HYDROPEDOLOGICAL ASSESSMENT GUIDELINES: Theory and application in a South African wetland management context

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HYDROPEDOLOGICAL ASSESSMENT GUIDELINES:
Theory and application in a South African wetland management context

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND

Implementing the National Water Act (Act 36 of 1998) and achieving global initiatives like the UN Sustainable Development Goals (SDGs) related to water management necessitates a thorough understanding of fundamental hydrological processes. This understanding is especially critical in the protection, management, and restoration of wetlands. The interactive dynamics between soil and water, encapsulated as "hydropedology", seek to bridge disciplines and scales, aiming for a comprehensive understanding of hydrological processes.

The Department of Water and Sanitation (DWS) acknowledges the valuable contribution of hydropedological assessments in enhancing water management, particularly in the context of preserving wetland water regimes and ecosystem services amidst evolving land-use patterns. These assessments are now an integral part of the Water Use License Application (WULA) process for projects involving significant land-use changes, such as open-cast mining, extensive infrastructure development, and sizable residential projects.

Regrettably, clear and comprehensive guidelines on how to conduct hydropedological studies within the context of wetland management have been lacking. Literature on hydropedological theory is dispersed across various journal papers and book chapters, lacking a cohesive methodological structure. The primary objective of this report is therefore to amalgamate and streamline previous guidelines into a comprehensive document, offering both theoretical and practical guidance on conducting hydropedological assessments, with a central focus on wetland management.

The guidelines are organised into two main sections. Section A provides a theoretical foundation encompassing hydrological processes, soil property interpretation, and hydropedology of hillslopes. This section can serve as training material for scholars seeking to acquaint themselves with the theory of hydropedology. Section B offers practical guidance for conducting hydropedological surveys for wetland assessments and interpreting the results. It is intended to guide consultants on when, and how hydropedological assessments should be conducted, and by whom, within the context of wetland management.

SECTION A: THEORETICAL BACKGROUND

Hydrological processes at plot and hillslope scale

At the plot scale, the soil water balance comprises water inputs and outputs. Inputs include rainfall, infiltration, and lateral flows from upslope landscape positions. Evaporation, infiltration, root water uptake, deep drainage, and lateral flows occur at this scale and are largely determined by the soil's hydraulic properties and their vertical distribution in the profile.

At the hillslope or catchment scale, the flow from one plot to another occurs through specific flowpaths. The occurrence, length, and connectivity of these flowpaths are determined by environmental conditions such as topography, vegetation, and, importantly, soil distribution. Flowpaths are typically categorised into overland flow (surface runoff), subsurface lateral flow, and bedrock flow. The contribution of subsurface lateral flowpaths in the vadose zone has long been overlooked as a crucial hydrological process that keeps wetlands wet and streams flowing in semi-arid landscapes.

The preferred or dominant flowpath of water determines the residence time of the water in the landscape. For example, if overland flow is dominant, most of the rainfall will exit the hillslope or catchment within a few hours after a rain event, resulting in high stormflow events. Conversely, if recharge of bedrock flowpaths is dominant, it could take months or even years before the water reaches a wetland or stream in lower-lying positions. These residence times significantly impact water quality and ensure water availability during dry conditions.

Soil properties as indicators of hydrological behaviour

Soil morphological properties rarely exert a direct influence on hydrological processes. However, given that water plays a fundamental role in soil formation, the soil's morphology can serve as a valuable indicator of the hydrological processes predominant during its development. Among these properties, soil colour is arguably the most easily correlated with hydrology. Grey hues indicate reducing conditions, associated with periods of saturation and absence of oxygen. Mottles in the soil indicate varying water regimes, alternating between wet and dry, while oximorphic colours (red and yellow) suggest well-drained conditions. Other morphological properties, such as macropores and soil structure, can also be linked to hydrology, as they determine preferential flow paths through the soils.

Hydraulic properties encompass water retention, texture, depth, porosity, and storage capacity. These properties dictate the rate at which water moves through the soil and the quantity of water that the soil can retain for evapotranspiration and other biochemical reactions.

Diagnostic horizons as hydrological functional units

A soil horizon, a fundamental unit of soil classification in South Africa, represents a layer with distinct properties. Understanding the hydrological behaviour of these diagnostic horizons is crucial in soil characterisation. This understanding, derived from hydropedological research, significantly influenced the revision of the South African Soil Classification System (SASCS) in 2018. The revisions included descriptions related to bedrock interface, differentiation between fractures and solid rock, and recognition of saprolitic weathering at the family level, all based on hydropedological interpretations. Different soil horizons have differing hydrological functions within the South African soil classification. The functions are contingent on the vertical sequence of horizons within the profile and their position in the landscape, allowing a diagnostic horizon to have multiple functions. These functions are summarised in Table A.

Hydropedological grouping of South African soil forms and families

The soil forms and families of South Africa's latest soil classification system was regrouped into nine hydrological soil types based on their dominant response. This is an improvement from the previous grouping of the 1991 edition, which only considered 73 soil forms. In this new grouping a total of 1 657 soil families were assigned to different groups, which also includes 28 anthropogenic families. The main characteristics of the hydrological soil types are summarised in Table A.

Table A. Key characteristics of hydrological soil types.

Hydrological soil type	Key characteristics
Recharge (deep)	Deep, freely drained soils overlaying impermeable bedrock or weathered saprolite exhibit no signs of saturation. Evapotranspiration-excess downward flow dominant.
Recharge (shallow)	Shallow, freely drained topsoil horizons overlying fractured rock or saprolite. Limited contribution to transpiration.
Recharge (slow)	Slow vertical movement is the dominant flowpath. Typically clay-rich (luviated) subsoil horizons which act as a store, rather than a conduit of water. Evapotranspiration is dominant.
Interflow (soil/bedrock)	Lateral flow is generated, either due to low permeability of the bedrock which restricts vertical drainage or due to return flow from the bedrock flowpath to the soils. Flow maintained on seasonal basis.
Interflow (shallow)	Marked by vertical anisotropy in hydraulic conductivity where a permeable topsoil overlies a restricting subsoil layer. Flow generated by specific rain events and duration of lateral flow is short.
Interflow (slow)	High clay content low conductivity subsoil horizon at soil/bedrock interface. Serve as a store rather than conduit of water.
Responsive (shallow)	Soils with limited depth and hence small storage capacity. Underlying rocks are slowly permeable and rapid recharge of bedrock flowpaths not likely. Overland flow generated as normal rainfall events will the exceed the storage capacity.
Responsive (wet)	Saturation close to the surface layers for extended periods, especially during the wet season. Additional precipitation will not infiltrate but overland flow will be generated (saturation excess).
Responsive (Hortonian)	Vertic horizons will swell close during wet periods with very low hydraulic conductivity/infiltration rates. Degraded soils with surface crusting or sodic soils. Overland flow created due to infiltration excess (Hortonian flow).

Hydropedology of hillslopes

The hillslope, acknowledged as a fundamental unit within the landscape, is governed by the interplay of topography, soils, climate, and vegetation. These elements yield distinct patterns and laws, offering crucial insights into their functioning and hydrological response. Understanding hydrological processes depends on a profound grasp of the hillslope, which serves as a critical building block in this context. The hydrological response of catchments is a result of the collective hydrological response of hillslopes within a specific catchment.

The structured organisation and symmetry of hillslopes serve as a foundation for a classification system. Soil properties, storage volume, parent material, lithology, weathering patterns, and prevailing climate collectively shape the hydrology of hillslopes and find representation in the distribution of soils across the landscape. Recent advancements in understanding soil hydrology have led to a re-evaluation of existing hillslope classes, resulting in the proposal of 12 hillslope-wetland response classes that provide standardised representations of dominant water delivery mechanisms from hillslopes to wetlands (see Figure A). These classes reflect various hydrological responses and consider factors that influence water movement rates. Ongoing efforts are directed towards refining and improving these proposed classes over time.

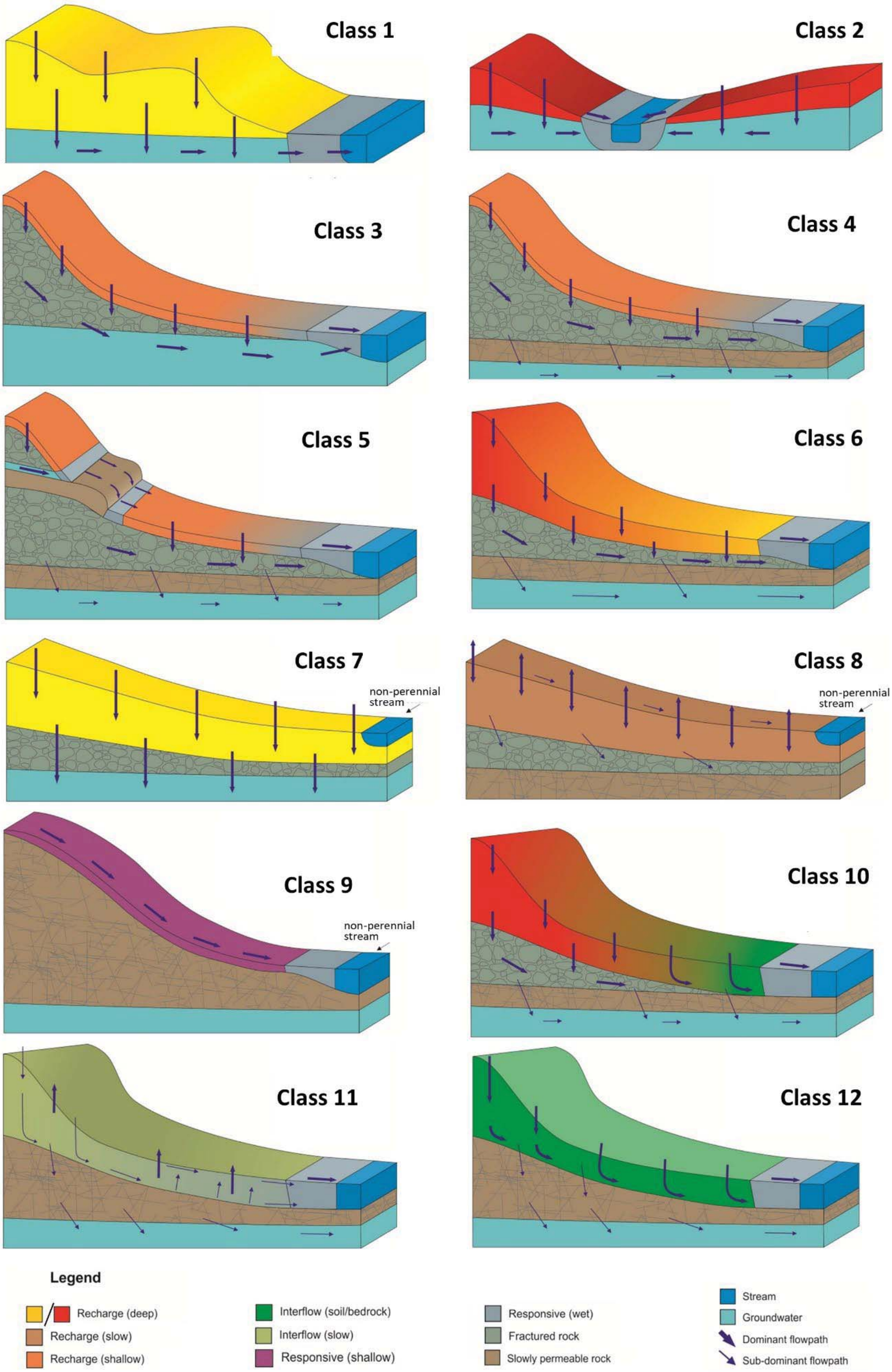


Figure A. Graphical summary of hillslope hydropedological response classes.

SECTION B: PRACTICAL GUIDELINES FOR PRACTITIONER AND DECISION MAKERS

Hydropedology of hillslopes in a wetland management context

Due to differences in flowpaths, connectivity and residence times, the impact of a land use change on wetland functioning will be different on different types of wetlands. The contribution that an hydropedological assessment could make to mitigate the impacts or improve management is also different (Table B). For example, in landscapes where the wetland receives most of its water from a regional groundwater aquifer, local changes in hillslope hydrology is unlikely to influence water regimes.

To facilitate the decision-making process, a decision tree has been developed, taking into account six different land use change impacts to determine whether a hydropedological assessment is necessary (Figure B). Climate plays a crucial role. In drier regions, the vadose zone's role in wetlands diminishes and hydropedological assessments might not be needed. The decision tree distinguishes among three possible outcomes: i) no hydropedological assessment required, ii) basic assessment required, or iii) full assessment needed. The required level depends on the risk associated with a specific activity relative to hydropedological hillslope types and wetland resources.

Additionally, this section provides norms and standards for hydropedological assessment reports to aid practitioners in producing high-quality assessments and assist decision-makers in evaluating the quality of the assessment reports.

Modelling approaches and key insights based on case studies

Hydropedological modelling should aim to quantify the relative importance of various flowpaths and the impact land use change on these pathways as well as how they replenish the wetlands. The models used should be able to reflect the hydrological processes at hillslope scale. It is important that the modelling is used in support of the conceptual model based on soil morphology and modelling outputs should not be used to reject the conceptual model.

In investigating three case studies, we addressed four critical issues and concerns from consultants regarding the practicality of previous hydropedological survey recommendations:

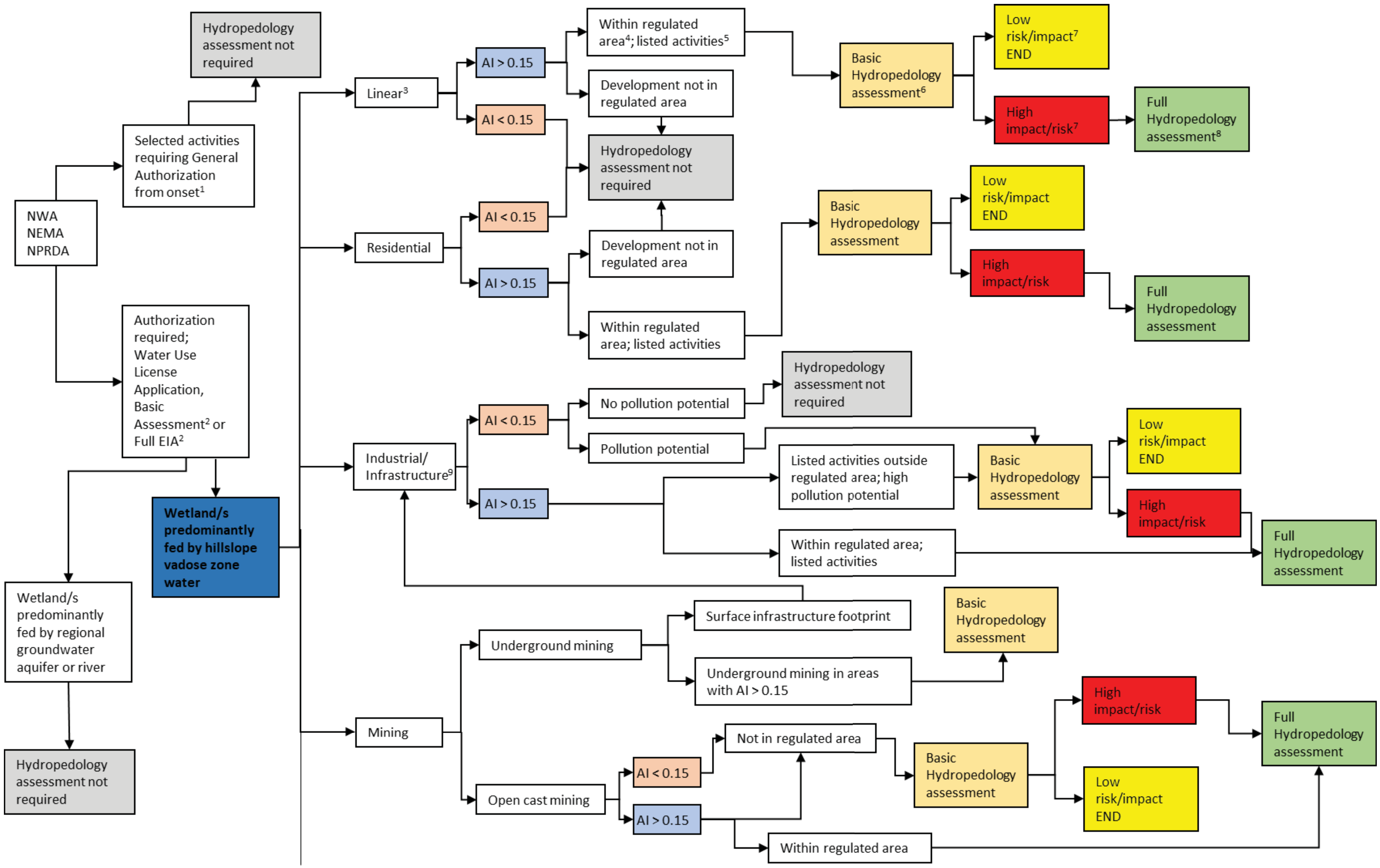
1. Sole reliance on land type data is inadequate for hydropedological assessments. While useful for identifying representative hillslopes, land type information alone cannot sufficiently inform hydropedological models.
2. Describing the soil profile up to the bedrock is essential. The soil/bedrock interface significantly influences lateral flows, and an accurate description is crucial for understanding dominant flow mechanisms.
3. Utilising PedoTransfer Functions (PTFs) for model parameterisation provided acceptable simulations, although local function derivation is preferable for accuracy. Until regional PTFs are developed, direct measurement of relevant properties is recommended.

