plastic bottles wearing gloves and rinsed a few times before sampling. Where appropriate it is ensured that there is no air in the samples, and it is placed and transported in a cooler box with ice. For the Urban Water studies (Hartbeespoort Dam and Roodeplaat Dam) the 2024 samples were submitted on the same day as sampling to ensure that the microbiology can be analysed as within the preference period.



**Figure 5-5** (a) Sampling surface water in a river, (b) sealing the bottle, and (c) storing the samples in a cooler box with ice (photograph by Smith, 2024; Makonto 2023; Dippenaar 2024).

### 5.2.2 General water quality

Water quality is compared to the WHO (2017) and SABS (2022) guidelines for drinking water, most notably SANS 241. General analyses include the major cations and anions, microbiology and selected metals. Typical analyses conducted by Aquatico Laboratories in Pretoria are shown in Table 5-1. Water samples were collected in 500 ml plastic bottles, sealed, and labelled. The bottles were then placed in a cooler box with ice and stored in the fridge until they could be delivered to the laboratory.

**Table 5-1** Aquatico Laboratories, SANAS accredited analyses.

Method	Variable/Description
ALM 01	Total Alkalinity
ALM 02	Chloride (Cl)
ALM 03	Sulphate (SO <sub>4</sub> )
ALM 04	Orthophosphate (PO <sub>4</sub> ) as P
ALM 05	Ammonium (NH <sub>4</sub> ) as N
ALM 06	Nitrate (NO <sub>3</sub> ) as N
ALM 07	Nitrite (NO <sub>2</sub> ) as N
ALM 08	Fluoride (F)
ALM 20	pH @ 25°C
ALM 26	Bicarbonate alkalinity
ALM 30	Calcium (Ca), Magnesium (Mg), Potassium (K), Sodium (Na)

Method	Variable/Description
<b>ALM 31</b>	Iron (Fe), Manganese (Mn)
<b>ALM 37</b>	Dissolved Uranium (U)
<b>ALM 30</b>	Calcium (Ca), Magnesium (Mg), Potassium (K), Sodium (Na)
<b>ALM 91</b>	ICP-MS: Aluminium (Al), Antimony (Sb), Arsenic (As), Barium (Ba), Beryllium (Be), Bismuth (Bi), Boron (B), Cadmium (Cd), Cerium (Ce), Cesium (Cs), Chromium (Cr), Cobalt (Co), Copper (Cu), Dysprosium (Dy), Erbium (Er), Europium (Eu), Gadolinium (Gd), Gallium (Ga), Germanium (Ge), Gold (Au), Hafnium (Hf), Holmium (Ho), Indium (In), Iridium (Ir), Iron (Fe), Lanthanum (La), Lead (Pb), Lithium (Li), Lutetium (Lu), Manganese (Mn), Mercury (Hg), Molybdenum (Mo), Neodymium (Nd), Nickel (Ni), Niobium (Nb), Osmium (Os), Palladium (Pd), Platinum (Pt), Praseodymium (Pr), Rhenium (Re), Rhodium (Rh), Rubidium (Rb), Ruthenium (Ru), Samarium (Sm), Scandium (Sc), Selenium (Se), Silicon (Si), Silver (Ag), Strontium (Sr), Tantalum (Ta), Tellurium (Te), Terbium (Tb), Thallium (Tl), Thorium (Th), Thulium (Tm), Tin (Sn), Titanium (Ti), Tungsten (W), Uranium (U), Vanadium (V), Ytterbium (Yb), Yttrium (Y), Zinc (Zn), Zirconium (Zr)

### 5.2.3 Stable Isotope analysis of water sources

Rainwater, groundwater, and surface water samples were taken to iThemba LABS in Johannesburg where hydrogen and oxygen isotope ratios and tritium were analysed in the Environmental Isotope Laboratory (EIL). The analysis was done using a Los Gatos Research (LGR) Liquid Water Isotope Analyser and laboratory standards, calibrated against international reference materials with each batch of samples. In the tritium analysis process, the samples undergo distillation followed by electrolysis enrichment. The electrolysis cells used consist of two concentric metal tubes, electrically insulated from each other. The outer anode, which also functions as the container, is constructed from stainless steel. The inner cathode is composed of mild steel with a specialized surface coating. The procedure begins with the introduction of approximately 500 ml of the water sample into the cell, which has previously undergone distillation and contains sodium hydroxide. A direct current ranging from 10 to 20 amperes is then passed through the cell. To mitigate heat generation, the cell is actively cooled. Over the course of several days, the electrolyte volume decreases to approximately 20 ml. This substantial volume reduction, around 25-fold, results in a corresponding tritium enrichment factor of approximately 20. To ensure accuracy, each batch includes samples of known tritium concentration (spikes) run in one of the cells to assess the attained enrichment. For liquid scintillation counting, samples are prepared by directly distilling the highly concentrated electrolyte-enriched water sample. Specifically, 10 ml of the distilled water sample is combined with 11 ml of Ultima Gold and placed in a vial. These vials are then analysed using a Packard Tri-Carb 3170TR/SL Liquid Scintillation Analyser, with counting typically conducted over 2 to 3 cycles, each lasting 4 hours. The detection limits achieved for enriched samples are as low as 0.3 Tritium Units (TU). This method ensures precise tritium analysis and allows for the accurate measurement of tritium concentration in the samples.

### 5.2.4 Radon

The Durrigge RAD7 was used for the radon analysis. Samples were taken back to camp and analysed there as it was not possible to take the Durrigge machine into the field. Samples were analysed as soon after sampling as possible, usually within 12 h and often within 6 to 8 h, correction factors used can be seen in Table 5-2. Before samples were analysed the machine was purged for 10 minutes with the system being open but still being connected to the drying unit. This was done to remove any excess radon from the system left behind by previous analysis. After 10 minutes the system was closed, and the purging would continue until the relative humidity reading had dropped below 6%. The analysis of the sample would then be done. Results were printed out as the analysis was taking place. The same purging and drying process was completed between every sample analysis to prevent cross-contamination. Another precaution taken to prevent cross-contamination was to analyse the samples in order of least presumed radon to most presumed radon i.e., surface water samples

were analysed before groundwater. According to the RAD7 Instruction Manual, the device works by using an electrostatic collection of alpha emitters with a spectral analysis. The passivated ion-implanted planar silicon detector SNIFF mode counts polonium-218 decays while the NORMAL mode counts both polonium 218 and polonium 214 decays (Durrige Company Inc, 2022).

**Table 5-2 Time after sampling and the decay correction factors to be applied (Durrige Company Inc. 2022)**

Hours	Decay Correction Factors
0	1.000
1	1.008
2	1.015
3	1.023
4	1.031
5	1.038
6	1.046
7	1.054
8	1.062
9	1.070
10	1.078
11	1.087
12	1.095

**Table 5-3 RAD7 Specifications taken from the RAD7 Radon Detector Product Brief (2019).**

<b>Technology</b>	Passivated Implanted Planar Silicon Detector Enables high resolution alpha spectroscopy of decay energies
<b>Sensitivity</b>	0.0067 cpm/(Bq/m <sup>3</sup> ) (SNIFF mode) 0.013 cpm/(Bq/m <sup>3</sup> ) (NORMAL mode) Virtually background-free raw-data readings
<b>Spectral Resolution</b>	50 keV: high enough for independent radon and thoron measurements and near perfect <sup>210</sup> Pb background rejection
<b>100% immune to <sup>210</sup>Po background build-up over life of instrument</b>	Yes
<b>Operating Range</b>	4–750 000 Bq/m <sup>3</sup> 4–7 500 000 Bq/m <sup>3</sup> (with optional Range Extender accessory) RAD7 + Range Extender provide 3.75x AlphaGuard range, maintain accuracy over lifetime, at a significantly lower price
<b>Response Time</b>	15 minutes (SNIFF mode) 3 hours (NORMAL mode)
<b>Instrument calibration error</b>	± 5%
<b>Intrinsic Background</b>	0.2 Bq/m <sup>3</sup> for lifetime of the instrument

### 5.2.5 Aquaread AP-5000 (Aquaprobe)

The Aquaread AP-5000 was used in the field to measure the following parameters: temperature, pH, dissolved oxygen (DO), electric conductivity (EC), total dissolved solids (TDS), salinity (SAL), oxidation reduction potential (ORP), nitrate (NO<sub>3</sub><sup>-</sup>), nitrite (NO<sub>2</sub><sup>-</sup>) and ammonium (NH<sub>4</sub><sup>+</sup>). The Aquaread optical electrodes are described as being standalone, fixed frequency fluorometers specifically tuned to excite and detect

fluorescence of selected substances in water. They do this by emitting short pulses of high energy light at the excitation wavelength and respond to fluorescence in the detection range. Inaccuracies in measurements can be due to microbiological species, compounds which fluoresce at similar wavelengths and differences in fluorescence caused by temperature, ambient light, and turbidity.

**Table 5-4 Ion Selective Electrodes Detailed Specification taken from the Aquaread Manual (2021)**

<b>Ammonium</b>	<b>Range</b>	0 – 9,000mg/L (ppm)
	<b>Resolution</b>	2 Auto-range scales: 0.00 - 99.99 mg/L, 100.0 – 8,999.9 mg/L
	<b>Accuracy</b>	± 10% of reading or 2ppm (whichever is greater)
	<b>MLD*</b>	1.0 ppm
	<b>Interfering Ions**</b>	Potassium, Sodium and Magnesium
	<b>pH Range</b>	5–8
<b>Nitrate</b>	<b>Range</b>	0–30 000mg/L (ppm)
	<b>Resolution</b>	2 Auto-range scales: 0.00–99.99 mg/L, 100.0–29 999.9 mg/L
	<b>Accuracy</b>	± 10% of reading or 2ppm (whichever is greater)
	<b>MLD*</b>	0.5 ppm
	<b>Interfering Ions**</b>	Chloride, Bromide, Fluoride, Sulphate, Chlorate and Perchlorate
	<b>pH Range</b>	3–10
<b>NOTES</b>	<p>* Minimum Level of Detection</p> <p>** Each ion selective electrode is prone to interference from ions that are similar in nature to the target ion. The main interfering ions for each electrode type are listed here. If the water under test contains interfering ions, the electrode will produce erroneous readings. Ion Selective Electrodes are not recommended for use in brackish or salt water due to the high level of interfering ions.</p>	

### 5.3 TRACER TESTS

In order to study the unsaturated flow behaviour of dissolved compounds through the vadose zone a wide range of environmental and/or artificial tracers can be used. Generally, contaminants that are released at the surface can migrate through the vadose zone and pollute the underlying aquifer (Zhuang et al., 2021). In terms of the risks associated with contaminating an aquifer system, it is vital to gain an understanding of the fate and transport of contaminants in the vadose zone. Although advection and dispersion are considered the main transport mechanisms, further evidence suggests that solute diffusion in the vadose zone is a key parameter that affects solute residence times in both the liquid and gas phase. While the flow mechanisms in unsaturated unconsolidated material have been studied in considerable detail (Freeze et al., 1979; Nimmo, 2005; Bear et al., 2012); the practical implications of this research for monitoring groundwater contamination within the vadose zone have often been neglected. Despite the advancement in understanding contaminant dispersion in relation to soil water content (Bear et al., 2012), the vadose zone has not received sufficient attention as a crucial monitoring area above the water table. As mentioned, the principal fate and main transport mechanisms of concern in the subsurface include advection, molecular diffusion, mechanical dispersion, hydrodynamic dispersion, sorption, and decay. In terms of solute migration, the solute can only be transported by one or a combination of the above-mentioned transport processes if it is dissolved in water.

Environmental (or natural) tracers are chemical substances measured in groundwater that are either naturally present or produced because of man’s activities, but not specifically released for tracing purposes; in contrast, artificial tracers are deliberately introduced into a system. In addition, tracers can be categorised in terms of being stable (e.g.  $^{18}\text{O}$ ,  $^2\text{H}$ , salts, solid tracers and fluorescent dyes) or unstable (e.g. radioactive; subject to biodegradation;  $^{14}\text{C}$ ; rhodamine WT); whether they are of natural or anthropogenic origin; whether their delivery to the environment is natural, accidental, or deliberate (Ho et al., 2006). Tracers are also useful for

characterising water flow in the vadose zone and to infer environmental processes. In terms of its practicality of use, the main differences between environmental and artificial tracers are the spatiotemporal timescales about which they provide information; environmental tracers generally provide information on processes that have occurred over many years and over larger spatial scales, while artificial tracer studies have a shorter time frame (usually measured up to several years) over a relatively small area (Cook, 2015). A prerequisite for the application of tracers is that the spatial or temporal differentiation of tracer signatures should exceed the sampling and analytical precision. These differentiated isotopic signatures can be inherent from the infiltrating water or acquired during passage of water through the vadose zone and rocks where the composition of dissolved substances takes place (Wachniew, 2015).

The ideal characteristics of tracers include being non-toxic and easily transportable, soluble, and clearly visible (in the case of dye tracers), possessing a stable spectrum, exhibiting high detection sensitivity, and being affordable and widely accessible. Moreover, tracers should not experience noteworthy hinderance from the soil or aquifer matrix, maintaining their non-reactive nature (conservative) and allowing for easy measurement. (Flury et al., 2003; Geyh et al., 2008). An ideal tracer should display these characteristics; however, no single tracer may meet all these requirements (Singhal et al., 2010). The subsurface displays substantial heterogeneity and anisotropy, creating an opportunity for the application of tracer techniques. Consequently, these techniques aid in effectively narrowing down the properties of the system under investigation. (Leibundgut et al., 2011).

There are two basic groups of tracers:

1. Environmental tracers encompass naturally present dissolved constituents, isotopes, and physical properties as well as chemical components found in water. By examining their spatial and temporal variations, valuable insights can be gained regarding the movement and behaviour of water and solutes within the environment.
2. Artificial tracers, on the other hand, are deliberately introduced into the hydrological system in order to deduce information about environmental processes.

A systematic review of tracer tests is available in Van Wyk et al. (2024), and conducting tracer tests is shown in Figure 5-6(a).



**Figure 5-6 (a) Conducting tracer tests and (b) using the infrared thermography technique (photographed by Maoyi and Van Wyk, 2024).**

## 5.4 INFRARED THERMOGRAPHY

Infrared thermography, a non-invasive imaging technique, has a unique ability to capture and process thermal information through images or videos. This is achieved by detecting the infrared radiation emitted by the target object and converting it into a temperature value above absolute zero (Pappalardo et al., 2016). Unlike the human eye, which is limited to visible light, infrared thermography can analyse or monitor thermal patterns, thereby indicating the thermal properties of the object (Vollmer and Möllmann, 2018).

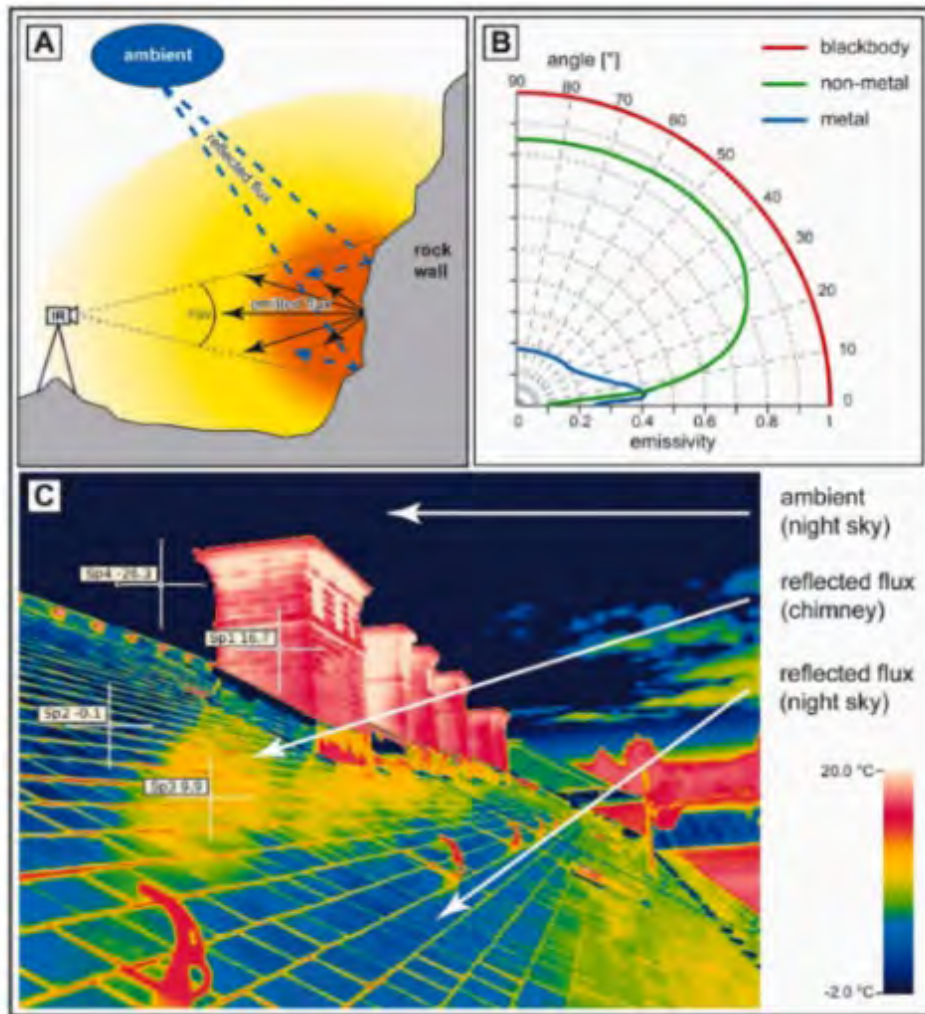
The principle of infrared thermography is based on the link between an object's surface temperature and its emitted infrared radiation. This direct correlation allows for the derivation of accurate temperature values by analysing the target object's radiation (Meola, 2012). Infrared cameras, with their ability to generate thermograms or visible images constructed from this radiation, provide a detailed depiction of the surface temperature variations on the target object. Different colours on the thermogram correspond to various temperature levels, further enhancing the accuracy of the analysis and enabling the identification of slight thermal abnormalities. However, Usamentiaga et al. (2014) explain that temperature variation also depends on the material's thermal properties and subsurface anomalies, which may result in different temperatures on a surface.