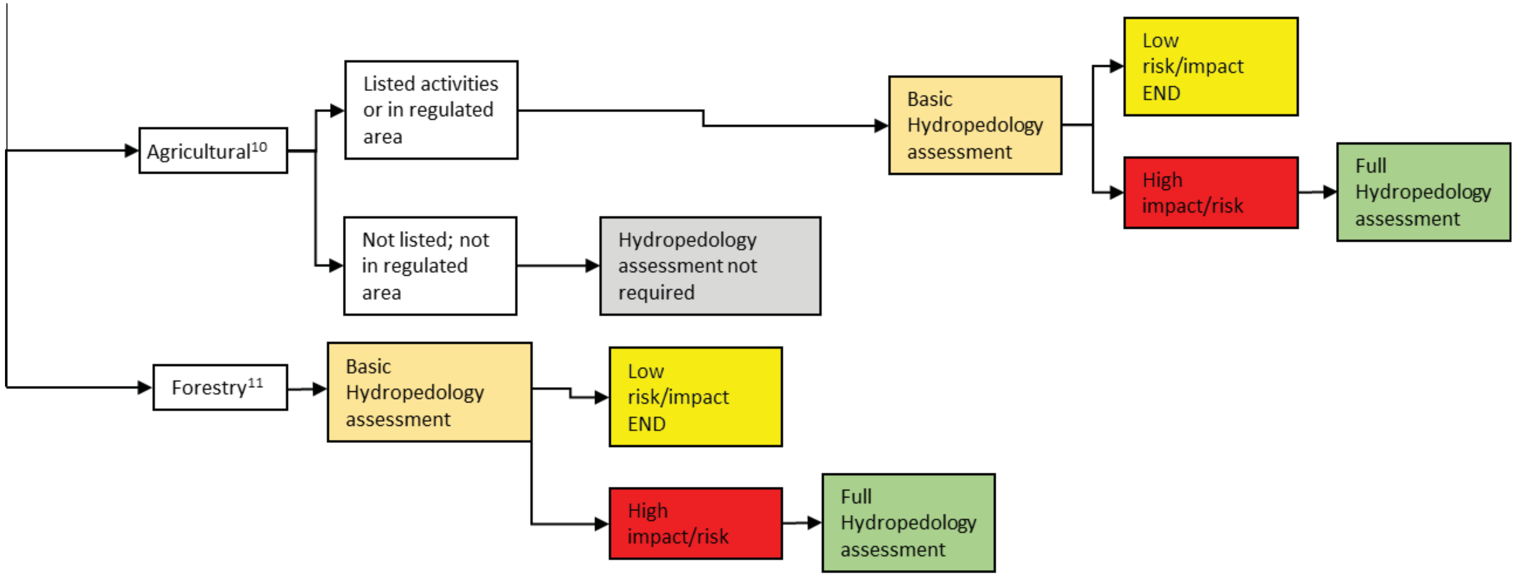
4. The 100 m observation density is excessive; focus should shift to capturing soil distribution patterns across various terrain units. Observations should prioritise topographical variations and vegetation differences as indicators of distinct water regimes.

Table B. Summary of risk of local activities impacting on the wetlands' functions based on hydropedological hillslope types.

Wetland group	Wetland-hillslope class (Figure A)	High-impact activities		Risk zone	Risk to wetland	Potential contribution of hydropedological assessments[1]
		Hydrological impact	Activities			
Groundwater-dependent, permanent	**1**: Recharge deep soils dominant	Abstraction (broadscale lowering of regional aquifer from groundwater abstraction)	boreholes	Anywhere within the wetland catchment	Moderate	**Low**: Groundwater driven
		Reduction (regionally extensive water-reduction activities)	commercial plantations	Anywhere within the wetland catchment	Moderate	**Low**: Groundwater driven
Groundwater-dependent, permanent	**2**: Recharge deep soils dominant	Abstraction (broadscale lowering of regional aquifer from groundwater abstraction)	boreholes	Anywhere within the wetland catchment	Moderate	**Low**: Groundwater driven
Groundwater-dependent, permanent	**3**: Recharge shallow soils dominant	Surface sealing and diversion (prevents infiltration of recharge water, changes recharge infiltration rates, diverts and converts water into peak flows and concentrated runoff)	urbanisation: buildings, roofs, roads	Anywhere within the wetland catchment	Low	**Low**: Groundwater driven
		Reduction (interception and extraction of available recharge volumes)	water-intensive woody alien invasive species	Anywhere within the wetland catchment	Low	**Low**: Groundwater driven
Hillslope-dependent, permanent	**4**: Recharge shallow soils dominant	Surface sealing and diversion (prevents infiltration of recharge water, changes recharge infiltration rates, diverts and converts water into peak flows and concentrated runoff)	urbanisation: buildings, roofs, roads	Anywhere within the wetland catchment	Moderate	**High:** Identifying and characterising recharge zones
Hillslope-dependent, temporary to permanent	**5**: Recharge shallow, to fractured aquifer	Surface sealing and diversion (prevents infiltration of recharge water)	urbanisation: buildings, roofs, roads	Midslope, fractured rock recharge as well as soil return flow areas	Moderate	**High:** Identifying and characterising recharge zones
Hillslope-dependent, seasonal to permanent	**6**: Recharge deep soils dominant	Surface sealing and diversion (prevents infiltration of recharge water, changes recharge infiltration rates, diverts and converts water into peak flows and concentrated runoff)	urbanisation: buildings, roofs, roads; land use conversion	Recharge area, typically at hillslope crest	Moderate to high	**High:** Identifying and characterising recharge zones
		Reduction (interception and extraction of available recharge volumes)	alien invasive plants	Recharge area, typically at hillslope crest	Moderate to high	**High:** Identifying and characterising recharge zones
Wetlands rare or absent	**7**: Recharge slow soils dominant	Not applicable		Not applicable	Low	**Low:** Limited lateral landscape connectivity
Wetlands rare or absent	**8**: Recharge deep soils dominant	Not applicable		Not applicable	Low	**Low:** Limited lateral landscape connectivity
Hillslope-dependent, temporary	**9**: Responsive shallow soils dominant	Surface sealing and diversion (increased, concentrated overland flow can change hydroperiod of a naturally seasonal or temporary wetland to more permanent)	urbanisation: buildings, roofs, roads; mining	Anywhere within the wetland catchment	Low	**Low:** Overland flow dominant
Hillslope-dependent, seasonal to permanent	**10**: Recharge deep soils to interflow soils	Surface sealing and diversion (prevents infiltration of recharge water, changes recharge infiltration rates, diverts and converts water into peak flows and concentrated runoff)	urbanisation: buildings, roofs, roads	Fractured rock recharge area, areas of return flow from interflow	High	**High:** Identify and characterising recharge and interflow zones
Hillslope-dependent, seasonal	**11**: Interflow (slow) soils dominated by evapotranspiration	Limited risk		Hillslope has limited flow generation	Moderate to low	**Low:** Lateral connectivity limited
Hillslope-dependent, seasonal	**12**: Interflow soils dominant	Surface sealing and diversion (interception or disruption of shallow flowpaths, diverting flows away from the wetland)	urbanisation: buildings, roofs, roads; mining	Bedrock interflow areas	High	**High:** Identifying and characterising interflow zones

[1]The contribution of hydropedological assessments to understand the hydrological behaviour of the landscape and contribute to protecting the wetland and manage the water resources more sustainably.


NWA
NEMA
NPRDA
Selected activities requiring General Authorization from onset1
Hydropedology assessment not required
Authorization required; Water Use License Application, Basic Assessment2 or Full EIA2
Wetland/s predominantly fed by hillslope vadose zone water
Wetland/s predominantly fed by regional groundwater aquifer or river
Hydropedology assessment not required
Linear3
AI > 0.15
AI < 0.15
Within regulated area4; listed activities5
Development not in regulated area
Hydropedology assessment not required
Basic Hydropedology assessment6
Low risk/impact7 END
High impact/risk7
Full Hydropedology assessment8
Residential
AI < 0.15
AI > 0.15
Development not in regulated area
Within regulated area; listed activities
Basic Hydropedology assessment
Low risk/impact END
High impact/risk
Full Hydropedology assessment
Industrial/ Infrastructure9
AI < 0.15
AI > 0.15
No pollution potential
Pollution potential
Hydropedology assessment not required
Listed activities outside regulated area; high pollution potential
Within regulated area; listed activities
Basic Hydropedology assessment
Low risk/impact END
High impact/risk
Full Hydropedology assessment
Mining
Underground mining
Surface infrastructure footprint
Underground mining in areas with AI > 0.15
Basic Hydropedology assessment
Open cast mining
AI < 0.15
AI > 0.15
Not in regulated area
Within regulated area
Basic Hydropedology assessment
High impact/risk
Low risk/impact END
Full Hydropedology assessment



Notes:

1) Activities that are generally authorised for any person, institution and / or SOCs subject only to conditions of the General Authorisation for Section 21 (c) and (i) water uses do not require any level of hydropedological assessment (see examples in Table 8.1)
2) See triggering actions in listing notices in Appendix A
3) Linear in the context of the decision tree refers to belowground linear development (e.g. pipes and drains) and roads. Aboveground linear developments do not require hydropedological assessment as they do not significantly alter flow paths. However, authorities may request hydropedological assessment based on the specific development, method statement and expected impacts.
4) Regulated area as defined in the National Water Act (1998) – see definition under terms and definitions
5) Activities listed in Appendix A which will require basic or full Environmental Impact Assessment
6) Basic assessment focus only on conceptual description of pathways and connectivity (flow drivers) and the potential impact of the development on these
7) Risk/impact is based on risk matrix associated with different hillslope types (Section 6.4 & 6.5 and Table 7.4)
8) Full assessment: Include quantification of fluxes and loss/gain of different water balance components
9) Includes renewable solar energy projects. Wind farms typically excluded.
10) Agricultural activities include dams, planting in water source areas and changes from rainfed to irrigation agriculture. Water quality impacts (pesticides, herbicides and nutrients) should also be considered.
11) Changing of natural vegetation or cultivated agriculture to commercial plantations.

Figure B. Decision tree for when and the type of hydropedological assessment required.

Steps for integrating hydropedology in wetland management

- **Step 1:** Delineate wetland boundary on desktop.
- **Step 2:** Delineate wetland catchment boundary on desktop.
- **Step 3:** Identify influence of groundwater or rivers.
- **Step 4**: Characterise the wetland catchment environment.
- **Step 5:** Identify representative hillslopes.
- **Step 6:** Delineate wetlands in the field.
- **Step 7:** Conduct hydropedology transect survey.
- ***Step 8:*** *Conduct hydraulic measurements; in-situ and in lab.*
- **Step 9**: Regroup soil observations into hydropedological groups.
- **Step 10:** Conceptualise hillslope hydrological responses.
    - Hillslope classes
    - Contribution to wetlands
- **Step 11:** Describe impacts on processes and wetland responses.
- ***Step 12:*** *Quantify hydropedological fluxes.*
- **Step 13**: Develop mitigation and management plans to reduce or avoid impacts.

Note: Steps 8 and 12 are only for *Full* hydropedological assessments.

At a minimum, practitioners should be capable of classifying South African soils up to the family level, ideally supplemented with a short course on hydropedology in the context of wetland management.

THE WAY FORWARD

During the development of the guidelines, drafts were presented at workshops and conferences, engaging stakeholders, such as government officials, environmental impact practitioners, and consultants. The guidelines garnered strong support and highlighted three stakeholder requests:

1. Provide additional training for enhanced enforcement and application, especially focusing on government officials' accessibility to training.
2. Develop a spatial layer or screening tool to identify areas requiring hydropedological surveys, building upon the provided decision tree.
3. Expand guidelines to cover hydropedological assessments for pollution, engineering, modelling, and agricultural projects, tailoring recommendations for specific disciplines to enhance usability.

These requests should direct the way forward to improve the guidelines and ensure that they are contributing to effective water resource management in South Africa.

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TERMS AND DEFINITIONS

Aquiclude: solid, virtually impermeable area underlying or overlying an aquifer.

Aquifer: a geologic formation, group of formations, or part of a formation that contains sufficient saturated, permeable material to yield substantial quantities of water.

Aquitard: a geologic formation or stratum with reduced permeability that lies adjacent to an aquifer and that allows only a small amount of liquid to pass.

Baseflow: the contribution to runoff from previous rainfall events where rainfall percolates through the soil horizons into the vadose and groundwater zones and then contributes a very slow delayed flow to streams whose channels are 'connected' to the groundwater. These constitute the 'dry weather' flows which are significant in sustaining flows in non-rainy seasons (Schulze, 1985).

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

Catena: a series of soils linked by their topographic relationship (typically from crest to valley floor).

Confining layer: a body of relatively impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers that restricts the movement of water into or out of those aquifers.

Critical zone: the thin outer layer of the earth's surface, extending from the top of the vegetation canopy to the bottom of the groundwater extent (NRC, 2001).

Evapotranspiration: the sum of water lost from a given land area during any specified time by transpiration from vegetation, by evaporation from water surfaces, moist soil and snow, and by interception (rainfall that never reaches the ground but evaporates from surfaces of plants and trees).

Flowpath: zones where water flows in the unsaturated zone, between the soil surface and the groundwater table.

Groundwater: water below the land surface in the saturated zone.

Groundwater level/groundwater table: the surface of the saturated zone at which the liquid pressure in the pores of soil or rock is equal to atmospheric pressure.

Hydraulic conductivity: measure of the ease with which water will pass through porous media (mostly soil and fractured rock in this document).

Hydrograph: the ratio of volume of water flow over time, presented in a graph.

Hydrological hillslope: areas that have distinct hydrological regimes which are both cause and consequence of a particular combination of plant cover, soil, slope characteristics (e.g. gradient, curvature and aspect) and slope position.

Hydrology: the study of the occurrence, distribution and movement of water.

Hydromorphy: soil morphology related to reduction due to water saturation or near saturation.

Hydropedology: study of the hydrological interaction of water with soil and the fractured rock zone.

Hydroperiod: degree, duration, frequency and seasonality of inundation or saturation. The seasonal pattern of the water level in a wetland.

Interflow: lateral movement of water through the unsaturated zone.

Overland flow: water flowing on the soil surface.

Oxidised morphology: soil, saprolite or fractured rock with no signs of reduction.

Pedon: the smallest three-dimensional portion of the soil mantle needed to describe and sample soil in order to represent the nature and arrangement of its horizons.

Permanent saturation or inundation *(of wetland)****:*** wetland area characterised by saturation within 50 cm of the soil surface for most of the year, for most years (DWAF, 2005; Ollis et al., 2013).

Polypedon: a group of adjoining pedons.

Recharge: filling-up zones that can be replenished including soil horizons, saprolite, fractured rock or groundwater with water.

Redox: reactions involving the transfer of electrons from donor to acceptor, i.e. reduction-oxidation reactions.

Regulated area of a watercourse: in terms of the Water Act means:

a) the outer edge of the 1 in 100 year flood line and/or delineated riparian habitat, whichever is the greatest, measured from the middle of the watercourse of a river, spring, natural channel, lake or dam.

b) In the absence of a determined flood line or riparian area within 100 m from the edge of a watercourse where the edge of the watercourse is the first identifiable annual bank fill flood bench or

c) A 500 m radius from the delineated boundary (extent) of any wetland or pan.

Residence time: *(hillslope)* the time water spends in the hillslope from time of recharge entering the soil to the time it surfaces in wetlands or rivers; *(wetland)* the time necessary for the total volume of water in a wetland to be completely replaced by incoming water.

Resource quality: means the quality of all aspects of a water resource including:

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

Response: flow rate, volume, and timing of hillslope water or wetland hydro-pattern, e.g. after a rainfall event. Often presented in a hydrograph.

Return flow: rainwater infiltrating the earth through soil, saprolite, fractured rock or hard rock, moving with the gradient down slope and returning to the soil surface at a lower point in the landscape.

Runoff: water leaving the catchment, not to be confused with overland flow.

SASCS: South African Soil Classification System: A Natural and Anthropogenic System for South Africa (Soil Classification Working Group, 2018).

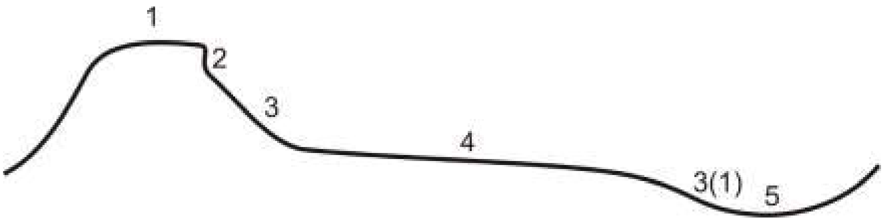
Saturated: all voids filled with water. This is seldom reached in natural conditions. Related to exclusion of air to the point where soil has anaerobic conditions.

Saturated zone: groundwater.

Seasonal saturation or inundation *(of wetland)****:*** wetland area characterised by saturation within 50 cm of the soil surface for three to nine months of the year, usually during the wet season (Ollis et al., 2013).

Temporary saturation or inundation *(of wetland)****:*** wetland area characterised by saturation within 50 cm of the soil surface for less than three months of the year (DWAF, 2005).

Terrain morphological unit (TMU): TMU1 represents crest, TMU2 scarp, TMU3 midslope, TMU3(1) secondary midslope, TMU4 footslope and 5 valley floor (Land Type Survey Staff, 1972-2006).



Unsaturated zone: includes soil horizons, saprolite and fractured rock above the surface of the regional groundwater table.

Vadose zone: the unsaturated zone, part of earth's mantle between the land surface and the top of the phreatic zone (groundwater aquifer). This includes soil, fractured rock and saprolite.

Water budget: an accounting of the inflow to, outflow from, and storage within a wetland or catchment.

Water resource: includes a watercourse, surface water, estuary or aquifer.

Watercourse means:

- a river or spring,
- a natural channel in which water flows regularly or intermittently,
- a wetland, lake or dam into which, or from which, water flows, and
- any collection of water which the Minister may, by notice in the *Gazette* declare to be a watercourse, and a reference to a watercourse includes where relevant, its bed and banks.

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

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CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

The implementation of the National Water Act (Act 36 of 1998) requires a clear, holistic understanding of key hydrological processes. From a wetland perspective, this requires that wetland ecosystem drivers such as the flow regime, water quality and quantity are described and quantified to ensure that wetlands are managed sustainably. Such an integrated approach to water and wetland management is also imbedded in international agreements such as the United Nations Sustainable Development Goals (UN-SDG), notably SDG#6 focusing on the *availability and sustainable management of water and sanitation for all* by 2030 (UN, 2017). Each of the SDGs are accompanied by specific targets and for SDG#6 two targets are of particular importance for these guidelines namely:

- Target 6.5: implement **integrated water resources management** (IWRM) at all levels, including through transboundary co-operation as appropriate.
- Target 6.6: **protect and restore water-related ecosystems,** including mountains, forests, **wetlands,** rivers, aquifers and lakes.

Protecting and restoring water-related ecosystems, such as wetlands, is not possible without implementing an IWRM approach. IWRM considers the entire hydrological cycle and recognises the intimate relationship between groundwater, surface water and vadose water at different spatiotemporal scales (Savenije and van der Zaag, 2008). Vadose zone water is often ignored in IWRM, but there is a growing recognition that sub-surface lateral flow through the vadose zone of terrestrial areas can be the primary streamflow generation process and the main source of water which sustains wetlands (e.g. Retter et al., 2006; Ticehurst et al., 2007; Lin et al., 2010; Van Tol et al., 2010a; Van Tol et al., 2013a; Van Tol and Van Zijl, 2022), especially in semi-arid landscapes. Ideally, IWRM should be supported by measurements of key hydrological processes such as the flowpaths, residence times, connectivity storage mechanisms and hydroperiods of the entire catchment (Uhlenbrook et al., 2005). These processes, especially the sub-surface processes, are difficult to observe (let alone measure) with strong spatiotemporal variation.

Soil has the ability to transmit, store and interact with water and can therefore act as a first order control on the partitioning of hydrological flowpaths, residence time distributions, water storage and water quality (Park et al., 2001; Soulsby and Tetzlaff, 2008). Water, on the other hand, is a primary agent in the genesis of most soil properties. The resulting soil properties, therefore, contain morphological properties (signatures) of the way they were formed. Correct interpretation of these properties and their spatial distribution can be related back to the hydrological processes which formed them. This interactive relationship between soil and water serves as the foundation for the interdisciplinary field of **hydropedology** (Figure 1.1).

The term 'hydropedology' was first introduced in by Kutilek (1966) and can be defined as the *"…synergistic integration of pedology with hydrology to enhance the holistic study of soil-water interactions and landscape-soil-hydrology relationships across space and time, aiming to understand pedologic controls on hydrologic* *processes and properties, and hydrologic impacts on soil formation, variability, and functions*" (Lin et al., 2008). Bridging gaps between pedology, soil physics, hydrology and geomorphology and also across scales (from micro to landscape) is a key aim of hydropedological studies. For reviews and comprehensive discussions on hydropedology see Lin (2003), Kutilek and Nielsen. (2007), Van Huyssteen (2008) and Lin (2010), and hydropedological research in South Africa (Van Tol, 2020).

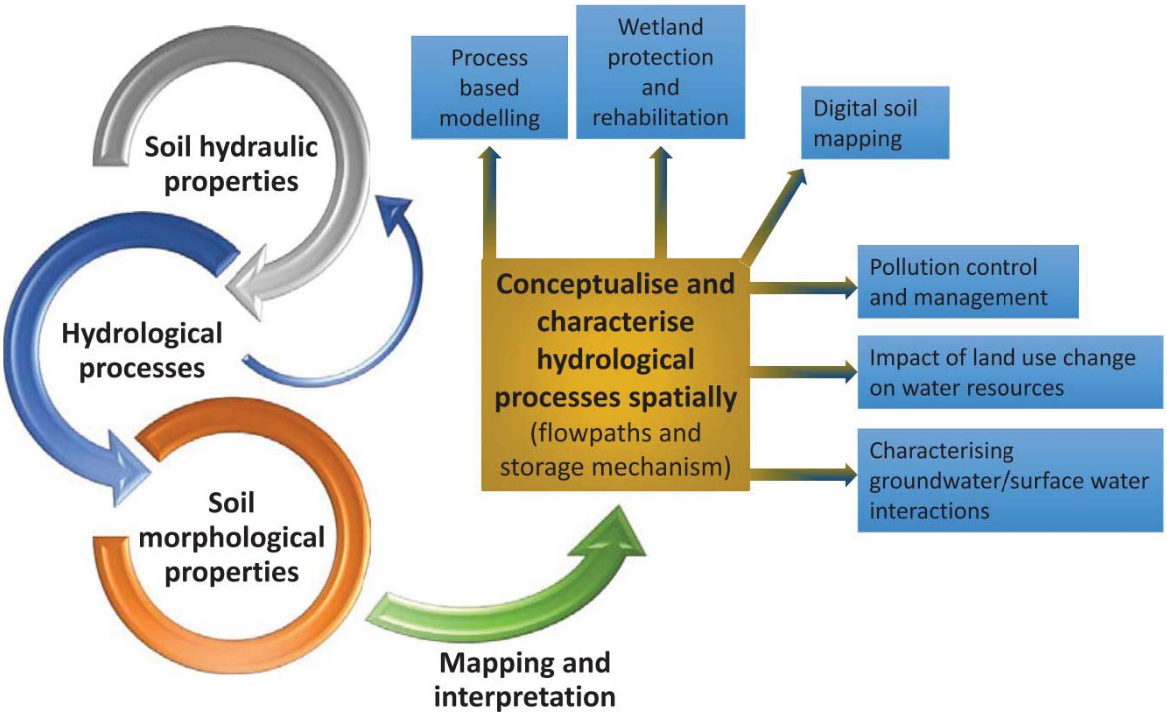

Figure 1.1. The basis of hydropedology and its implication (Van Tol et al., 2017).

1.2 THE NEED FOR HYDROPEDOLOGICAL GUIDELINES

The Department of Water and Sanitation (DWS) recognises the importance of vadose zone water in maintaining wetland water regimes and functioning. DWS also realise that land-use change can change flowpaths of water, the connectivity between flowpaths as well as the residence time of water which can drastically change the wetland water regimes and could negatively impact the ecosystem services delivered by them. DWS views a hydropedological assessment as a cost-efficient approach to understand terrestrial hydrological processes and how they interact with water-linked ecosystems (wetlands, riparian zones, and streams). A hydropedological assessment now forms part of the Water Use Licence Application (WULA) for any project where drastic land-use is planned. This includes, for example, open-cast mining, infrastructural development, as well as residential developments. Hydropedological studies are also required for projects with relatively small footprint, but which will have a direct impact on wetlands (for details on when, where and what type of hydropedological assessments are required, see decision tree in Part B).

Currently there are two existing guidelines for hydropedological assessments in South Africa:

- *Preliminary guidelines to apply hydropedology in support of wetland assessment and reserve determination* (Job et al., 2018) which aimed to explore the spatial and temporal contribution of hillslope (terrestrial) water to wetlands, and how this can be used to support wetland assessment.
- *Guidelines for hydropedological assessments and minimum requirements* (Van Tol et al., 2021a) which aimed to provide practitioners with a practical guidance on how to conduct the hydropedological survey and quantify the responses with modelling.

Hydropedology is, per definition, a multidisciplinary field, requiring a combined background in soil classification, hydrology and soil physics. In order to apply hydropedology in wetland management, additional training in wetland assessment and delineation is required. The aim of this report is to provide comprehensive guidelines which combine and simplify the previous versions into a single document. The new guidelines strive to provide a sufficient background on these disciplines in a single document for a practitioner or decision maker to conduct a hydropedological assessment and interpret the findings in terms of the impacts on water-linked ecosystems. Although the main focus is on how hydropedology can improve wetland assessments, the guidelines can also be used to conduct surveys for other applications such as process based modelling and pollution control (Figure 1.1).

The guidelines are structured into two sections. Section A provides a theoretical background on hydrological processes at different scales, interpretation of soil properties, horizons and forms, and hydropedology of hillslopes. Section B then provides practical guidance for practitioners and decision makers of how to conduct hydropedological surveys for wetland assessments and how to interpret them.

SECTION A: THEORETICAL BACKGROUND

CHAPTER 2: HYDROLOGICAL PROCESSES AT PLOT AND HILLSLOPE SCALE

2.1 INTRODUCTION

Hydrological processes operating at plot scale differ from processes at landscape scale. Here we start with a description of the processes at plot scale (vadose zone water balance). This is also later used to classify and group soils into hydrological classes (CHAPTER 5:). Small-scale theories and laws are typically developed at plot scale (e.g. Darcy's Law for hydraulic conductivity and Hortonian overland flow). Upscaling these to landscape scale is, however, unrealistic due to considerable heterogeneity in properties and processes.

Processes at hillslope scale are, however, of particular importance for hydropedological studies, especially when wetland assessments are conducted. The hillslope is a fundamental landscape unit (Weiler and McDonnell, 2004; Lin et al., 2006) which has a common form of organisation and symmetry. The interaction between topography, soils, climate and vegetation results in patterns or laws which determine hillslope hydrological functioning (Sivapalan, 2003a). In hydrological science, the hillslope is an important building block for understanding and simulating hydrological processes, as most processes operate at this level (Tromp-Van Meerveld and Weiler, 2008). How catchments, streams and wetlands behave are determined by the particular mix of different hillslopes (shapes and sizes) in the particular catchment (Sivapalan, 2003b).

2.2 VADOSE ZONE WATER BALANCE

The soil water balance at plot scale is a well-known concept which describes additions and losses from the soil profile. The standard equation of soil water balance is:

$$\boldsymbol{\Delta S = P + I - E - T - D \pm SR \pm LF}$$

Where $\Delta \boldsymbol{S}$ is the change in soil water storage. $\boldsymbol{P}$ and $\boldsymbol{I}$ are precipitation and irrigation. $\boldsymbol{E}$ is evaporation from the surface and $\boldsymbol{T}$ is transpiration through the plants. $\boldsymbol{D}$ is deep drainage or percolation out of the root zone. $\boldsymbol{SR}$ is surface runoff and $\boldsymbol{LF}$ is lateral flow. The latter two can be either a loss or an addition to soil water in a unit area.

The typical presentation of the soil water balance ignores the contribution (and losses) from the saprolite or fractured rock. This layer can play a very important role in root water uptake and lateral flows towards lower lying areas. The deep percolation (***D***) is therefore not automatically recharge of groundwater but can supply the saprolite with water. In hydropedology studies it is important to include the entire vadose zone water balance which includes the soil, saprolite and rock above the permanent groundwater levels (Figure 2.1). Roots can absorb water from the saprolite and, depending on the type of lithology, from cracks and fissures in the 'solid' rock layers. In most areas of South Africa, evaporation and transpiration forms the major component of the vadose zone water balance and typically accounts for >60% of the balance.

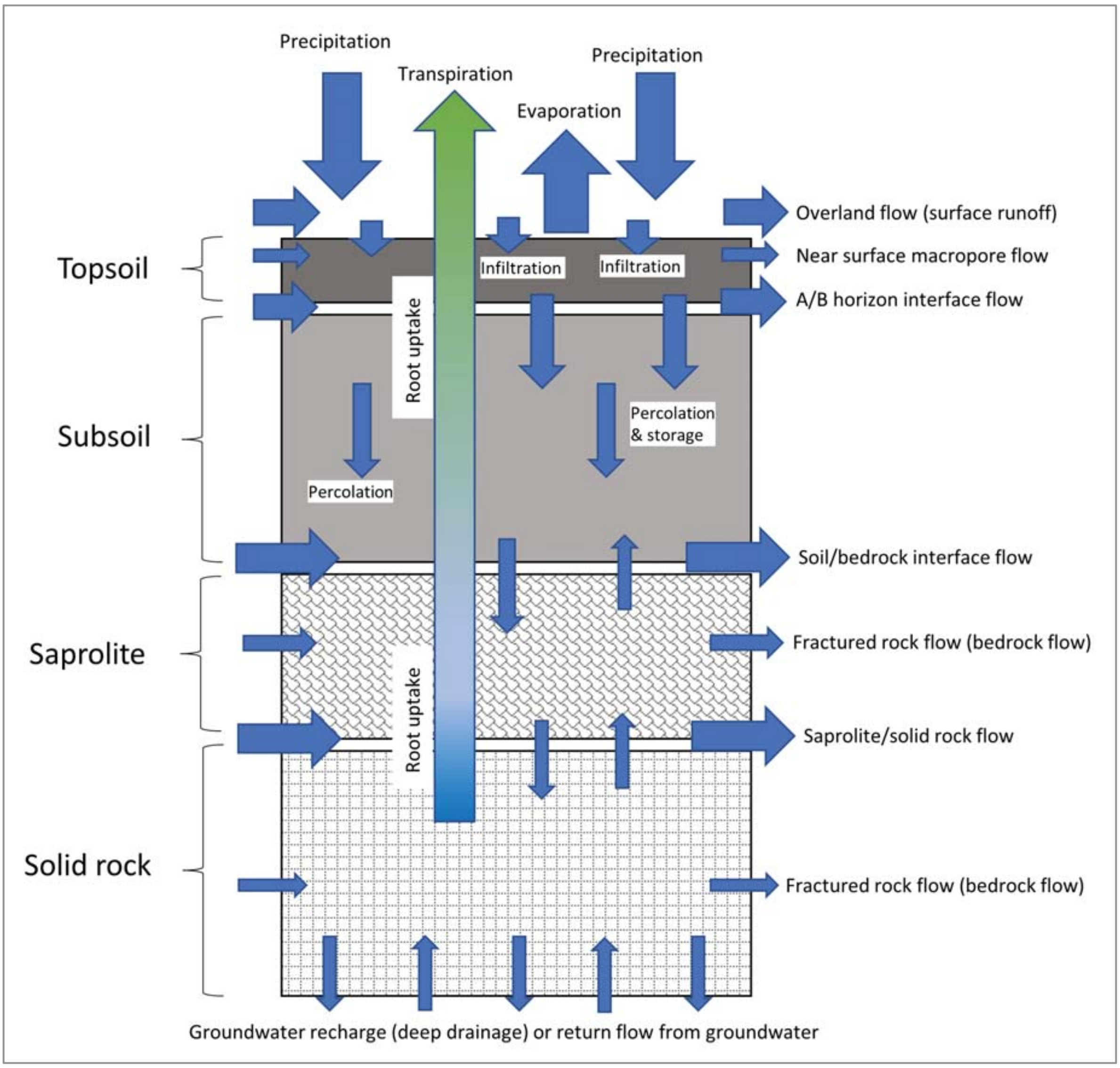

Figure 2.1. Vadose zone water balance.

In Figure 2.1 we distinguish between different types of lateral flows in and out of the profile:

- **Overland flow**: Overland flow[1] can be generated due to infiltration excess or saturation excess. Infiltration excess occurs when the rainfall intensity exceeds the infiltration rate of the surface horizon (also termed Hortonian flow). Bare patches with crust formation, compacted surface layers and soils with high clay contents are prone to generate infiltration excess overland flow. Saturation excess overland flow is generated when soils are close to saturation before a storm (even low-intensity storm). Topography is also a factor controlling overland flow. Ticehurst et al. (2007) found that more infiltration and therefore less overland flow occurs on gentle slopes than steeper slopes. Changes in

[1] sometimes called 'surface runoff', although the latter refer also to streamflow. Overland flow is mainly used to describe flow over land surface outside of channels.

land use, such as urbanisation with associated surface sealing will increase overland flow generation.

- **Near surface macropore flow:** Lateral flow in this zone occurs through dead root and animal channels close to the surface (Lorentz et al., 2007). The topsoil has higher density of roots and carbon and typically host more meso- and macrofauna thus providing ideal conditions for macropores to form.
- **A/B horizon interface flow:** Lateral flows are generated due to differences in texture, structure, carbon content and consequently hydraulic conductivity between topsoils (A-horizons) and subsoils (B-horizons). This vertical anisotropy causes water that percolates downwards through the topsoil to accumulate on top of the subsoil. When saturation is reached, and the slope permits, lateral flow will start (Van Tol et al., 2013a).
- **Fractured rock flow:** Flow through cracks and fissures in the partially weathered saprolite and solid rock can account for considerable gains and losses from the vadose zone on plot scale. Deep rooted plants also make use of these cracks and root water uptake can be significant. The size and connection between these cracks determine the rate of flow.
- **Soil/saprolite and saprolite/solid rock interface flow:** At this transition, lateral flow is also generated due to differences in the hydraulic conductivity. If the bedrock is poorly weathered or high in clay, the difference in conductivity between the subsoil horizon and the saprolite/bedrock will result in a build-up of water and lateral flows down the slope. As this zone is normally below the dense root zone of plants, water can flow downslope without being transpired.