Infrared thermography offers a wide range of practical applications with its two distinct methods: active and passive. Passive infrared thermography, a natural process without external stimulation, measures the infrared radiation that an object's surface naturally emits. This method is beneficial when external stimulation is not feasible or desirable (Herraiz et al., 2020). Conversely, active thermography employs an external source to create thermal contrasts on an object's surface, enhancing the detection of subsurface anomalies or material qualities (Hung et al., 2009). This versatility of infrared thermography, with its ability to adapt to different scenarios and requirements, has potential uses in various industries.

The Institute of Infrared Thermography (2023) highlighted the limitations of infrared thermography in specific applications, which included the emissivity, reflective surfaces and depth limitations. The ability of an object to emit infrared light was measured by its emissivity, since various materials have different emissivity values. The accuracy of temperature measurements can also be influenced by the emissivity value of the target object. For example, shiny metals often have a low emissivity. As a result, incorrect temperature readings can occur (Biscarini et al. 2020). In addition, infrared radiation can be reflected off shiny surfaces, where 'false positives' or misleading readings may result from this reflection, mainly if the camera detects the reflected infrared light from a hotter item nearby. Infrared thermography is very useful for surface-level inspections. Conversely, the ability of this thermal imaging technique to sense thermal anomalies through objects is limited, as it might not always identify thermal variations deep within walls (Institute of Infrared Thermography 2023).

Furthermore, the accuracy of infrared thermography is significantly influenced by several factors, including ambient conditions and calibration of the infrared camera. Ambient conditions, such as different weather conditions, can influence wind, rain and sunlight, which can influence the surface temperature of an object. For example, direct sunlight warming a wall can mask underlying features like insulation gaps. Several additional variables might affect how thermal radiation is measured, including radiation from surrounding light sources sometimes referred to as "parasite radiation", which can lead to inaccurate temperature readings (Mineo et al., 2015). The atmosphere not only absorbs thermal radiation but also disperses it, acting as a medium for transmitting the radiation Figure 5-7. Therefore, a calibration setup is necessary for accurate measurements, as the substance's temperature affects the radiation. Prendes-Gero (2013) emphasised that the higher the temperature, the more intensely the infrared energy is emitted. Therefore, the total radiation received by the infrared camera is a combination of the emission of the target object, the surroundings reflected by the object, and the atmosphere. Moreover, the efficacy of an infrared camera depends on the operator, much like any other complex instrument. It takes knowledge of the inspected object, training, and experience to interpret thermographic images correctly.

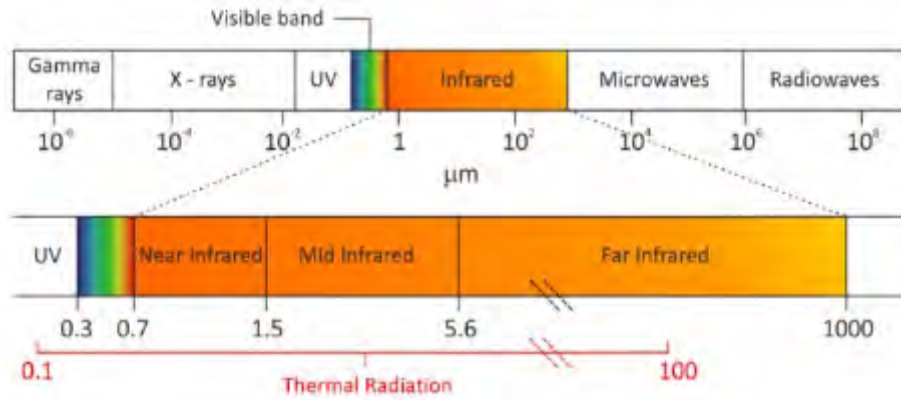
Conducting infrared thermography tests are shown in Figure 5-6(b).



**Figure 5-7** Examples of the problem of reflectivity in IR thermography application. (a) Sketch of possible ray paths, showing that different portions of skylight are reflected from different rockwall positions. (b) Typical course of the angular dependence of the emissivity for metal and non-metal bodies. (c) IRT image of chimneys over a roof in Garaz, Austria: The warmer chimneys cause distinct reflections on the roof shingles, while the night sky causes a cool reflection (Biscarini 2020).

#### 5.4.1 Thermal radiation infrared bands

Infrared bands refer to the specific ranges of infrared radiation with longer wavelengths than visible light but shorter wavelengths than microwaves. The electromagnetic spectrum is usually divided into several bands and the infrared band is important in infrared thermography located between the visible and microwave bands with wavelengths ranging from 0.78 to 1000  $\mu\text{m}$ , as shown in Figure 5-8 (Mineo and Pappalardo 2021). Infrared bands are employed in thermal imaging to create images based on object temperature differences. This is centred around the idea that any object heated above absolute zero will release electromagnetic radiation from its surface into the infrared region of the electromagnetic spectrum. Therefore, the different surface temperatures of the objects will be detected by their infrared radiation and recorded by applying infrared thermography (Zhou et al., 2022a).



**Figure 5-8** The electromagnetic spectrum with the range of occurrence of thermal radiation and infrared band highlighted (Mineo and Pappalardo 2021).

According to Usamentiaga et al. (2014), the wavelength regions are not sharply defined and differ for different disciplines, where the most common infrared wavelengths used in infrared thermography include:

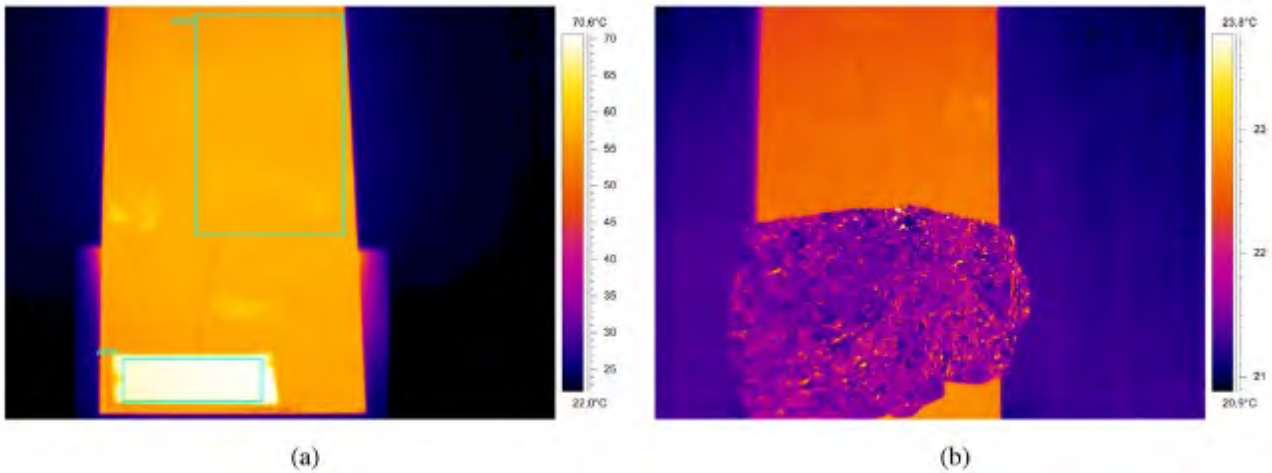
1. Near-infrared (NIR) from 0.8  $\mu\text{m}$  to 1.7  $\mu\text{m}$
2. Short-wavelength infrared (SWIR) from 1  $\mu\text{m}$  to 2.5  $\mu\text{m}$
3. Mid-wavelength infrared (MWIR) from 2  $\mu\text{m}$  to 5  $\mu\text{m}$
4. Long-wavelength infrared (LWIR) from 8  $\mu\text{m}$  to 14  $\mu\text{m}$ .