2.3 HILLSLOPE WATER BALANCE

In a typical hillslope, we distinguish between three major flowpaths: overland flow, subsurface lateral flow and bedrock flow (Ticehurst et al*.,* 2007). Subsurface lateral flow can be divided into subsurface macropore flow, subsurface lateral flow at the A-B horizon interface, return flow at the footslope and toeslope, and flow at the soil-bedrock interface (Lin et al*.,* 2006). At hillslope scale, these flowpaths are not mutually exclusive, and water tends to move between them (Figure 2.2). For example, overland flow in upslope areas can re-infiltrate in lower lying areas and contribute to sub-surface lateral flow, or bedrock flow can return to the soil in the valley bottom and cause saturation which promotes overland flow. Some flowpaths are only connected when the hillslope is wet. Soil characteristics, macropore network, surface and bedrock topography, and land use determine the relative importance of the various pathways (Mosley, 1979). The role of topography varies with the moisture content of the soil. In drier periods, the main controlling factor of movement is soil characteristics. In wetter periods, the topography becomes increasingly important (Lin et al., 2006; McGlynn et al., 2002; Park and Van de Giesen, 2004).

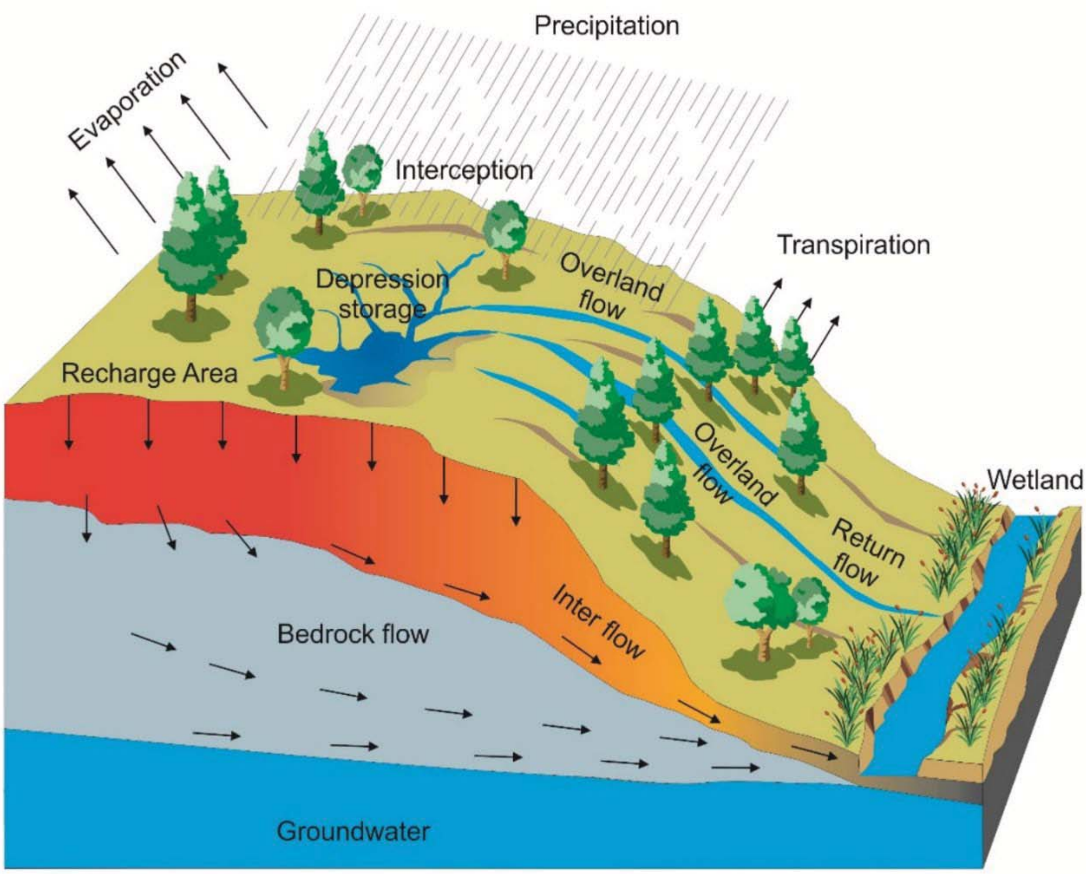

Figure 2.2. Hydrological flowpaths at hillslope scale.

2.3.1 Overland flow

At hillslope scale, overland flow occurs either as infiltration excess or as saturation excess. In general, steeper slopes with shallow soils generate large volumes of overland flow with significant erosive energy. Thinner A horizons usually indicate that the overland flow is dominant, in thicker soils more infiltration due to the greater volume of water needed to saturate the soil is expected. Soil depth is also positively correlated with vegetation density, and thicker soils with more vegetation will decrease overland flow generation (Ticehurst et al., 2007). Overland flow is also impacted by the soil texture. Sandy soils generally have higher hydraulic conductivity than clay rich soils, and the latter is more prone to generate overland flow. Sandy soils are prone to crust formation which could lower the surface infiltration rates and promote overland flow generation.

As water flows overland, it may encounter an area where the soil water deficit has not yet been satisfied, the water then infiltrates. This is called the run-on pathway and is often ignored in rainfall and runoff studies. The actual volume of infiltration then includes the precipitation as well as water supplied from upslope. Breaks in slope (normally between midslopes and valley bottoms) reduce the velocity of water and enhance infiltration. The soils at the transition between midslopes and the valley bottom are also thicker due to alluvial or colluvial deposits, this will further increase infiltration. In valley bottoms the runoff rate tends to slow down because of the smaller gradient. These soils are however the wettest in typical hillslopes and the saturated conditions can promote saturation excess overland flow.

2.3.2 Subsurface lateral flow

Subsurface lateral flow (also termed interflow) is a dominant flowpath in many catchments (Lin, 2006) and occurs either through the soil matrix or through macropores (Atkinson, 1979), especially when "*i) the land is sloping, ii) surface soil is permeable, iii) a water-impeding layer is near the surface, and iv) the soil is saturated*." For significant lateral flow to occur through the soil matrix, three conditions must be met: 1) deflection of vertical moving water by an impeding layer (layer with lower conductivity), 2) development of saturation on top of the impeding layer, and 3) hydraulic gradient in a downslope position, i.e. a sloping landscape (McGlynn et al., 2002). Theoretically, lateral flow can only occur when the vector of the saturated hydraulic conductivity of the conducting layer, parallel to the slope, is larger than the vertical conductivity of the impeding layer (Jackson, 2005). Ticehurst et al. (2007) found that a slope of 10% to 15% was enough to generate interflow.

The main subsurface lateral flowpaths at hillslope scale are at the A/B horizon interface, the soil/bedrock interface, return flow, and macropore flow (Figure 2.3) (Lin et al., 2006; Ticehurst et al., 2007). At the A/B horizon interface and the soil/bedrock interface (including both soil/saprolite and saprolite/solid rock interface – see Figure 2.1), lateral flows are generated due to vertical anisotropy in hydraulic conductivity. Once a condition close to saturation is attained above the impeding layer, subsurface lateral flow occurs (Whipkey, 1965; Whipkey et al., 1979; Woods and Rowe, 1996; Kim et al., 2005; Retter et al., 2006). Unsaturated subsurface lateral flow can also occur but the direct contribution of this process to streamflow is considered insignificant (Whipkey et al., 1979).

Unlike lateral flows at plot scale, lateral flowpaths at hillslope scale are not mutually exclusive. For example, at the end of a root channel (macropore lateral flow) the water may reach the bedrock and contribute to soil/bedrock interface lateral flow. If there is bedrock shelving (present in several of our geological formations) the same water can return to the surface (return flow) before contributing to A/B interface lateral flow. However, some lateral flowpaths may be more dominant in different parts of the hillslope or at different degrees of saturation periods.

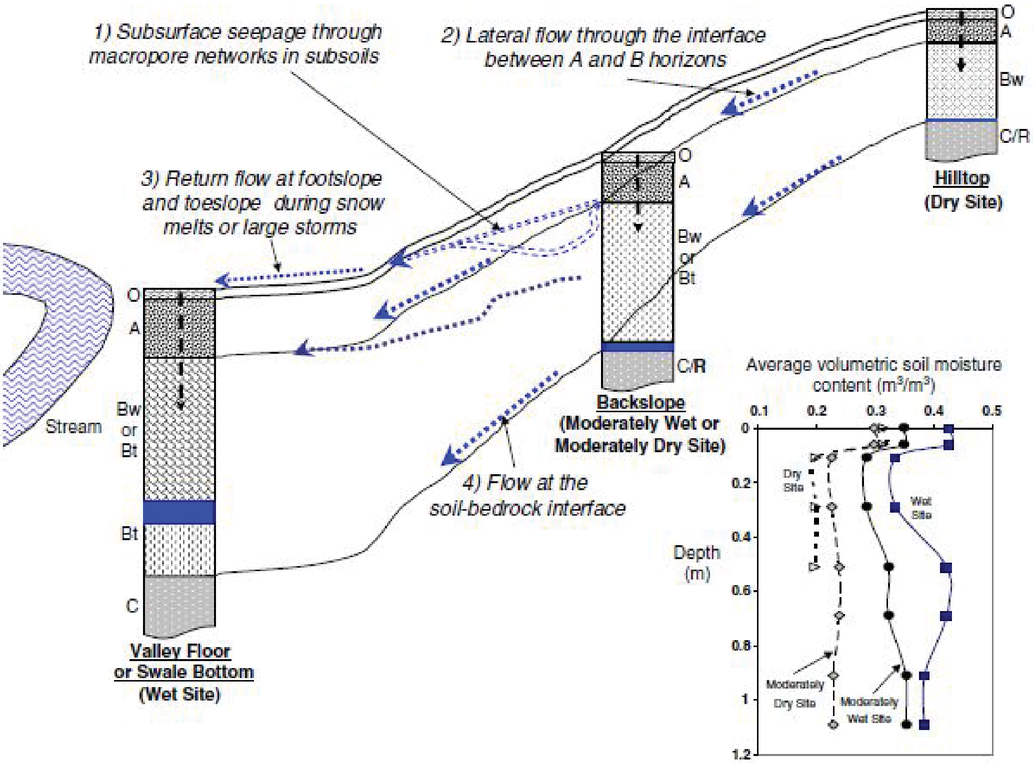

Figure 2.3. Subsurface lateral flowpaths at hillslope scale (Lin et al., 2006).

2.3.2.1 Soil/bedrock connectivity and the 'fill and spill' hypothesis

Subsurface topography (bedrock topography) can differ substantially from surface topography (Tromp-Van Meerveld and McDonnell, 2006a). In the generation of lateral flow at the soil/bedrock interface, the subsurface topography controls this flowpath (Tromp-Van Meerveld and McDonnell, 2006b). In the studies of Tromp-Van Meerveld and McDonnell (2006a, 2006b) they found that threshold values in rainfall amount are extremely important in determining the amount and rate of lateral flow. In their case, after 55 mm of rain, isolated 'pockets' in the bedrock become connected and lateral flows increased more than fivefold.

Tromp-Van Meerveld and McDonnell (2006b) termed this the 'fill and spill' hypothesis where depressions in the bedrock topography first need to be 'filled' before it can 'spill' downslope (Figure 2.4). The same principle applies to topographical depressions on the surface and explains why, in wet years, everything flows. This 'fill and spill' is also evident in deeper soils (Spence and Woo, 2003), where, regardless of the bedrock topography, the storage capacity of soil first needs to be filled before the lateral contribution of flow into streams is generated. The 'fill and spill' is therefore more related to the antecedent water content than the storm size. Volumes and rates of interflow can, therefore, differ considerably between different horizons in different landscape positions based on different antecedent conditions.

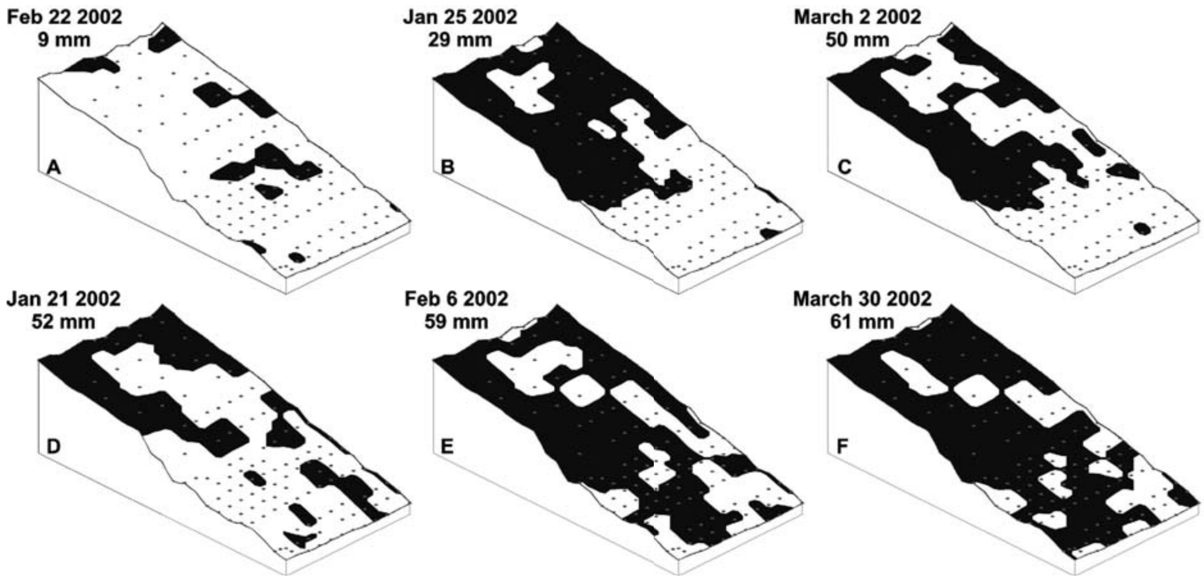

Figure 2.4. Subsurface saturation in the Ponola hillslope with varying rainfall amounts (Tromp-Van Meerveld and McDonnell, 2006b).

2.3.2.2 Macropore interflow

Macropores are defined as pores having a diameter greater than 0.5 mm (Luxmoore, 1981) where the middle of the pore/pipe is large enough that flowrates are determine by gravitation and water particles are not attracted by the soil matrix. There are four main types of macropores: 1) pores formed by soil fauna; 2) pores formed by plant roots; 3) structural macropores; and 4) natural soil pipes (Van Tol et al., 2012).

In forested catchments, macropores can conduct considerable amounts of water at fast rates. Water moves through tree root channels, pores created by organisms (earthworms), as well as cracks. Cracks are usually present in soils with a high 2:1 clay content (vertic soils), especially in drier periods (Lin et al., 2006). There are three factors determining the contribution of subsurface macropore flow to streamflow namely, the size of the macropores, the accessibility and continuity of the pores. The continuity of these pores seems to increase with an increase in soil moisture (Nieber et al., 2000). There is also evidence that networks of connected lateral flow pathways may develop, including at the base of the soil profile (e.g. Freer et al., 2002; Buttle and McDonald, 2002; Graham et al., 2010), even when there is percolation into the bedrock (e.g. Tromp-Van Meerveld et al., 2007). This is presumably because small increases in penetration resistance can cause roots to grow laterally. Soil pipes usually flow parallel with the slope and are formed by soil fauna (moles and mice) as well as dead root channels. They contribute a significant amount of subsurface water to streamflow and are quick to respond to rainfall. Although macropores are normally restricted to the depth of the soil profile, they can link to cracks in the saprolite and bedrock which may extend to considerable depths in the fractured rock system.

2.3.2.3 Measurement of lateral flow

Measurements of subsurface lateral flow can be divided into three categories: i) interception of flow, ii) additions of tracers, and iii) indirect methods (Atkinson, 1979). Interception is typically measured using a trench where water draining out of the vertical face is collected (e.g. Bachmair et al., 2012; Du et al., 2016; Tromp-Van Meerveld et al., 2007). This method is criticised because flow lines are distorted to form a saturated wedge at the bottom of the vertical face, so the conductivity will therefore be greater than under natural conditions. Additions of tracers is a non-destructive method to determine the pathways and residence times (e.g. Rodgers et al., 2005; Soulsby and Tetzlaff, 2008; Soulsby et al., 2009; Speed et al., 2010). Lateral flows can be indirectly inferred from measurements of soil water contents and hydraulic gradients along the slope (Bouwer et al., 2015; Freer et al., 2002; Uchida et al., 2003). Hydromorphic soil properties can also serve as an indication of accumulation of water at the A/B horizon or soil/bedrock interface. If the land is sloping, the assumption is that discharge will occur in a predominantly lateral direction (e.g. Bouwer et al., 2015; Kuenene et al., 2011; McDaniel et al., 2008 Van Tol et al., 2010a, 2010b; Soulsby et al., 2006; Ticehurst et al., 2007).

2.3.3 Bedrock flowpaths

Water percolating through the soil into fractured rock can drain down to the groundwater table (groundwater recharge) or flow downslope via cracks in the rock. The latter is termed the bedrock flowpath and could return to the surface in the midslope or in the valley bottom or contribute directly to streamflow. Depending on the nature of the bedrock, soils on the summit area are often intake areas for water supply to the bedrock flowpath (Ticehurst et al., 2007). The bedrock flowpath is extremely important for recharge of lower slopes, groundwater levels and generating baseflow in some catchments (Fanning and Fanning, 1989; Ticehurst et al., 2007; Van Tol and Lorentz, 2018).

2.4 RESIDENCE TIMES

The residence time (also resident or transit time) of water refers to the time which water will remain in a specific *system*; this could refer to the profile, hillslope or catchment. Residence times can reveal a lot about the storage mechanisms, pathways and the sources of the water (McGuire and McDonnell, 2010). Biochemical reactions are also dependent on the residence time, and residence time can also impact water quality.