Due to their unique properties, mid- and long-wavelength infrared light play a significant role in infrared thermography. These wavelengths (2  $\mu\text{m}$  to 5  $\mu\text{m}$  and 8  $\mu\text{m}$  to 14  $\mu\text{m}$ ) are the most widely utilised due to their ability to pass through atmospheric windows, making them ideal for thermal imaging cameras. Most thermal imaging cameras are sensitive to the spectral range of 3–5  $\mu\text{m}$  or 8–14  $\mu\text{m}$  because of atmospheric windows (Frodella et al., 2017).

#### 5.4.2 Emissivity

*Emissivity* is a surface property that characterizes all forms of matter capable of emitting thermal radiation; Each object's emissivity measures its capacity to absorb and release heat energy in the infrared spectrum ranging from 1  $\mu\text{m}$  to 0.1 cm (Mineo et al. 2015). The radiation released depends on the material's temperature; the higher the temperature, the more intensely the infrared energy is released. Subsequently, a portion of the radiation received by the body can be absorbed, reflected, or transmitted (Zimmerman and Zimmerman, 2012, cited by Sass et al., 2023).

A target object's emissivity can either be determined by applying the contact or material method (Biscarni et al. 2020). The reason for the various methods to determine emissivity is because slight variations in emissivity can lead to significant variations in the measured temperature. As shown in (Figure 5-9), a thermocouple can be used to get a reference temperature for the contact method. Contrarily, in the material method it is more common to use the same infrared device for temperature measurement at low temperatures and to attach a piece of electrical tape with a known emissivity to the sample. Thereafter, the emissivity configuration is then adjusted until the actual temperature is observed, at this point the final emissivity configuration is determined (Biscarni et al. 2020).



**Figure 5-9 Infrared images acquired during calibration. (a) Measurement of the emissivity using the reference emissivity material method. (b) Measurement of the reflected temperature using the reflector method (Biscarini et al. 2020).**

Rocks are materials with high emissivity; however, this also depends on the rock type (Mineo & Pappalardo, 2021). Table 5-5 shows the different emissivity ranging between 0.92 and 0.84, and some of the radiation emitted from natural rock outcrops is reflected from the surrounding environment. Sass et al. (2023) explained that the emissivity of a rock is also influenced by its dampness, surface roughness, rock type, surrounding weather conditions, and angle to the camera axis.

**Table 5-5 Emissivity of different rock types (Mineo and Pappalardo, 2021)**

Rock Type	Average emissivity	Emissivity range
Calcarenite	0.985	0.98-0.99
Calcisiltite	0.95	0.94-0.96
Limestone	0.95	0.94-0.96
Travertine	0.965	0.96-0.97
Dolostone	0.945	0.94-0.95
Marble (polished)	0.956	0.95-0.96
Marble (smooth)	0.98	0.97-0.99
Quartzarenite	0.92	0.91-0.93
Sandstone	0.925	0.92-0.93
Granite (smooth)	0.92	0.91-0.93
Granite (polished)	0.84	0.83-0.85
Red granite (smooth)	0.935	0.92-0.95
Red granite (polished)	0.845	0.83-0.86

## CHAPTER 6: PURPOSE AND OUTCOMES OF CASE STUDIES

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### 6.1 INTRODUCTION TO THE CASE STUDIES

Case studies are used to verify the use of different techniques and to provide context as to why the investigation of these areas are important. Changing the water storage and movement affect these systems, and it is exacerbated by increased development and population growth. The impacts are both in quality and quantity, and one should therefore anticipate the consequences of not planning properly for the anticipated change in water budgets.

The theory of this books follows on Dippenaar et al. (2022) and all the preceding work. Here the focus is on relevant new literature and proper descriptions of the relevant methods. The case studies are now presented in a concise format here with the elaborated parts in the second publications and the associated articles, PhD theses and MSc dissertations.

The case studies are placed separately to provide the background information, large data sets, and elaborate methodology that are not necessary for the book. This can be used to understand where the data come from and how it was interpreted to eventually contribute to the new findings. The case studies are very important seeing that they provide the first data points in the field and that continue in the laboratory. The case studies provide the references to the relevant theses and dissertations, as well as all the associated published articles.

The case studies were selected keeping the following in mind:

- Accessibility of sites and sample localities are important seeing that those determine the acquisition of field data.
- Different methods should be used on similar sites or in different laboratory techniques to relate the correlation between different methods.
- Different case studies relate to different soils, rocks and water conditions that are affected in different ways by climate and topography.
- Human impacts exacerbate problems associated with many natural problems given that the hydraulic and mechanic properties of the materials are altered.
- The members of the project team assisted to select and contribute to their own case studies based on their individual research-based passion, competence and skills.

The case studies contributed to our understanding of the complex systems in the vadose zone where human development impacts the natural environment. Developed areas are heterogeneous and anisotropic because spatial and vertical disruptions affect all the natural systems and their associated biodiversity and hydrology. Our negative impacts are inevitable and they are exacerbated by our development in areas where we don't understand the complexity of the materials that we investigate. There are many tiers in the process from first investigation to complete development where each time the factor of safety increases and the science is toned down to be appreciated by the general public. That is the purpose and it is correct, but it should not ever make the contribution of the scientific foundation less important or redundant.

The case studies therefore culminate in this part where the outcomes are presented based on the knowledge gained, and for all case studies presented in this chapter is to make it possible for the reader to navigate it into to Case Studies book, and all the case studies were conducted in South Africa. The case studies are listed in Table 6-1, and will be referenced as chapters in an edited volume.

**Table 6-1 Vadose Zone Study Areas (VZSAs)**

Number	Title	Reference
VSZA16	Hydraulic and Mechanical Properties of Completely Weathered Bedrock (Eastern Escarpment)	§6.2 Swart 2026a
VSZA 17	Weathering Profiles of Mn-Rich Dolomite in Humid to Sub-Arid Environments	§6.2 Swart 2026b
VSZA18	Contaminant Transport in a Fractured Rock System using Tracers and Isotopes	§6.3 Van Wyk 2026
VSZA 19	Analysis of Unsaturated Flow Behaviour through Discontinuities in Rock Mass	§6.4 Maoyi & van Rooy 2026
VSZA 20	Fresh Rock Granite Weathering Rims	§6.5 Bruyns 2026
VSZA 21	Urban Water related to Roodeplaat Dam and Hartbeespoort Dam	§6.6 Visagie & Smith 2026
VSZA 22	Timbavati Goundwater and Surface Water Quality	§6.7 Raible 2026

## 6.2 RESIDUAL SOIL AND WEATHERED ROCK

The references for this section are as follows:

Swart D. (2026). Chapter 2: Hydraulic and Mechanical Properties of Completely Weathered Bedrock (Eastern Escarpment). In: Dippenaar MA. (e.d). Framework for Natural and Anthropogenic Changes to the Urban Vadose Zone: Case Studies. Water Research Commission.

Residual soil and completely weathered rock were sampled from diabase dykes (Tzaneen), andesitic to basaltic lavas (Dullstroom), diabase dykes (Tzaneen), and Mn-rich dolomite (Graskop)

The methods included field work at existing exposed weathering profiles, excavation by means of machine dug test pits, and/or existing borrow pits or excavation faces. Undisturbed block and tube samples were retrieved together with disturbed soil samples. The samples were retrieved, stored, and analysed to ensure repeatability and comparability of results received for the different materials for the different analyses, including X-Ray Computed Tomography (XRCT). The tube samples were scanned with the samples rotated 360°, leading to the construction of two-dimensional and three-dimensional slices. was used

The study found that water moving through the profiles causes chemical reactions that release ions from the minerals that make up the rock and then leach away. This decreases the dry density and increases the void ratio, resulting in volume change due to weathering that opens the fissures.

In competent rock, water often flows in fractures (secondary pores) as opposed to water flowing through open pathways with a high flow rate, causing erosion to take place and move material from the weathered fractured face. Pedogenic coatings typically comprise goethite and hematite (Fe-oxides) with high density that were highlighted in the 2D slices due to X-ray attenuation.

XRCT was demonstrated to be the most effective technique to characterize metastable materials such as completely weathered rock. This improves the accuracy of soil classification, moisture flow assessment, and dual-porosity applications. Limitations of XRCT from this study include differentiation between minerals with similar density in close proximity, and distinguishing between water and air in pores. The scans show that the pores in rocks that are less weathered are not effective and exist in the relict structure. Primary porosity increases with weathering, causing open fissures to become flow paths. Pedogenic materials increase in the matrix, showing that the completely weathered rock becomes a dual-porosity system.

The reference for this section is as follows:

Swart D. (2025). Chapter 3: Weathering Profiles of Mn-rich Dolomite in Humid to Sub-humid Environments. In: Dippenaar MA. (e.d). Framework for Natural and Anthropogenic Changes to the Urban Vadose Zone: Case Studies. Water Research Commission.