Flow length, soil depth and the preferred flowpath determines the residence time (Asano et al., 2002; McGuire et al., 2005). In general, overland flow has the shortest residence time (hours or days, i.e. event driven), with lateral flows in the soil contributing to streamflow within days or weeks (post event). The bedrock flowpath has the longest residence time and its impact can often only be seen on a seasonal basis (Figure 2.5).

Event driven flow implies that the flowpath is only active during and immediately after a specific rain event or a series of rain events. This is normally associated with flowpaths on or near the surface (overland flow, near surface macropore flow and flow at the A/B horizon interface. It is common in topsoils. Event-driven slow interflow is associated with an E or bleached A horizon and related to high-lying positions.

Post-event driven flow occurs in deeper horizons and water from different rain events are sufficiently mixed that the contribution of individual events cannot be isolated. The first rain events need to saturate the soil and fill bedrock depressions, before flowpaths are activated. Once active, the flowpaths can contribute to flow long after rainfall ceases.

Seasonal driven flow relates to bedrock flowpaths. An increase in flow might be observed during the dry season due to rainfall from the previous rainy season. High baseflows can also be observed during dry years because of a preceding wet cycle.

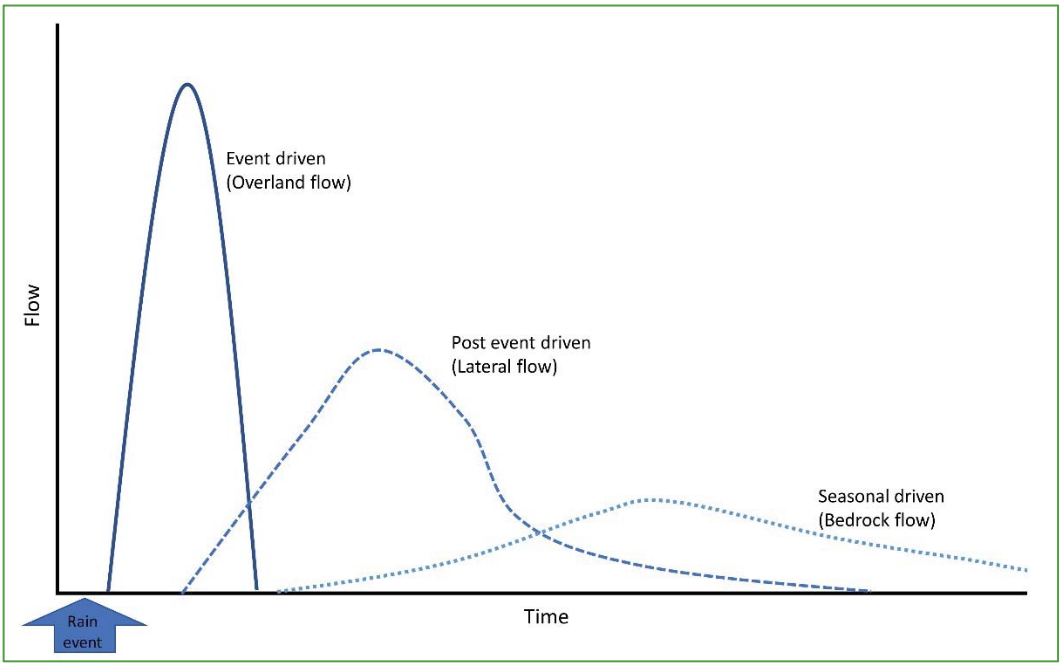

Figure 2.5. Residence times associated with various flowpaths.

The difference in residence times and connectivity of different flowpaths is a key reason why rainfall/runoff relationships are not linear. This emphasises the importance of understanding and predicting hydrological processes at different spatiotemporal scales. Relating soil properties to the processes which they govern, and which formed them, is important to understand the processes. This forms the basis of hydropedology and is dealt with extensively in CHAPTER 3:.

CHAPTER 3: SOIL PROPERTIES AS INDICATORS OF HYDROLOGICAL BEHAVIOUR

3.1 INTRODUCTION

Soil properties, soil horizons, soil profiles and soil patterns are not randomly distributed (Webster, 2000). These soil features are influenced by five soil forming factors, i.e. climate, topography, geology, organisms and time. The combination of these factors results in unique soil properties with distinctive vertical and horizontal distributions. Soil morphological properties seldom have a direct influence on hydrological behaviour, but, if interpreted correctly, can be related back to the hydrological processes which formed them. Soil hydraulic properties do determine the rate and direction of flowpaths of water in the soil as well as how water is stored in the soil. This impacts the hydrological behaviour, first at plot scale, but also at hillslope and landscape scale.

3.2 MORPHOLOGICAL INDICATORS

Soil morphology is a result of the interaction of water and soil. Soil morphology is generally a stable and reliable long-term indicator of the wetness of a soil horizon, soil profile, catena and wetland. Soil morphology is representative of the hydrological controls and processes. To assess the long-term variation in wetness of a profile over depth (one-dimensional), hillslope (two-dimensional) or a wetland unit (three-dimensional), the variation in indicators needs to be considered. Note that soil morphological indicators will vary between different climates and geologies. The environmental setting of a specific soil must be taken into consideration when hydropedological interpretation of soil properties are made (Van Tol, 2020).

3.2.1 Soil colour and redox morphology[2]

Soil colour is probably the most visible soil property and a valuable indicator of water regime and flowpaths (Van Huyssteen et al., 2005; Ticehurst et al., 2007). Iron (Fe), manganese (Mn) and organic matter (OM) are primarily responsible for the colour of the soil. Red colour found in soil is due to the presence of hematite (Fe_2O_3), whereas yellow soils are coloured by the presence of goethite (FeOOH). Dark colours are from the presence of organic material, humus and manganese. The dominant colours of the silicate clay, quartz and feldspar soil minerals are grey and typically an indicator that other colouring agents are absent (Vepraskas and Bouma, 1976). Understanding the significance of soil colour in terms of water regimes requires an understanding of reduction-oxidation (redox) morphology. Soil morphology developed by oxidizing, reducing and redox conditions serves as signatures of flowpaths, connectivity, storage mechanisms and hydroperiod in terrestrial and wetland soils, hillslopes and catchments.

[2] For a very detailed review on soil colour and the chemistry behind their occurrence and formation see Van der Waals et al., *undated*.

3.2.1.1 Oxidation-reduction in soils

Microorganisms utilise O_2, NO_3^-, Mn^{2+}, Fe^{3+} and SO_4^{2-} as oxidation agents (electron acceptors) and easily oxidisable organic matter as reduction agents. Microorganisms use these electron acceptors in the same order as above from the most likely to least likely to be reduced. In dry soils O_2 is present (oxidized) and reduction of the other elements will not take place. In conditions close to saturation, the soil environment gets depleted of O_2 (anaerobic). Saturation is defined as wetness characterised by zero or positive pressure of the soil water, where almost all the soil pores are filled with water (Vasilas and Vasilas, 2013; USDA-NRCS, 2010). True anaerobic conditions occur when 1) there is sufficient organic material present, 2) microorganisms are actively oxidizing the organic material, 3) the soil is saturated and 4) dissolved oxygen is removed from the pores (Vepraskas, 1995). Under anaerobic conditions microorganisms start to utilise the other electron acceptors. The anaerobic conditions promote many biogeochemical reactions, including iron and manganese reduction, redistribution and accumulation, sulphate reduction and organic matter accumulation (Vepraskas and Lindbo, 2012).

In the oxidized state, Fe^{3+} and Mn^{2+} are insoluble and stable, but in the reduced state, very soluble. Redox features in soils involve localities where there is depletion in Fe^{3+} and Mn^{2+} concentrations and localities where there is accumulation of Fe^{3+} and Mn^{2+}. Depletion in Fe^{3+} and Mn^{2+} is associated with low chroma values (grey colours), and accumulation of Fe^{3+} and Mn^{2+} is associated with high chroma colours (yellow, red and black) in the form of mottles and concretions (Le Roux, 1996) (Figure 3.1). Reduced localities have high Fe^{2+} and Mn^{+} concentrations in solution. They diffuse to oxidised localities where the concentration in solution is low to be oxidized again (Van Breedeman and Brinkman, 1976).

In basic terms, in a well-aerated soil, Fe will be present in the oxidised ferric form (Fe^{3+}). The ferric iron gives typical reddish to yellow colours to the soil (McBride, 1994). Under saturated conditions, ferric iron could be reduced to ferrous iron (Fe^{2+}), which is much more soluble than ferric iron, thus creating an increase in Fe mobility. The soluble and mobile ferrous iron can now be removed from the soil system with outflowing water and transported within soils and through the landscape (Fiedler and Sommer, 2004). After removal of Fe, the inherent grey low chromas are revealed. These low chroma colour patterns are commonly used to predict the depth of seasonal saturation (Hayes and Vepraskas, 2000).

Complete saturation seldom occurs in natural soils and several studies found that redox reactions can already be initiated when between 70 and 80% of the soil pores are filled with water (Van Huyssteen et al., 2005; Jennings, 2007; Kuenene et al., 2013; Mapeshoane, 2013). Reduction morphology can therefore occur above the water table in the capillary fringe. Factors determining the O_2 exchange rate, the time it requires for O_2 to be depleted by microbes and the relationship between easily oxidizable organic matter and soil depth still needs to be quantified in a range of soils and environmental conditions. For example, soils that are infrequently saturated may require an extended period of saturation for anaerobic conditions to occur, and in certain wetlands and wetland types, saturation itself, rather than anaerobic conditions, is responsible for the presence of hydrophytes (Tiner, 1999).

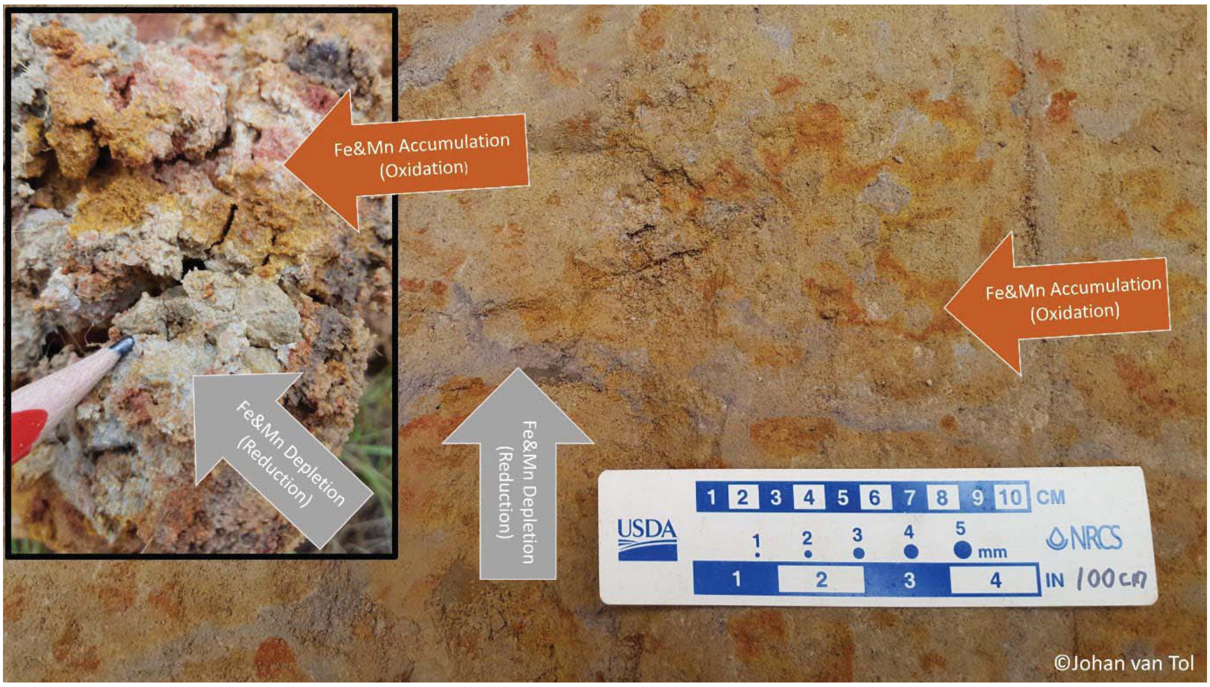

Figure 3.1. Examples of reduction-oxidation in the soil, showing zone of Fe and Mn accumulation (red/orange) and depletion (grey).

3.2.1.2 Interpretation of soil matrix colour

The average water content (or water regime) of a soil correlate well with the colour of soil horizons (Table 3.1). The general sequence follows the following order from dry to wet: *red and brown < yellow < grey* (Van Huyssteen et al., 2005). Increase in wetness is related to longer periods close to saturation which are associated with several factors and combination of these factors, for example, wetter climate (higher rainfall lower potential evaporation), lower lying position in the landscape and slower permeable bedrock.

Reducing conditions increase down the profile, down slope and with increasing rainfall if all other factors playing a role in the redox process remain the same. This is often expressed in a typical soil catena[3] (for example on the Mpumalanga Highveld) where red soils are generally found on the higher lying drier positions of the landscape, followed by yellow soils in the moderately drained areas and grey soils in the wettest (valley bottom) position (Fey, 2010).

Comparisons and interpretations of soil colour should be conducted with care as the soil colour is greatly influenced by the type of parent material. For example, high rainfall areas of alpine areas of the Maloti-Drakensberg exhibit bright red colours because of the abundance of Fe in the basaltic parent material, despite being saturated for long periods (Kunene et al., 2013), whereas soils derived from the Table Mountain Sandstone Group will be inherently grey in colour, regardless of the water regime.

[3] The *catena* (or chain) concept was introduced by Milne (1935) to describe soil sequences between interfluvial crests as if they are connected with a chain. The catena concept is synonymous with toposequence, pedosequence or soil distribution pattern. It forms the underlying foundation of the land type survey (Land Type Survey Staff, 1972-2006).

Table 3.1. Summary of soil colour, causes and hydrological interpretations (adapted from Le Roux et al., 1999).

Colour	Colouring agent	Identification	Occurrence	Implications for hydropedological interpretations
White	Salts	Soluble, taste	Top, sub- and lithic horizons, arid regions, pollution, salinisation	**Restricted leaching, caused by low rainfall in arid regions, restricted drainage or irrigation with salt rich water.**
	Gypsum	Crystals	Top, sub- and lithic horizons, arid regions, low lying	
	Lime	Effervesce with 10% HCl	Top, sub and- lithic horizons, arid regions	
	Quartz	Sand, silt	Top, sub- and lithic horizons, rock	**Soil particles coated with colouring agents and only visible if bleached.**
	Silicate clay	Rock	Top, sub- and lithic horizons, rock	
Grey	Bleached, Fe and humus removed	Colour	Albic and gley horizons, signs of wetness, regic sand	**Reducing conditions or inherited[1].**
Green and blue mottles	Reduced Fe	Colour	Gley horizons	**Very poorly drained.**
Yellow and yellow brown	Goethite	Colour	Top and subsoil horizons	**Well drained, seldom saturates, low clay content.**
	Geogenic	Colour, rock like	Saprolite	**Low Fe content.**
Red	Hematite	Colour	Top, sub- and lithic horizons	**Well drained, does not saturate under natural conditions / high Fe content[2].**
Maroon	Iron-oxide/ hydroxide	Colour	Subsoil and lithic horizons	**Highly erodible soils from the Elliot formation, rich in sodium.**
Dark brown and dusty black	Humus	Colour, organic matter content	Topsoil horizons, podzols, topsoil horizons as cutans	**High organic matter content.**
Black mottles (metallic)	Mn (Pyrolusite)	Effervesce with cold, fresh H_2O_2	Top, sub- and lithic horizons	**First sign of periodic saturation and limited Drainage[3] or inherited.**
Red, yellow and grey mottles	**Fe and Mn**	**Colour**	**Top, sub- and lithic horizons**	**Poorly drained, periodic saturation in the natural condition[4].**

[1]Active (pedogenetic) grey colours differ from relicts in the gradual boundary to the adjacent colour, and the colours are present juxta-positioned on micro scale and in the profile (see mottles). [2]In arid regions lack of subsoil saturation is due to the climate. [3]Periodic subsoil saturation coinciding with leaching results in redistribution of Mn. [4]Indicates an impermeable underlying layer causing subsoil saturation under natural conditions.

If the dominant flowpath is relatively fast and supplies oxygenated water to the soils, or if the organic carbon and/or microbial activity is low, anaerobic conditions will not be attained. In such cases, soils could exhibit oximorphic (red/yellow) colours despite long periods of saturation. Here the soil chemistry and relative changes in the soil chemistry could be a better indicator of water regimes than soil morphology (Bouwer et al., 2015). The duration of saturation required for changes in soil colour are therefore dependent on the environmental conditions (climate, geology) as well as the flowpaths dominating in the landscape. Soil colour can change from red to yellow to grey relatively quickly. A good example is the human-induced colour changes in the Vaal-Harts irrigation scheme. Bright red sandy soils were over irrigated leading to the build-up of a water table on the hardpan carbonate present as a third horizon. Lateral flows from the neighbouring plots added more water to the soils and the red soils changed to grey in less than 20 years. Subsoil plinthic[4] mottling formed within the same time in the red soils of several irrigation schemes of South Africa and Namibia. The general consensus is that the reverse colouration, i.e. from grey to yellow and red is slow (Bouwer et al., 2015). Grey colours could therefore persist for decades and might be a relict indicator of historic climates.