The work focused more on Mn-rich dolomite, seeing that those areas underlie highly developed areas in South Africa. Dolomite residuum includes wad and residual dolomite, and wad can be structured or non-structured. Lenses of completely weathered chert can occur in the wad, and weakly to strongly cemented Fe and Mn nodules.

### 6.3 USE OF TRACES IN A FRACTURED ROCK SYSTEM

The reference for this section is as follows:

Van Wyk Y. (2026). Chapter 4: Contaminant Transport in a Fractured Rock System using Tracers and Isotopes. In: Dippenaar MA. (e.d). Framework for Natural and Anthropogenic Changes to the Urban Vadose Zone: Case Studies. Water Research Commission.

The same site was used as for §6.4 and includes the relevant background information for the fractured quartzite quarry. This study, however, used fluorescent dyes including uranine and rhodamine WT. This was to investigate subsurface flow and connectivity using several boreholes that provided successful breakthrough in one borehole (BH3), and with no detection in the other six boreholes. Breakthrough curves (BTCs) and flow rate data are integrated in an equation to evaluate actual tracer recovery against predictions made by models. Parameters such as longitudinal dispersivity, effective diffusion coefficients, and fracture velocity characteristics are used to validate and refine the parameters to enhance the accuracy of tracer behaviour simulation in complex fractured systems.

The Multi-Flow Inversion of Tracer Breakthrough Curves (MFIT) assumes that movement from the injection site to the monitoring points happens within independent, distinct, one-dimensional channels. The software results showed 12 flow channels discharging at 3.24 m<sup>3</sup>/h, and the Conceptual Site Model (CSM) for the fractured quarry emphasises the relationship between geology, mining activities, and hydrological processes. For mine closures, insights can be provided to enable effective mitigation strategies to be designed. This can be achieved by combining tracer data with analytical models to develop a robust CSM to account for, in wet and dry seasons, the complex groundwater and surface water dynamics, flow patterns, and fracture networks.

### 6.4 ANALYSIS OF UNSATURATED FLOW BEHAVIOUR THROUGH DISCONTINUITIES IN ROCK MASS

The reference for this section is as follows:

Maoyi M., Van Rooy JL. (2025). Chapter 5: Analysis of Unsaturated Flow Behaviour . In: Dippenaar MA. (e.d). Framework for Natural and Anthropogenic Changes to the Urban Vadose Zone: Case Studies. Water Research Commission.

The stability of rock masses and slopes may be influenced by changing moisture contents due to water flowing through interconnected discontinuities in highly fractured rock masses under unsaturated conditions. A case study examining unsaturated flow behaviour through discontinuities in rock mass was referenced to study this phenomenon. The study focused on a slope failure in an open-pit quarry operation, where varying moisture conditions led to interflow through discontinuities, ultimately causing a localised planar slope failure. This highlights that identifying discontinuity sets present in rock mass does not always indicate which sets will have the most significant impact on flow behaviour in rock masses, potentially impacting rock mass stability.

Investigating the interplay of unsaturated flow behaviour and the rock mass characteristics is necessary. Therefore, the primary aim of this case study is to contribute to understanding flow patterns in rock masses by using infrared thermography methods and photogrammetry for unsaturated flow behaviour through discontinuities in rock mass.

The methodology employed in this case study includes characterising rock masses and analysing flow behaviour to understand flow through discontinuities in rock masses. The flow chart (Figure 6-1) illustrates the workflow process, including fieldwork for data acquisition and the application of remote sensing techniques such as photogrammetry and infrared thermography to rock mass studies. Due to the variability in geotechnical parameters and the potential for measurement errors that could lead to misinterpretation of data, the traditional scanline method to map discontinuities was complemented with photogrammetry. In addition, identifying zones of saturation is important; thus, infrared thermography is used to detect flow patterns. More detailed explanations of the experiments can be found in the case study.

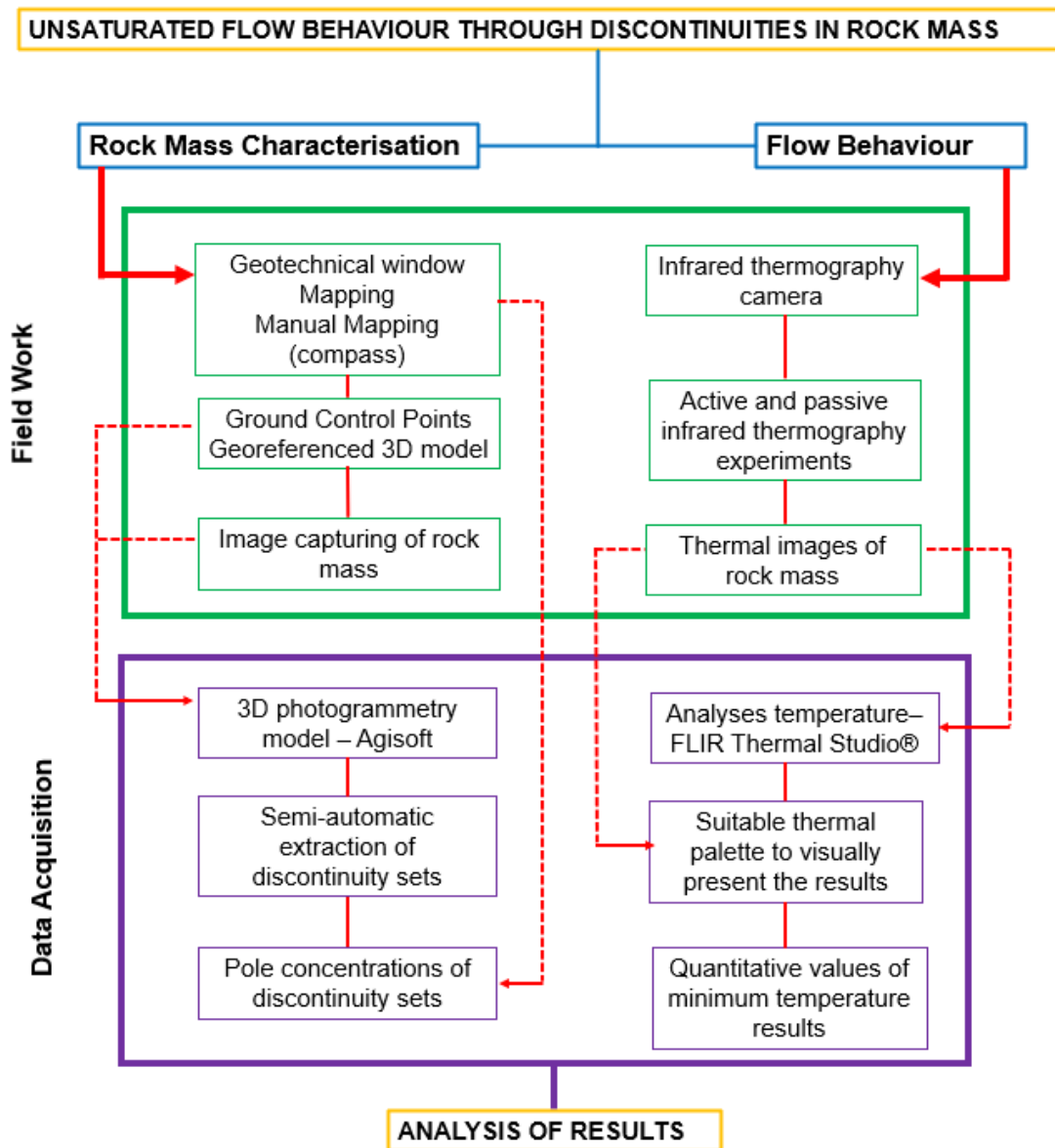


Figure 6-1 Flow chart showing the work process for this case study (Maoyi 2026)

## 6.5 FRESH ROCK GRANITE WEATHERING RIMS

The reference for this section is as follows:

Bruyns, L. (2025). Chapter 6: Fresh Rock Granite Weathering Rims. In: Dippenaar MA. (e.d). Framework for Natural and Anthropogenic Changes to the Urban Vadose Zone: Case Studies. Water Research Commission.

Propagation of weathering into rock materials from joints was investigated in this study, and the methods included X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF) spectroscopy, weathering indices, Joint Compressive Strength (JCS), Joint Roughness Coefficient (JRC), microscopy (thin sections), and Scanning Electron Microscopy (SEM). Different rocks were analysed, but only the granite formed part of this project to test the methods and outcomes.

Clear weathering effects were revealed by petrographic analyses of adjacent rock material, and fractures that originated at the exposed surface are due to weathering processes. Discolouration and weathering advanced along the fractures, highlighting the fractures as being the primary pathways for the propagation of weathering. Granite experiences limited chemical weathering based on the weathering indices, and granite showed little impact on the material strength despite propagating weathering. Granite did show a linear relationship between both the degree and depth of visible propagation of weathering.