3.2.1.3 Mottling and plinthite formation

The colours of silicate clay, quartz and feldspar soil minerals are grey and therefore grey colours appear where the Fe coatings are removed (Vepraskas and Bouma, 1976). Yellow, red and black colours occur where Fe^{3+} and Mn^{2+} accumulate in sequence with an increase in Fe^{3+} and Mn^{2+} concentration (Le Roux, 1996).

Fe and Mn concretions and mottles are signs of periodic saturation. The prominence, size and colour of the mottles, the depth at which they occur and the colour of the horizon in which they occur, are indications of the degree of subsoil saturation and thus of the climate and the degree of drainage. An increase in size and abundance of concretions and mottles correspond to longer periods of saturation (Ticehurst et al., 2007; Van Huyssteen et al., 2005). Larger, more prominent and shallower occurrence of mottles indicate poorly drained conditions. The colour of the mottles and the matrix indicate poor drainage in the order: *black < red < yellow < grey*. Black mottles are the first signs of periodic subsoil saturation. This relationship, however, is not always as simple, if for example the movement of water through the soil is very slow, dissolved Fe and Mn might not be completely removed from the profile and when it dries out will oxidise again. On the other hand if the profile is saturated, but there is a continuous supply of fresh oxidized water, reduction will not take place and mottles are unlikely to form despite complete saturation. According to Amore et al. (2004), the number of mottles are not always indicative of the duration of saturation but rather an indication of a fluctuating water table.

The *juxta-positioning of mottles* in soil structural units (peds) of structured soil is the result of the distribution of the redox potential in the soil during saturation and it is an indication of the soil water regime (Bouma,1983). Red mottles in the macropore (interpedal pores and root channels) followed by yellow and grey colours away from the pores to the ped centre, indicates long periods of saturation in the peds during which the Fe in the ped dissolves and moves to the macropores, where it is oxidised, and precipitates. The opposite order of colours is more obvious as grey surfaces but represents shorter periods of saturation during which only the macropores reduce (Schwertmann, 1985).

[4] Plinthic mottling in the South African soil classification refers to soils where more than 10% of the soil matrix is coloured by Fe and Mn removal and accumulation due to varying oxidation/reduction conditions.

Redox features are easily observed in plinthic soils. Plinthic horizons have an accumulation of Fe in the form of oxides and hydroxides and are localised in the form of high chroma mottles and concretions. The simple processes leading to the formation of such a horizon are eluviation (removal of constituents), illuviation (accumulation of eluviated material), oxidation and reduction (Fanning and Fanning, 1989). Fe^{3+} is reduced and together with sesquioxides eluviated from the upper lying horizons and Fe^{2+} is oxidized and accumulates in the lower horizon. A fluctuating water level is necessary for this to take place.

Plinthite normally occurs in highly weathered soils of the regions with rainfall exceeding 500 mm and where a fluctuating water table is active. High temperatures and a high evaporative demand favour plinthite formation since they influence the fluctuation of water levels. The formation of plinthite on different topographical positions corresponds to the climate. In the drier climates, plinthite forms in the lower lying areas. Redoximorphic features occur in soils of semi-arid and more humid climates. The key factor is a ratio of rainfall/evapotranspiration resulting in water flowing to the deep subsoil and impermeable deep subsoil preventing water loss to the fractured rock and resulting in subsoil saturation. These conditions typically occur in semi-arid climates.

3.2.1.4 Age of redox features

The accumulation and hardening of Fe/Mn as concretions and horizons are often the subject of debate. Traditionally, these relict features have been considered irreversible and unrelated to current soil and climate conditions. However, Le Roux et al. (2005) discovered that the so-called "relict" hard plinthite, as described in previous literature, was actually in phase with the present soil and climate conditions in South Africa. This suggests that these features are influenced by the current soil conditions or a climate related to the existing climate distribution in South Africa.

To determine whether a feature is relict or active, we suggest a systematic evaluation of soil formation and hillslope processes. Examining the relationship between different soil horizons and their occurrence in the landscape can provide insights. For instance, if hard plinthic horizons are found overlying gley horizons that are currently saturated, it suggests that the hard plinthic horizon formed on the capillary fringe with distinct wet and dry cycles. Similarly, if an albic horizon formed within a drainage channel of an arid catchment, it could be attributed to significant periods of saturation during infrequent flood events. In both cases, the morphology of the soil is consistent with the prevailing climatic and pedogenetic conditions.

Bouwer et al. (2015) further emphasised the importance of considering both chemical and morphological properties to determine if the soil morphology aligns with the current environmental conditions. They suggest that changes in soil chemical properties will occur before corresponding changes in morphology are detected. Therefore, when evaluating soil features, it is recommended to assume that all hydropedological properties are "in phase" with the current conditions, unless evidence or explanations indicate otherwise.

3.2.2 Precipitation of bases

In arid and drier semi-arid climates, the hydrological response of landscapes is depended on specific rainfall events or a series of rain events. Seasonal flowpaths of lateral flow or bedrock flow is typically absent and reduction or redox expression in soil morphology is less common. The soils simply do not saturate long enough to generate anaerobic conditions. There are, however, morphological indicators of flowpaths of water in the soils of these drier climates. These are typically in the form of precipitates, such as lime ($CaCO_3$), which form extremely slowly and are often perceived as relict but can be good indicators of hydrological flowpaths (Van Tol et al., 2010b). This is because $CaCO_3$ easily dissolves in water and will flow with the water until the water is extracted by roots where the $CaCO_3$ will precipitate. The occurrence of these precipitates is therefore an indication that the water did flow there. The solubility of calcareous, gypsum and salt compounds increase, in the order listed. They are distributed in the soil profile, hillslope and in climates ranging from borderline semi-arid to hyper-arid, in the order of their solubility (Ellis, 1988).

Calcification is one of the main processes in soils with carbonate rich parent materials. Weathering of the parent material results in the formation of soils with calcium as the major cation on the cation exchange complex. $CaCO_3$ (lime), the dominant carbonate in these soils, is pedogenically formed as follows:

$$\boldsymbol{Ca^{2+} + CO_2 + H_2O \rightarrow CaCO_3 + H_2}$$

Weathered Ca^{2+} dissolves in water, leaches towards lower soil horizons and flows downslope, filling voids and pores. Plant roots extract water and precipitation in the form of $CaCO_3$ occurs due to the presence of CO_2. The CO_2 is present in the soil as a consequence of diffusion from the atmosphere, but CO_2 generated by oxidation of plant roots enhance this process. This process is the first stage of the formation of a calcic horizon (Fanning et al*.,* 1989; Shankar and Achyuthan, 2007).

The dependence of calcareous precipitates on the presence and behaviour of water makes it a good indicator of hillslope hydrology. Where lime accumulates in horizontal layers it is a good indicator of the ineffectiveness of rainfall to leach these bases out of the profile (Figure 3.2). Under low rainfall and high evaporative demand conditions, i.e. low Aridity Index[5] (AI), rainwater will not drain through the profile but will be pumped out through evapotranspiration. The depth to which rainwater can infiltrate is the effective precipitation depth and also the depth where lime accumulations can be expected. The lower the AI (more arid) the closer to the surface lime can be expected. Lime accumulations will occur deeper and deeper in the profile with an increase in the AI (more humid conditions). Lime accumulations can also be due to restricting soil layers which hinders leaching (Driessen and Deckers, 2001; Netterberg, 1978).

Where lime accumulates is therefore an indication of where water flowed (and also where it stopped flowing). In the case of the lime accumulations in an apedal soil presented by Figure 3.2a, water flowed uniformly to a depth of around 1 000 mm (effective rainfall depth), from there water was evapotranspired and lime

[5] Aridity Index (AI) is the ratio between rainfall and potential evaporation: *AI = P/ET0*
Hyper-arid AI < 0.05; **Arid** 0.05 < AI <0.2; **Semi-arid** 0.2 < AI < 0.5; **Subhumid** 0.5 < AI < 0.65; **Humid** AI > 0.65 (Middleton & Thomas, WAD2, 1997).

accumulated. In the strongly structured vertic horizon in Figure 3.2b, lime accumulations were visible between the structural units (outside of aggregates) and not present in the inside of the peds. The preferred flowpath was therefore around the structures and not through them. Lime accumulations were present in infilled root channels of an Augrabies soil presented by Figure 3.2c indicating the preferred flowpath of water through these soils.

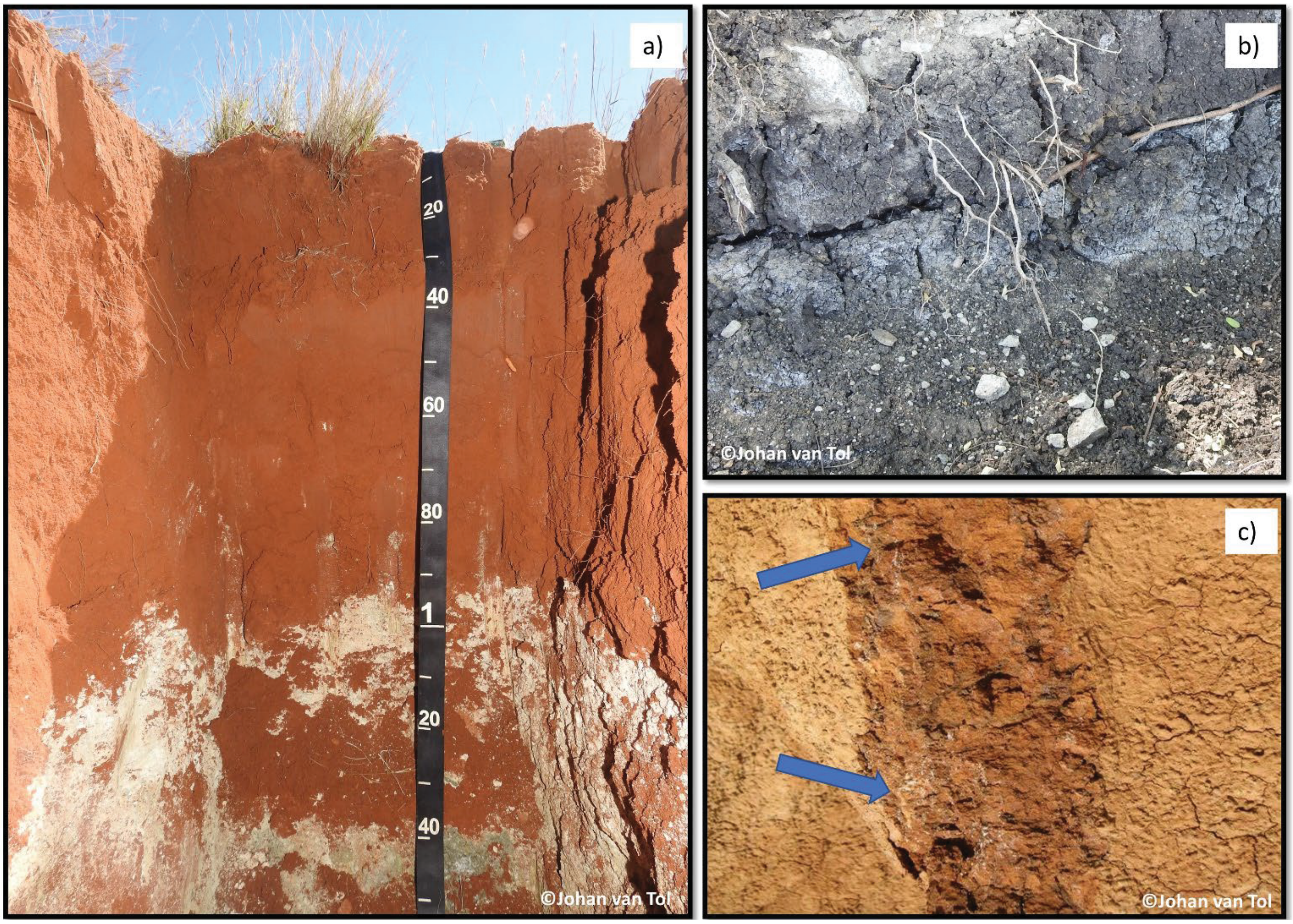

Figure 3.2. $CaCO_3$ accumulations a) below red apedal horizon in a Kimberley soil form near Hope Town, b) between structural units in a Vertic horizon near Rustenburg, and c) in infilled root channels of an Augrabies soils near Bedford.

Gypsum precipitates occur lower down the flowpath than calcareous precipitates, as gypsum is more soluble. When looking for visual evidence in moist soils, the precipitates should be allowed to be exposed for an hour or longer for them to crystallise.

Salts (sodium chloride) precipitate even lower down the flowpath. In arid climates, the distribution of the full range may be present, with calcareous deposits on the crest to midslope, gypsum lower down in the midslope or footslope, and salt accumulations on the valley floor. It is common that the position of the precipitate moves down the hillslope with increased rainfall (personal observation).

3.2.3 Macropores

Macropores conduct a considerable amount of water through the soil at rates much faster than the conductivity of the soil matrix. These pores can be dead tree root channels, pores created by organisms (e.g. earthworms; burrowing animals, birds), as well as cracks (Figure 3.3). Cracks are usually present in soils with a high 2:1 clay content (like vertic soils), especially in drier periods (Lin et al., 2006) (see 3.2.5). There are three factors determining the contribution of subsurface macropore flow of water namely, size of the macropores, the accessibility and continuity of the pores (Nieber et al., 2000). These properties of macropores must be adequately captured in the description of soils.

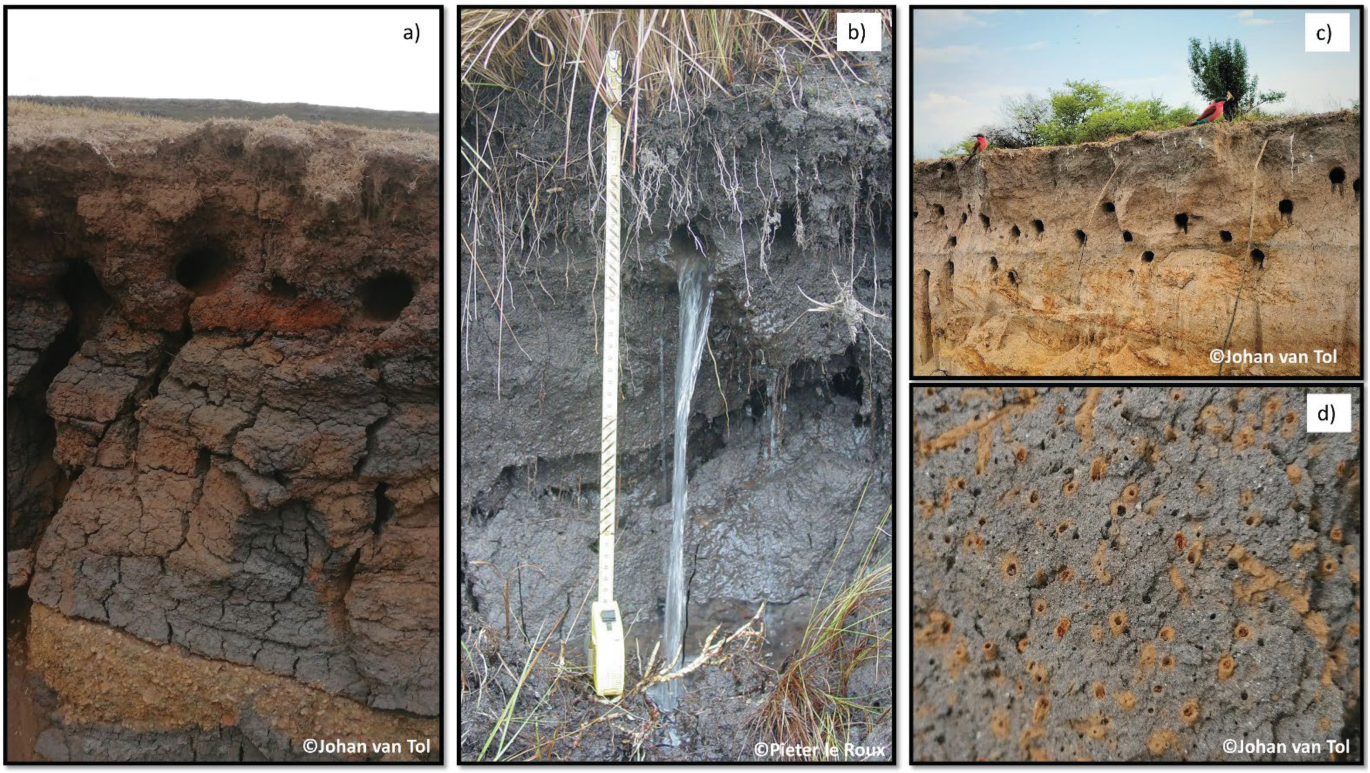

Figure 3.3. Macropores a) ice rat burrows above structural macropores in a degraded peatland in the Lesotho Highlands, b) water flowing out of an animal burrow after heavy rainfall in Weatherley, c) Carmine bee-eater nests serves as macropores in Dundee soils in the Zambezia region, and d) dead root channel macropores in a peat horizon.

3.2.4 Soil texture (particle size distribution)

Texture is not a soil morphological property *per se* but can be estimated in the field as part of standard soil description. Texture refers to the relative composition (percentage) of different size particles in the soil which are broadly grouped into sand, silt and clay (also termed particle size distribution). The composition can then be grouped into textural classes using the well-known texture triangle (Figure 3.4). Clay particles are very small (<0.002 mm in diameter) and have a very high internal and external surface area[6] which impacts the adsorption

[6] The surface area is also influenced by the type of clay; detailed discussions on clay mineralogy and how that influence water relations are not within the scope of these guidelines and the reader is referred to soil science textbooks, e.g. Brady and Weil, 2016.

capacity of the soils for water and nutrients. Texture therefore plays an important role in the storage and movement of water in soils (see Section 3.3.1 and 3.3.2). The amount and type of clay minerals dictate the rate of water movement and the water-holding capacity. Clay contents can be estimated in the field, using the ‘feel method’ but the full particle size distribution is measured in the lab using pipette or hydrometer methods. Both of these lab methods are based on Stoke’s law for the movement of different size particles through a liquid.