## 6.6 URBAN WATER QUALITY IN RIVERS AND DAMS

The reference for this section is as follows:

Visagie M., Smith N. (2025). Chapter 7: Urban Water – Roodeplaats Dam and Hartbeespoort Dam. In: Dippenaar MA. (e.d). Framework for Natural and Anthropogenic Changes to the Urban Vadose Zone: Case Studies. Water Research Commission.

The Upper Crocodile and Jukskei River catchments have different land uses that affect surface water quality differently. The tributaries of the Roodeplaats Dam (Hartbeesspruit) and Hartbeespoort Dam (Jukskei River) run in part through Pretoria and Johannesburg, respectively, meaning that urban impacts may affect the water quality.

The Jukskei River, which flows past a large township, had higher total suspended solids (TSS) concentrations and lower dissolved oxygen (DO) concentrations, with the DO possibly being due to oxygen being consumed by bacteria during decomposition of organic material from the township. This river also had a rise in nitrate, ammonium, orthophosphate, and total organic carbon, and very high microbial counts in the river. The nitrates may also be linked to blasting in a quarry. This shows one example of the anthropogenic impacts on the surface water quality in cities.

The Colbyn Wetland in Pretoria formed part of the Hartbeesspruit that was investigated as part of the Roodeplaats Dam tributaries. An industrial area may cause a rise in ammonium concentration, and blasting at a quartzite quarry may also contribute to nitrates in this system.

Mixed land uses that include agriculture, industrial activities, formal residential areas, and informal residential areas all influence the urban water quality. Malfunctioning wastewater treatment plants (WWTW) together with increasing population density are the biggest impacts on the water quality, and informal settlements worsen the water quality because of inadequate sanitation together with poor waste management and derelict stormwater drainage. Agricultural impacts have a smaller impact.

## 6.7 ISOTOPES AND RADON IN A CATCHMENT

The reference for this section is as follows:

RAible K. (2025). Chapter 8: Timbavati Water Quality. In: Dippenaar MA. (e.d). Framework for Natural and Anthropogenic Changes to the Urban Vadose Zone: Case Studies. Water Research Commission.

New methods were tested to allocate the origin and movement of water. Isotopes and radon were used to determine the origin of different waters in the environment, as was evident in the study of the Timbavati Catchment. Radon is a field method, seeing that it is analysed well within the half-life but during the same day of sampling. The equipment has been used (with accessories) to sample hydrogen in soils, meaning that one can trace the movement of both radon and hydrogen through the vadose zone. Isotopes (hydrogen and oxygen) are analysed in a laboratory and the results are used to link the different isotopes with respect to rain, surface water and groundwater. Three different geological lithologies underlie the area.

Most groundwater and all surface water were found to be alkaline, with mean pH values being 7.48 and 8.30, respectively. In the water samples, several samples exceeded recommended guidelines, including (in different instances) fluoride exceeding the WHO guideline of 1.5 mg/L, arsenic and nickel at toxic levels. Nitrate levels were also read in the field with an Aquaread.

Nitrate concentrations were generally lower in the surface water samples than the groundwater samples. The source of nitrates is most likely due to human, animal, and agricultural waste, given its proximity to communities with pit latrines and cattle kraals that were upstream.

Groundwater had a lighter mean isotopic composition compared to surface water and groundwater, meaning that groundwater is due to recharge from heavy rainfall events. Radon concentrations showed no link to geology, but the detection in surface water samples may indicate the discharge of groundwater into surface water (rivers and dams).

Groundwater and surface water characterization showed relationships and patterns between the local geology and geography with the quality and geochemistry of the water. "Elevated nitrate concentrations and heavy metals in certain groundwater samples highlight the impact of anthropogenic activities on water quality".

## CHAPTER 7: OUTCOMES AND WAY FORWARD

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### 7.1 ANTHROPOGENIC RECHARGE

Different aspects affect recharge, and it is increased or decreased based on various aspects that are associated with development or any form of anthropogenic change. Residential development can densify urbanised areas that have the associated new infrastructure, including high-rise buildings, factories, fuel storage facilities, landfills, roads and railways, tunnels and pipelines, and housing. These affect both the quantity and quality of water, meaning that recharge can be increased and result in deteriorating water quality together with this.

The 2026 floods in Worcester and the surrounding area show the devastation of water that removed infrastructure and vegetation that disrupts the surface water-groundwater system entirely. Here, the ponding water over the disrupted surface can increase infiltration, further saturating the subsurface. The flood waves from the ocean destroyed roads and buildings, thereby also creating more space for water ingress into previously sealed surfaces.

Some factors affecting anthropogenic and urban recharge include the following:

1. Leaking underground pipelines can be filled with water, sewage, or any other fluids that can be contaminated.
2. Irrigation of golf courses amounts to very large additional precipitation that is well above the annual rainfall.
3. Flooded basements and excavations will cause water to collect and infiltrate or seep out over time.
4. Canals that divert water from sealed surfaces or pipes can leak or have its outlet in a localised locality.
5. Blasting in quarries or any other place will induce more fracturing in the rock and thereby induce more water flow.
6. Sealed surfaces include pavements and roads that will cause water to flow onto the edges for further concentrated recharge.

Different phases of development exist, and our human impact can start in greenfield land where there is absolutely no human interference to those brownfield areas where development is continuing on developed land, with the latter being probably more prone to anthropogenic recharge (Figure 7-1). Other aspects increasing it include development that diverts or concentrates recharge, together with the influence of the intensity of the rainfall events.

Having more of these in the red zone will result in synergetic rather than additive consequences, where the quality and quantity impacts will be more pronounced than the individual components. In the case where it is not the same, for instance leaking pipes in a rural area, the anthropogenic recharge will be low (the example of the non-revenue water map in Figure 3-3).

Together with urban recharge, some anthropogenic and urban water quality impacts are imminent and include the following:

1. Petroleum storage facilities provide liquids and gas pollutants in the form of alkanes and aromatic hydrocarbons that can ignite and explode.
2. Mine activities with the associated metals and acidity associated with the activities and tailings.
3. Waste disposal and everything associated with the variety of wastes dumped in landfills.
4. Pollution of streams and rivers through using them for bathing and washing and throwing various wastes into the water.

5. Microbiological contamination associated with the introduction of coliforms and other microorganisms into the aquatic environments by human impact such as bathing, waste disposal, and decaying biota.