Category	Size (mm)
Very coarse sand	1 – 2
Coarse sand	0.5 – 1
Medium sand	0.25 – 0.5
Fine sand	0.1 – 0.25
Very fine sand	0.05 – 0.1
Coarse silt	0.02 – 0.05
Fine silt	0.002 – 0.02
Clay	< 0.002

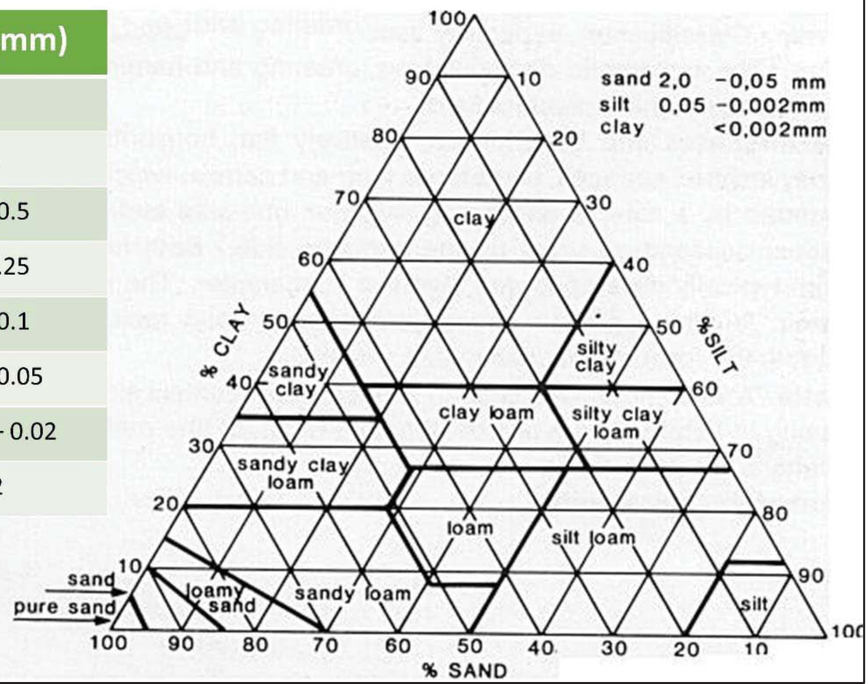

Figure 3.4. Particle size categories and texture triangle to describe textural classes.

An increase in clay content from the top to subsoil is an indication of luviation, which is a downward movement of clay, and suggest that vertical flow is dominant. Abrupt increases in clay from top to subsoil, can restrict vertical flow and cause temporary build-up of water on the top/subsoil interface and promote lateral flow in this area. Ferrolysis[7] and clay removal (eluviation) result in lower clay contents in the horizon, increasing the hydraulic conductivity and the potential to generate lateral flow. Luviation can also occur at landscape scale, where an increase in clay from the upslope, midslope to the valley bottom can be an indication that sub-surface lateral flow is a dominant process (Ticehurst et al., 2007).

3.2.5 Soil structure

Soil structure is defined by FAO (2006) as the “*natural organisation of soil particles into discrete soil units (aggregates or peds) that result from pedogenic processes”.* Soil structure is described in the field in terms of type/shape, size, and degree of development (strength). Structure greatly influences the porosity and number of macropores in the soil. The characteristics of the macropore flow, their tortuosity and connectivity, are determined by the soil structure (Figure 3.5). An increase in the size and grade of structural units typically results in higher water-storage capacity and more macropores which promote preferential flow. Moderate and

[7] Ferrolysis is the break-down of clay associated with intense wetting and drying conditions (Brinkman, 1970).

strong soil structure, consisting of very fine and fine aggregates (e.g. granular, fine and medium angular blocky and subangular blocky) will result in an increase in the microporosity and higher conductivity in the soil (O'Geen, 2013). Coarse-sized structural units (prismatic or blocky) and platy structure can restrict drainage as flow is limited to inter-structural voids (O'Geen, 2013). Structureless soils (apedal soils), typically have high conductivity and a low water holding capacity due to the low clay contents. Soil structure can be changed through management practices: poor soil management destroys soil aggregates whilst proper management can restore aggregation. When aggregates are destroyed it will reduce the macroporosity of the soil and thereby reduce the hydraulic conductivity (Kutílek, 2004). Additions of soil organic matter, or practices which enhance the accumulation of organic matter, is beneficial for structure formation and protection and maintaining macropores.

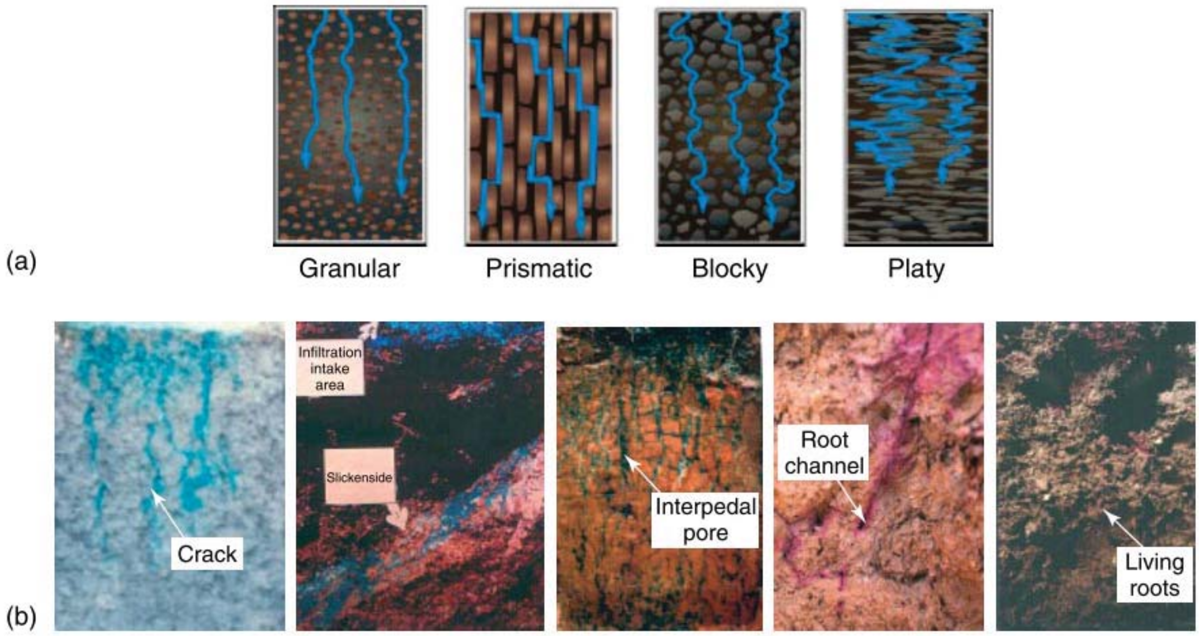

Figure 3.5. a) Conceptual model of flowpaths in differently structured soils, and b) Soil structure influence on preferential flowpaths (Lin et al., 2008).

3.3 SOIL HYDRAULIC PROPERTIES

3.3.1 Water retention characteristics

Soil water retention refers to the ability of soil to retain water against gravitation. This allows soil to store water during rain free periods for plant uptake. It influences the rate at which water is redistributed through the soils. Soil water retention characteristics are determined by the pore space and the pore size distribution, which is governed by texture, structure and porosity (O'Geen, 2013). Consider soils as a three phased system consisting of solid phase, air and water (Figure 3.6). The solid phase fraction, consisting of mineral and organic matter, is relatively stable, but the relative fraction of soil air and water fluctuates continuously. In dry soils hygroscopic water can be held so tightly by particles and in small pores that it is not available for root water uptake by typical mesophyte plants. This is the lower limit (LL) of plant available water (PAW). The Drained Upper Limit (DUL) refers to the water content where soils can hold water against gravitation. PAW is then the difference between DUL and LL[8]. If the water content exceeds DUL, the water will drain from the soil under the influence of gravitation, termed 'free water' or 'drainable porosity'. Saturation is when the entire pore space is filled with water[9]. Flow is the highest under saturated conditions as all the pores are conducting water (saturated hydraulic conductivity). Significant flow through the vadose zone, especially lateral flows, is only likely when conditions close to saturation are reached.

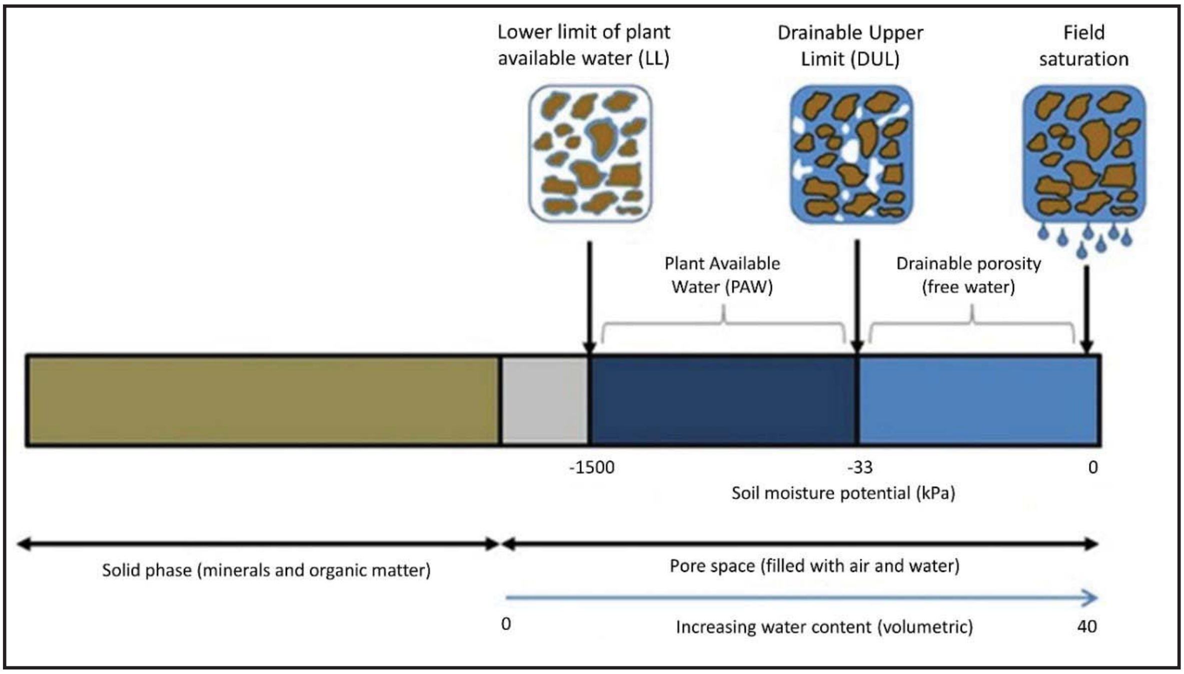

Figure 3.6. Soil as a three-phase system with different soil water retention characteristics: Lower limit (LL) of plant available water (PAW), Drained Upper Limit (DUL) and saturation (altered from O'Geen, 2013).

3.3.2 Permeability and hydraulic conductivity

Water movement through the soil, or the hydraulic conductivity, is strongly related to the water content of the soil. Conductivity rates in unsaturated soils are very low, as the soil particles will adsorb the water molecules. Once the soils are above DUL, the hydraulic conductivity increases until it reaches the maximum rate which is the saturated hydraulic conductivity (K_s). The hydraulic conductivity of the soil is determined by the texture (Table 3.2), structure, organic carbon and other factors that determine the microporosity of the soil. K_s can be measured *in situ* using double or single ring infiltrometers, Guelph permeameters or in the lab on undisturbed soil cores. These methods are generally based on Darcy's law for movement of water through a permeable substrate.

K_s is an important parameter in most hydrological models and very important to describe flowrates through the vadose zone. It is important to emphasise the K_s is not only a function of texture. Very often PedoTransfer

[8] This concept is often criticised for oversimplifying water retention in soils, but for practical hydropedology it will suffice to know that flows, especially lateral flows, only make considerable contributions under conditions close to saturation.
[9] Complete saturation will not be reached under natural conditions as some micropores will still be air filled, hence the term *field saturation.*

Functions[10] (PTFs) only make use of particle size distribution or textural classes to estimate K_s, but the macropores from structure or floral and faunal activity can play a more prominent role than that of the texture. It is also important to understand the clay mineralogy. For example, soils with high clay contents (1:1 kaolinite), can have very high hydraulic conductivities as these clays typically have low water holding capacity and well-developed microstructure. Similarly, high clay-content soils with well developed, fine structure can have conductivity rates which are similar to soils with much coarser texture. Measuring the conductivity *in situ* or on *undisturbed* cores, instead of sieved and repacked samples, is therefore of utmost importance.

Table 3.2. Approximate hydraulic conductivity rates for different texture classes (The National Co-operative Soil Survey).

Permeability Class	Conductivity (mm/h)	Textural class
Very slow	<1.3	clay
Slow	1.3-5.0	sandy clay, silty clay
Moderately slow	5.0-20	clay loam, sandy clay loam, silty clay loam
Moderate	20-63	very fine sandy loam, loam, silt loam, silty clay loam, silt
Moderately rapid	63-127	sandy loam, fine sandy loam
Rapid	127-254	sand, loamy sand
Very rapid	>255	coarse sand

3.3.3 Soil depth, porosity and storage

Soil depth is very important to determine the storage capacity, flowpaths and flowrates of the soils. The depth of the soil is dependent on the rates of weathering and erosion and these are influenced by the type of parent material, climate, topography, organisms and the age of the soils. In general, warm wet climates promote weathering and results in deep soils. Under similar climate and hydro-topographical conditions the rate of weathering of the parent material is controlled by the nature of the rock. Porosity ($\boldsymbol{f}$) is a measure of the total void space in a porous material and is measured, either as a percentage (between 0 and 100%), or as a fraction (between 0 and 1) of the bulk volume. It is defined by the ratio:

$$\boldsymbol{f = V_v \div V_T}$$

Where V_V is the volume of the void – space and V_T is the total or the bulk volume of material, including the solid and void components. Porosity can be calculated by:

$$\boldsymbol{f \ = \ 1 - (\rho_d \div \rho_s)}$$

Where $\boldsymbol{\rho_d}$ is the bulk density (Mg. m^{-3}) and $\boldsymbol{\rho_s}$ is the particle density (Mg. m^{-3}, generally taken as 2.65 in soils low in organic matter). Soil depth together with the porosity determines the storage capacity of the soil.

[10] PedoTransfer Functions describe interrelationships between various soil properties. They are typically used to estimate the value of one property, which is tedious and expensive to measure, from other properties which are measured during routine analysis (Pachepsky and Rawls, 2004).

In a South African case study, the storage capacity of two semi-arid catchments near Bedford in the Eastern Cape was determined (Van Tol et al., 2010a). The average soil depth of catchment B3 was 450 mm and that of B4&5 was 190 mm (due to similarities in B4 and B5 they were considered as one catchment). The average porosity of B3 was 301.5 mm compared to 130.6 mm of B4&5. Although the area of B3 is smaller (40.7 km^2) than that of B4&5 (49.4 km^2), it can store almost twice the volume of water (12.5×10^6 m^3 compared to 6.7×10^6 m^3). This facilitates more water infiltration, greater water holding capacity, a greater volume of water contained at saturation and at DUL. This results in more interflow at the A/B-horizon interface and at the soil/bedrock interface, more water contributing to groundwater bodies and consequently a longer duration of streamflow and a longer residence time of water (Hughes and Sami, 1993). More water is available for transpiration resulting in a denser vegetative cover. Shallow soils, in these catchments, tend to saturate quickly after rain events and this promotes overland flow generation with a short residence times and high peak flows (in other catchments where shallow soils overlie permeable bedrock flow, long residence times are dominant – see Section 2.4). According to Asano et al. (2002), the soil depth is more important in determining the residence times than the slope length or the upslope contribution area.

Very important when the depth and porosity is considered is to include the entire soil profile, i.e. not only the 'solum' as in the case with most soil databases but the weathering zone as well. In the case of the Bedford catchments, the lithocutanic horizon in B3 was weathered and could allow infiltration and storage. In catchments B4&5, the relatively un-weathered rock with low infiltration rate promoted overland flow generation.

In a modelling study of the KwaZulu-Natal midlands, realistic simulations could only be obtained when the entire vadose zone was accounted for in the model inputs (Van Tol and Van Zijl, 2022). Average soil depths from regional soil databases are around 700 mm, but field observations show that the saprolite layer (weathering zone) could be ten times deeper than this (Figure 3.7).

Figure 3.7. Depth of the weathering zone in soils in the KwaZulu-Natal midlands, geological hammer for scale (Van Tol and Van Zijl, 2022).

3.3.4 Organic carbon accumulation

The accumulation of organic material, and consequently organic carbon (OC), is recommended for increased soil health as well as reducing the impact of climate change by sequestering atmospheric carbon. Increasing the organic carbon content can be achieved from additions of organic material or through applying sustainable practices for example, minimum tillage, maintaining residues, incorporation of a variety of crops and animals in production practices and sound grazing practices.