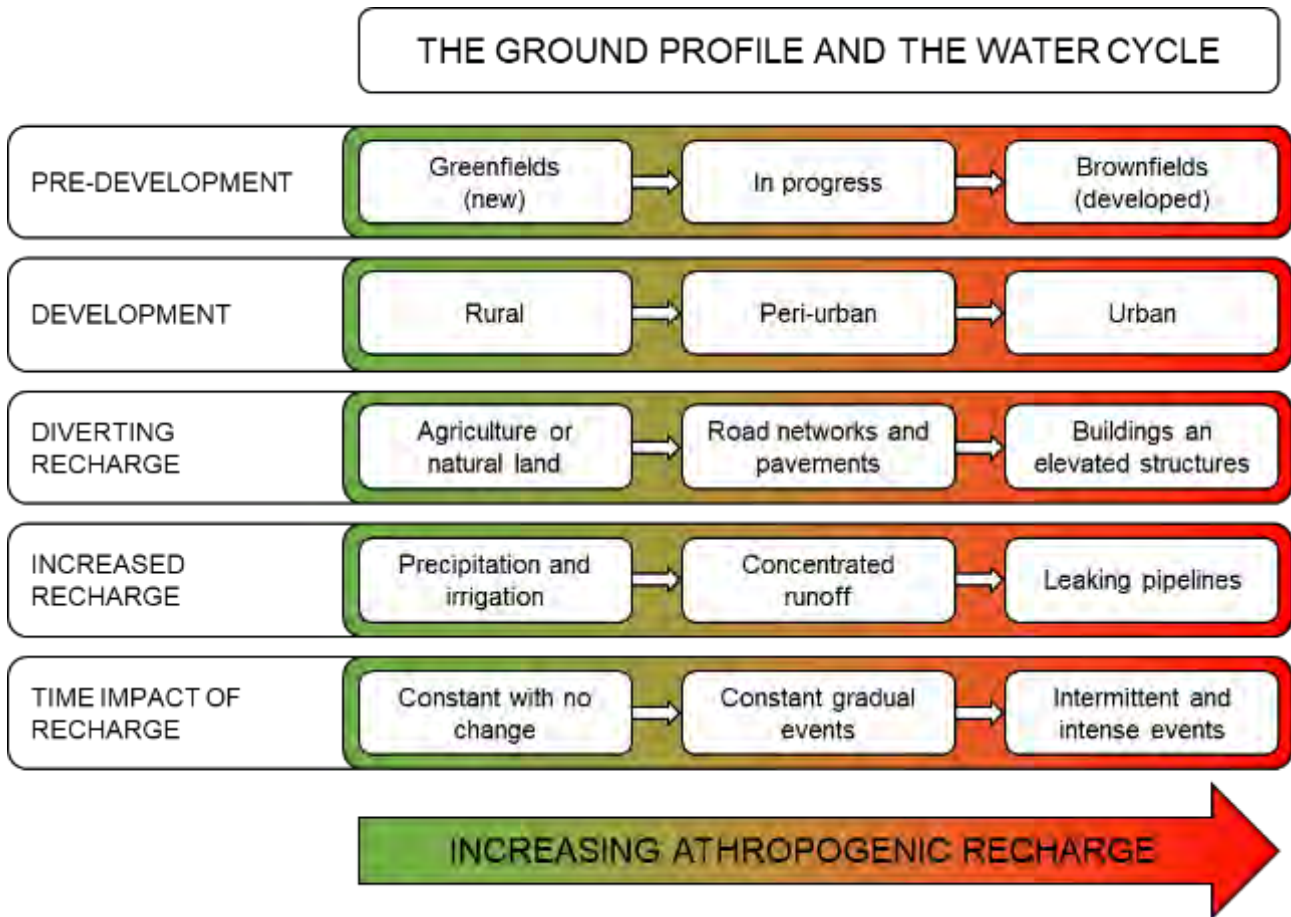


Figure 7-1 Anthropogenic influences on groundwater recharge

## 7.2 PROFESSIONALS AND FUNCTIONS

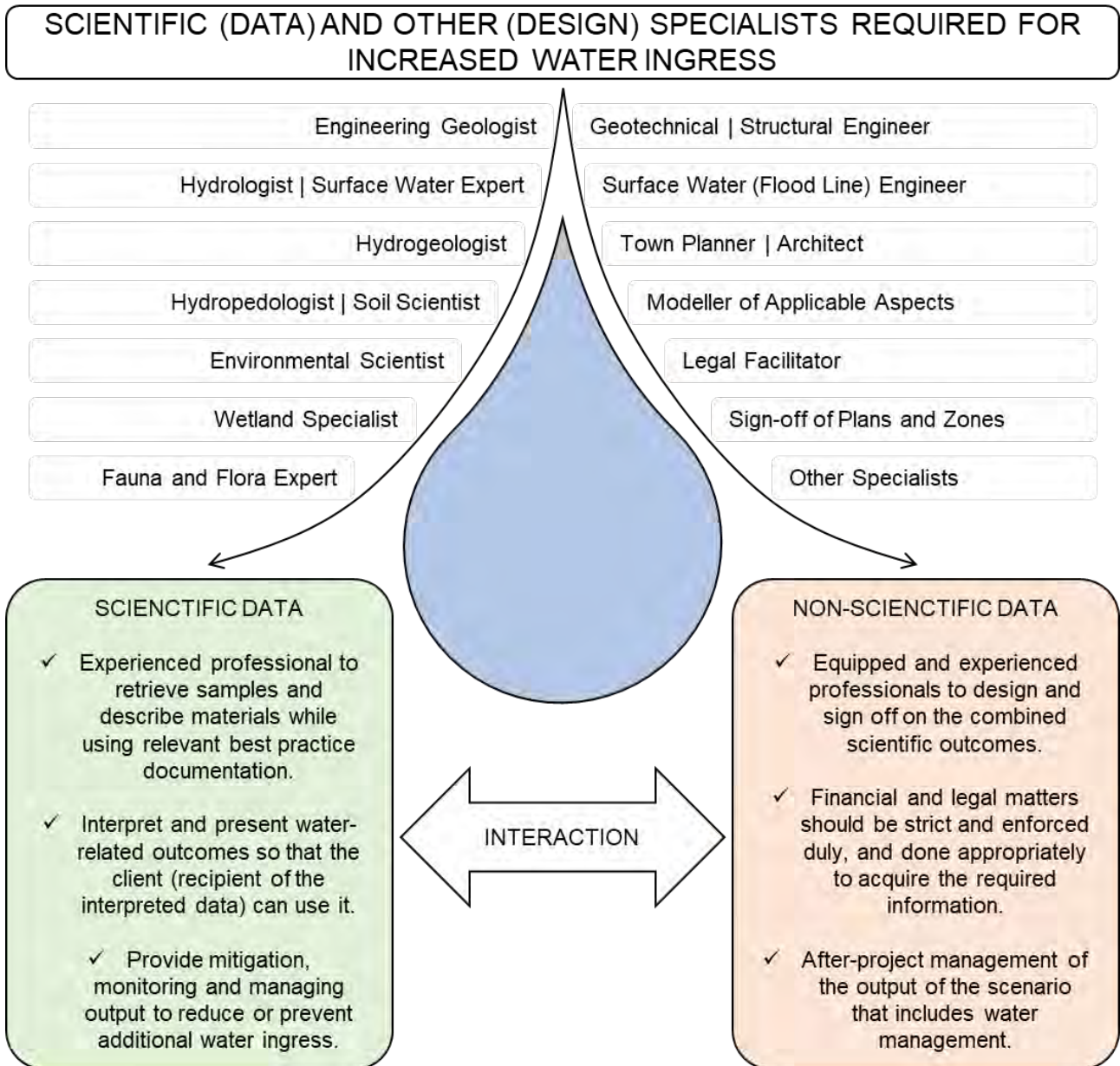
Different professionals serve different functions, and those are provided in Figure 7-2. Different specialists employ different techniques, but all of these presented here are in the engineering geology and hydrogeology domains. These are fundamental parts constituting the first data points and being responsible to provide all the non-science professionals with the defensible and useable data. It is important to establish the list of professionals who contribute to a single investigation. Science remains the first datapoint and therefore the technical foundation of any development. Scientists are there to establish an overview of everything that is to be affected by the proposed development. The input of specialists into the environmental impact assessment is there to ensure that all aspects have been covered, and that all interested and affected parties had the opportunity to participate.

The engineering geological investigation, for instance, is the one that the civil engineer needs to design suitable structures. The other investigations are there to define whether land is developable for soil water or ecological reasons. The land is usually developable if the consensus is that (1) the area is not in a defined riparian wetland of importance, and (2) the engineer does not outline it as 1:100-year flood lines.

Personal Protective Equipment (PPE) should always be available for in case it is needed, and to indemnify yourself from any potential mishaps. Ensure that you know what you are intrinsically liable for (for instance):

- Declaring an opening that you get into safe

- Declaring the water that you touch or get into to be safe.



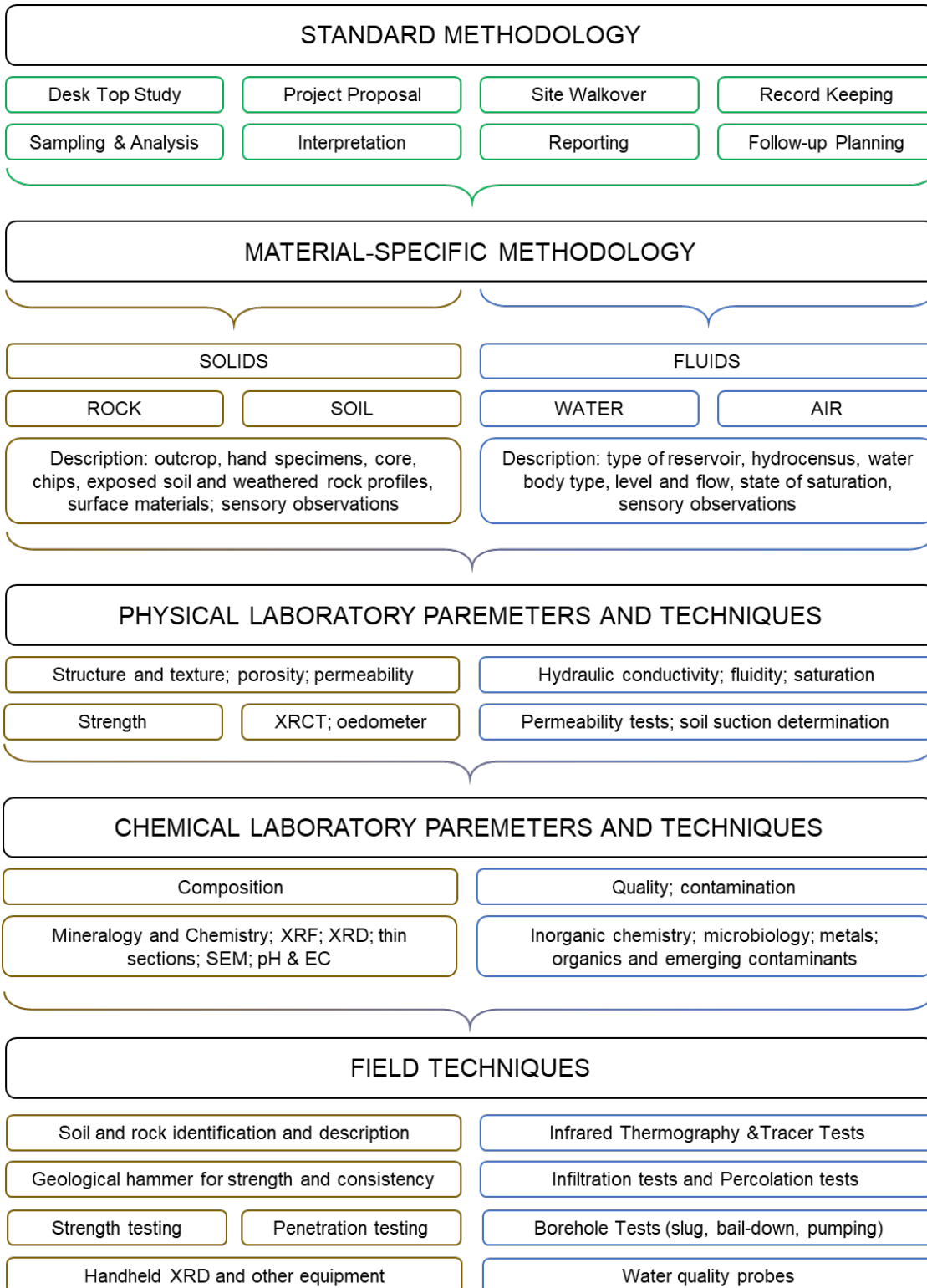
**Figure 7-2 Different data are generated by different professionals and both are required to assess the conditions.**

### 7.3 TECHNIQUES AND METHODS

Different techniques are used for different materials, and rock, soil, water and air almost always co-exist where these professionals operate. Some of the different methods and techniques to be employed are shown in Figure 7-3 and those can be used if and where they are appropriate. Shallow rock will be investigated differently that thick soils, and thick vadose zone will be investigated differently than shallow groundwater levels. Nonetheless, it is at the discrepancy of the professional to determine what is required.

A project proposal is done by any professional to dictate what work is being done. Some call this a quotation, but the purpose remains the same. It is important to state what is needed, and then to pre-empt for what a new

cost proposal with new scope of works will be required. Different techniques will be employed by different professionals in different capacities, but what is presented here is in the fundamental domain of understanding the subsurface water in context of the underlying soils and rocks.



**Figure 7-3 Different methods and techniques that can be used for the investigation of anthropogenic changes to the water cycle and ground profile**

The geoscientist and hydrologist are the individuals who have the obligation and capacity to work with these matters. This is not a domain where incompetent people can work. It is professional conduct to ensure that the

practitioner is capable to investigate the terrain, and to ensure that the development is done with the anticipated knowledge of what will happen in terms of water.

## 7.4 PROPOSED METHODS AND APPROACHES

The first rule here is to have the same person do the work, and/or to accompany and supervise the other people who are doing the work. The human error is increased with each person who does something slightly different to someone else. In the description of materials (Dippenaar et al. 2025), subtle changes in the description of colour or moisture will be interpreted as different materials, as will be the description of soil textures such as clay, silt, and sand (Swart et al. 2023). You still do the work yourself if you train someone to ensure that everything remains professionally usable and defensible. Sampling of water and soils should be done correctly, and with the appropriate methods and materials.

Artificial tracers and heat tracers were used to investigate the flow in a fractured rock quarry. The former is based on the injection of a substance and then measuring the advection rate (linear flow velocity) by detecting the tracer at an endpoint. For infrared thermography, the change in temperature is recorded, and the visual output is investigated. These two methods provide different means of determining flow rates. Together, they are synergistic and provide improved results. The engineering geological and hydrogeological expertise overlap here where the two professions work together for an improved unified outcome. The data are acquired for different purposes:

- The engineering geologist acquires this data to characterise the rock mass to improve the understanding of how water will move through it to affect its strength and stability.
- The hydrogeologist acquires this data to characterise the flow velocity of water and the advection of contaminants to provide input in the planning for water supply and protection.

The qualities of surface water and groundwater are influenced significantly by land use and urbanisation. Nitrogen compounds, metals, and microbiology are some of the very important contaminants that can easily become pollutants. Multiparameter field probes are useful to acquire immediate data to better plan the remainder of your field work. This can be verified by laboratory analyses to substantiate the finding. This project showed that the combination of field and laboratory data works better together, and that multiple sampling runs contribute to the dataset. Comparative studies (Timbavati Catchment, Roodeplaat Dam, Hartbeespoort Dam) strengthen the evidence for the methods used and for the problems posed.

The land uses on-site and upstream of the site are the most important first indicators of what should be anticipated. The Colbyn Wetland that is situated in Pretoria (administrative capital of South Africa) and its tributary, the Hartbeespoortspruit, are unique and should, in this context, be protected for its ecological and aesthetic importance, seeing that it is not common in urban areas.

Sampling for soils and using different and unique testing methods makes the extra time and effort worthwhile. The extra data not only assists the client, but it also makes you the professional more competent and knowledgeable in your topic and speciality. You become the expert because you acquire the know-how in the field to make judgements based on your knowledge and confidence. You become the mentor, and the person who can communicate that to the land use planner, engineer, environmental specialist, government official, municipal officer, or general member of the public. Create your own field sheets and your own operating procedure to ensure that everything that you do gets done the same every time that you do it.

With a water problem, the relevant parties have to attempt to get that problem identified and resolved. For this you need to do the following (Figure 7-4):

1. The first part is to find out all the important matters through queries as to what happened, and why it happened. Without questions, problems can't be solved, seeing that questions provide an open-ended starting point. [?].
2. The second part is about expanding as part of the resolution of your questions. [:]
3. The third part is about envisaging and planning with open-ended options and opinions. [...]
4. The fourth part is about finalisation and solutions with a forward-looking ending. [.]



Did you, or someone else, identify your water-problems?

Are your problems related to quantity, quality, or both?

Do your problems affect only you or other proximate receptors?

Do you have evidence of your problems?



Elaborate on your water-problems or introduce a collated summary.

Present the evidence for your type of problems (quantity and/or quality).



Identify and label the proximate receptors whether they are affected or not.

Name the type and provide the evidence of your problems.

Anticipate solutions to your water-problems.



Compile potential means of data-collection and quantification of your problems.

Approach and inform the receptors of the potential impacts of the problems.

Facilitate outcomes and ways forward to expand your evidence.



Fix your water-related problem by employing the appropriate professionals.

Implement a future monitoring and mitigation plan to prevent the same scenario.

Educate the community regarding combined efforts in managing the problem.

Enhance your evidence-based problem solving with similar water-problems.

**Figure 7-4 Questions, Comments, Resolutions, and Recommendations**

## 7.5 CLOSING REMARKS

The authors hope that this is a valuable contribution to the previous work of this project team. The case studies were selected to be diverse and intriguing while still focused on the diverse geology and landscapes in South Africa. The case studies should be read individually as needed to accompany the text in this book or provide more thorough information.

Always define the problems related to the matters that you are involved in. There are experts for different purposes, and those depend on the reason for your investigations. Urbanisation is increasing rapidly in vertical and spatial directions. More pollution can be expected in the water, soil, and air. Natural disasters in urban areas exacerbate these problems by altering the interface between the land surface and subsurface through, for instance, flooding and erosion.

Groundwater monitoring and management (Dippenaar 2025) is hard, and it is more difficult in areas where urban recharge floods basements and prevent infiltration of rainwater during floods. It is the collaboration between the hydrogeology and engineering geology experts that improve the planning for development of these areas while also being able to address the problems.

Scientific integrity is required in all spheres of involvement of all aspects of urban development. The vadose is the hardest part to understand, and it is therefore hoped that this book and the accompanying case studies can shed some light on this topic. Monitoring urban pollution is hard, and remediating it even harder with industrial areas and mines in proximity.

To close of all of this, the following holds stronger than ever (in literal sense):

- “All things are poisons, for there is nothing without poisonous qualities. It is only the dose which makes a thing poison.” (Paracelsus)
- “Water, water everywhere, nor any drop to drink”. (*Ancient Mariner*, a poem by Samuel Taylor Coleridge).

## CHAPTER 8: REFERENCES

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# FRAMEWORK FOR NATURAL AND ANTHROPOGENIC CHANGES TO THE URBAN VADOSE ZONE

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