The benefits of OC to soil health are well studied and includes chemical, physical, biological and nutritional advantages (Brady & Weil, 2016). From a hydropedological perspective OC accumulation increases the microporosity of the soil and thereby results in more infiltration and less overland flow. This will result in less flooding, erosion, pollution and general land degradation, as well as more stream flows and higher groundwater recharge. Higher OC contents also result in a higher water holding capacity due to the greater surface area associated with this material. More water is therefore available for plant root uptake.

Carbon accumulation is an indication of water saturation (see Section 4.2). The South African Soil Classification distinguishes between peat and organic topsoil horizons based on the carbon content. Peat horizons are permanently saturated or inundated and contain more than 20% OC whereas organic horizons are saturated for long periods and contain 10-20% OC (Soil Classification Working Group, 2018). Within the same environmental conditions, the carbon content can be related to the hydroperiod. Omar et al. (2014) found a good correlation between average water table depths, channel incisioning and OC in wetlands in Hogsback (Omar et al., 2014).

CHAPTER 4: DIAGNOSTIC HORIZONS AS HYDROLOGICAL FUNCTIONAL UNITS

4.1 INTRODUCTION

A soil horizon represents a layer of relatively homogenous properties and is the foundation of soil classification in the South African context. Understanding the hydrological response of diagnostic horizons is therefore pivotal in understanding and characterisation of the hydrological behaviour of soils. The hydrological behaviour of horizons, based on hydropedological research, was built into the revision of the South African Soil Classification System (SASCS) (Soil Classification Working Group, 2018). For instance, hydropedological interpretations influenced the inclusion of descriptions of soils to the bedrock interface, differentiation between fractures and solid rock, and the recognition of different types of saprolitic weathering at the family level. Additionally, the differentiation between gley and gleyic horizons was also based on hydropedological interpretations.

This chapter describes some of the key hydrological functions of different soil horizons as classified in the South African soil classification. It should become apparent that the function of the horizons is dependent on the vertical sequence of the horizon in the profile (i.e. what lies above and below a specific horizon) as well as the position in the landscape. A diagnostic horizon may therefore have more than one function.

4.2 TOPSOIL HORIZONS WITH SIGNIFICANT ORGANIC CARBON ACCUMULATION

Organic carbon (OC) accumulation is associated with high rainfall and/or saturated conditions. Peat, organic and humic topsoil horizons have high organic carbon contents. According to SASCS criteria the OC content should exceed 20, 10 and 1.8% for peat, organic and humic horizons, respectively.

The humic horizon is found in freely drained areas or soils and according to diagnostics is not allowed to overlie material with grey matrix colours (i.e. saturated). Vertical drainage into- and out of these horizons is the dominant flowpath. These horizons occur in climates with high rainfall and relatively low potential evaporation which favours vegetative growth. The accumulation of OC is therefore due to the climate and not because of saturation. These horizons typically occur in high lying areas and around the mist-belt of the eastern escarpment.

In contrast to humic horizons, peat and organic horizons contain high OC contents because of saturation and a slow break-down of organic material due to a lack of oxygen. In both the peat and organic horizon, inundation or long periods of saturation forms part of the diagnostic criteria. These horizons typically occur in landscape positions (valley bottom) or geomorphological settings (e.g. seeps or fountains) which are marked by a constant supply of water. Long periods of saturation in the topsoil, especially during the wet season, will imply that additional precipitation cannot infiltrate but will flow as overland flow. Soils with peat or organic horizons classify as wetland soils.

4.3 VERTIC AND OTHER STRONG STRUCTURED HORIZONS

Vertic horizons or soil horizons with vertic properties such as slickensides and high 2:1 clay content, are physically active. These horizons can shrink considerably during the dry season, forming large macropores which are interconnected. At the beginning of the wet season, these structural macropores allow fast infiltration. Once the landscape wets up, the soils adsorb water and the pores close. Due to the very high clay contents, the hydraulic conductivity in the absence of macropores is very low and the soils will likely generate overland flow due to infiltration excess flow.

4.4 MELANIC AND ORTHIC TOPSOIL HORIZONS

The hydrological response of melanic and orthic topsoil horizons is determined by the hydrological characteristics of the underlying horizons. When these horizons overlie freely drained subsoils (Section 4.6), they recharge (vertical drainage) horizons below if the infiltration and hydraulic conductivity is higher than the rainfall intensity. If the rainfall intensity exceeds the infiltration rate, overland flow is generated. This will normally occur in areas where the topsoils have high clay content with sparse vegetation or when the topsoils have been degraded (compaction or crust formation).

In the SASCS, we distinguish between 'bleached, dark and other colours' in orthic horizons. Bleached colours can serve as an indicator that the underlying horizon is not permeable and that there is periodic saturation in the orthic topsoil. When the parent material is inherently bleached (e.g. sandstone of the Table Mountain and Clarens formation), a bleached topsoil horizon does not imply saturation.

4.5 HYDROMORPHIC HORIZONS

Albic and gley horizons react differently to rain events which could be an indication that these horizons are fed by different water sources. Gley horizons are typically close to saturation for long periods at a time (Van Huyssteen et al., 2005) whereas albic horizons experience marked wet and dry conditions (Smith and Van Huyssteen, 2011). This results in differences between the amount and type of clay in these horizons. Wetting and drying cause clay degradation through the process of ferrolysis and 2:1 clays are broken down to kaolinite and kaolinite to silica. This in turn increases the conductivity and could result in significant lateral flow. Not all albic horizons are, however, formed through lateral flow and removal of clay, organic material and other colouring agents (Van Tol et al., 2013a). In soils with albic horizons with isotropic textural distribution, lateral flow generation is physically not possible. This typically applies to soils with podzols and deep sandy soils of the coastal regions.

Gleyic horizons, according to the diagnostic criteria have 'high chroma colouration' in the ped interiors, i.e. the inside of the peds did not saturate long enough for reduction to take place (see Section 3.2.1). Gleyic horizons are therefore saturated for shorter periods of time than gley horizons. Gleyic horizons are also marked by '*moderate or strong structure with prominent cutans*' according to the SASCS diagnostic criteria. In areas with moderate slopes, significant lateral flows are unlikely in these horizons, and they should rather be seen as a storage of water with a slow release to either the bedrock, groundwater, lower lying soils, wetlands or streams.

Plinthic horizons form due to alternating wet and dry conditions and consequently undergo ferrolysis as well. The diagnostic criteria only allow '*single grain, massive or weak structure*' due to low clay contents or kaolinitic clays and associated high hydraulic conductivity. Where plinthic horizons occur at the soil/bedrock interface, it is an indication that saturation occurs periodically and, because of the conductivity, significant lateral flow can occur. This is especially true in sloping landscapes.

The occurrence of hydromorphic horizons is detrimental to buildings (see exceptions of albic horizons which did not form due to lateral flow above), as the water is periodically under positive pressure and therefore can penetrate walls and rise up to 800 mm by capillary forces. Most gley and geyic horizons have a high plasticity index. It can therefore shrink and swell with changes in the water content. Most land use changes cause a reduction in the water content, and these horizons can shrink more than under natural conditions, causing severe damages to infrastructure.

4.6 FREELY DRAINED HORIZONS

4.6.1 Red structured horizon

These horizons typically overlie saprolite or fractured rock. Signs of deep interflow under the red structured horizon are not common. The overlying topsoil has similar structure and colour as the red structured horizon and indicates that the infiltration rate exceeds rainfall intensity in most cases. Calcareous families are not an indication of restrictive vertical movement, but less effective leaching associated with high evaporative demands. In all climates, calcareous soils may be due to parent material containing high concentrations of calcium. Interflow in the deep subsoil is possible, as black and red mottles may occur and indicate a high manganese content that buffers the redox potential for short periods of saturation and thus imply underlying drainage restriction. Occurrence of these mottles typically increases with depth and downslope.

4.6.2 Red apedal horizon

Red apedal horizons are the best examples of free vertical drainage. These horizons could be underlain by hydromorphic horizons (gleyic and plinthic). In such instances, the vertical drainage is restricted by the underlying bedrock. Red apedal horizons in the drier west of South Africa are typically coarse textured and derived from wind-blown sands. In the eastern parts, intense weathering results in deep red apedal horizons which may contain high clay contents, but still have hydraulic conductivity which exceeds the rainfall intensity.

4.6.3 Yellow-brown apedal horizon

The hydrology of the structureless yellow-brown apedal horizon is the same as that of the red apedal horizon. Although the general interpretation is that this horizon is wetter than the red apedal horizon (Van Huyssteen et al., 2005), the yellow colour could be derived directly from the parent material. In a landscape where both red and yellow-brown apedal horizons occur, the yellow-brown horizon will occur in lower lying, slightly wetter positions. The interpretation then is that this horizon undergoes short periods of saturation and reduction either because of resistance of the underlying layer or because of interflow. It can also be return flow from the fractured bedrock flowpath.

4.6.4 Depositional horizons

Aeolian (wind), alluvial (water) and colluvial (gravity) deposited horizons are typically of variable depth and controlled by external features. They are grouped under stratified alluvium, regic sand, or neocutanic horizons. The formation is not always related to hydropedological processes but rather of landscape or climatical conditions. In general, these horizons signify vertical drainage. Alluvial soils are, however, horizontally layered and when a sandy layer overlies a clayey layer it can promote lateral flow generation. In sandy aeolian soils, vertical drainage occurs very rapidly. This is a typical response of sand dunes and outflow might occur at the foot of the dune to form or contribute to a wetland. In arid land near the coast, lime may precipitate as layers forming effective interflow zones.

4.6.5 Lithic horizons

Lithic horizons occur as a visible weathered transition between soil and fractured rock. In high rainfall areas it has similar hydraulic properties as well drained apedal horizons and in dry areas it is physically weathered to broken rock particles. Infiltration rate into, and hydraulic conductivity of, the fractured rock typically exceeds the rainfall intensity and recharge of the fractured bedrock flowpath occurs. Where redox or reduction symptoms occur, it is an indication that the underlying rock resists drainage to recharge the fractured rock.

4.6.6 Fractured rock

Fractured rock can occur beneath almost any horizon. Cracks serve as macropores and govern the bedrock flowpaths which can recharge groundwater or return to the soil downslope. Tongues in the fractured rock are not limited to clay cutans on rock fragments but include vertical soil intrusions of several centimetres into the rock. This serves as an indicator of preferred vertical pathways and conduits towards the bedrock flowpaths.

4.7 SOIL HORIZONS AS FUNCTIONAL UNITS (SUMMARY)

The hydropedological interpretation of soil horizons for of different functional units is presented in Table 4.1. It is possible that one horizon could perform different hydrological functions during different times. This is related to the antecedent moisture content, the type of rainfall and other environmental factors.

Table 4.1. Hydrological interpretation of diagnostic horizons and other soil properties.

	Soil horizon/feature	Condition/description	Hydrological interpretation
Related to vertical flow (recharge)	***Melanic horizon***	Overlying permeable or impermeable horizons	The hydrological response of these horizons is controlled by the subsoil horizons. Recharge through underlying oxidised horizons. Locally, shallow interflow on solid rock at steep slopes. Slow recharge through fractured rock. Near surface macropore flow is possible when these horizons overlie hydromorphic horizons.
	Orthic horizon		
	Humic horizon		
	Vertic horizon	Overlying permeable or impermeable horizons	Infiltration rates are high in natural veld and no-till fields. In cultivated land it may generate overland flow in the peak rainy season. On impermeable horizons it indicates poor drainage of on-level positions and return flow in slopes.
	Albic horizon	Podzol soil forms	Recharge lower horizon. Interflow may be present deeper down the profile.
		Overlying red and yellow-brown apedal B horizons	Insufficient evidence that apedal horizons cause saturation. Bleaching is related to higher biological activity close to the surface under climatic conditions with low evaporative demand rather than periodic saturation due to impermeability of underlying material.
		Neocutanic B horizon	Saturated hydraulic conductivity of neocutanic horizon can vary considerably. Bleaching is most likely due to the same mechanism as with apedal horizons but lateral flow caused by a periodic perched water table is possible.
	Red apedal horizon	Subsoil in recharge soils. On saprolite or fractured rock	Indicates drainage is faster than rainfall infiltration.
			Non-calcareous families indicate effective leaching. In all climates, it may also be due to a lack of lime in the parent material.
			Black and red mottles indicate short periods of saturation. This implies an underlying drainage restriction. Occurrence typically increases down the profile and down slope.
	Red structured horizon	Subsoil in recharge soils. On saprolite or fractured rock	Indicates faster drainage than rainfall intensity.
			Calcareous families indicate less effective leaching likely caused by high evaporative demand (ineffective leaching).
			Black and red mottles indicate short periods of saturation. This implies an underlying drainage restriction. Occurrence typically increases down the profile and down slope.
	Yellow-brown apedal horizon	Subsoil in recharge soil. On saprolite or fractured rock. Lower in landscape	The hydrology is the same as for the red apedal horizon. The horizon indicates short periods of reduction either because the underlying layer resists drainage or because of interflow. Lower down the landscape it indicates a fractured rock to soil return flow.
	Neocutanic horizon	Subsoil in recharge soil when on saprolite, fractured rock or solid rock	The hydrology is dependent on the saturated hydraulic conductivity of the horizon which is inherently variable.
	Podzol horizon	Second or third horizon in profile	Vertical drainage in most soils with podzols is not restricted and recharge of underlying material is dominant.
	Placic pan	In podzol horizon	The extent and continuity of the horizon determine the hydrology. If the “pan” is not continuous and does not influence the hydrology of the podzol, but large areas covered by a continuous pan will cause lateral flow.
	Stratified alluvium	Floodplains	Hydraulic properties of individual stratification control water movement. Coarse material typically facilitate recharge.
	Lithic (Saprolite)	Transition between soil and fractured rock	Usually permeable and recharge of underlying fractured rock but may be impermeable, dense, high density clay creating interflow of water added from above. It excludes water from below.
	Fractured rock	Beneath soil and saprolite. Classified as “hard rock”	Draining water from the soil is released to fractured rock. Usually quick recharge.
	Solid rock	Rock without cracks	Impermeable, creating soil/rock interflow.

	Lithic horizon	Usually crest positions	In the case of geolithic and saprolithic vertical drainage through the soil and recharge into fractured rock is dominant.
	Soil depth	Soils are deeper because the horizons are thicker and/or more horizons are present	Thicker soils are associated with wetter climates due to higher weathering rate. Wetter positions in the hillslope are associated with thicker and increased number of horizons.
		Aeolian (wind), Alluvial (water), Colluvial (gravity)	Texture, layering and reduction or redox features dominate interpretation.
Related to lateral flow at soil/bedrock interface	***Albic horizon***	Third horizon or deeper. Often on solid rock	The horizon indicates seasonal to post-seasonal interflow. In the arid and dry semi-arid climates, it may generate lateral flow only in abnormally wet years.
	Gley horizon, grey	Third horizon or deeper	The horizon indicates permanent slow interflow, an impermeable underlying rock, a large recharge area and interflow feeding into it.
	Soft plinthic horizon	Third horizon or deeper	The horizon indicates seasonal or occasional saturation in the horizon and an underlying horizon, usually a G horizon, is saturated for longer. Mottling indicates slower flow contrary to the E or other overlying horizon.
	Gleyic horizon, mottled	Water flow above and/or below the G horizon	Mottling in overlying horizon indicates periodic saturation but underlying bright mottling under common gley horizons.
	Solid rock	Solid	Generate lateral flows at soil/rock interface.
	Soft carbonate	Increase down slope	The precipitate of calcium carbonate is the end of a flowpath. Common in arid climates, especially at the transition to dry semi-arid.
	Hardpan carbonate	In relationship with distribution of neo- and soft carbonate	The hardpan carbonate horizon sometimes has no other explanation than being relict. It often overlies the soft carbonate, indicating vertical leaching and re-precipitation. Event driven and post-event driven, depending on slope.
Related to shallow lateral flow (topsoil/subsoil interface)	***Orthic horizon***	Bleached and overlying less permeable horizons	Pedocutanic, prismacutanic, hardpan carbonate, solid rock. Event to post-event driven near surface macropore flow in long hillslopes.
	Orthic horizon	Chromic and on steep slopes	Near-surface macropore quick flow which is event driven.
	Albic horizon	Second horizon on impermeable horizons	Event and post-event driven, depending on the duration of the rain event and the position in the hillslope.
	Hardpan carbonate	At a slope. Also occur as responsive in flat landscapes	If layer is continuous, it can create event driven lateral flow.
	Dorbank	Shallow soil	If layer is continuous, it can create event driven lateral flow.
	Prismacutanic horizon	Shallow, structured subsoil	Event driven. Post-event driven in Estcourt soil form in the footslope positions of granite hillslopes where it usually occurs at the seep line.
	Pedocutanic horizon	Shallow, structured subsoil	The Klapmuts form behaves similarly to the Estcourt. See prismacutanic horizon.
Related to overland flow generation	***Vertic horizon***	Extreme swelling	In cultivated land, infiltration is very slow in the wet state.
	Gley near the surface	Permanently wet	Duplex soils are responsive during peak rain season and acts as shallow interflow soils after the rain season. Permanently wet soils are responsive all year round.
	High organic and peat soils	Stable water table	Organic soils indicate permanent saturation and are therefore responsive all year around..

CHAPTER 5: HYDROPEDOLOGICAL GROUPING OF SOUTH AFRICAN SOIL FORMS AND FAMILIES

5.1 INTRODUCTION

A key aspect of most hydropedological studies is the interpretation of soil information embedded in a soil classification. This information is derived from in-situ descriptions of soil morphology and supported by measurements of hydraulic properties (e.g. particle size distribution, hydraulic conductivity, and porosity). The soil information is typically organised into different tiers of soil classification, such as diagnostic horizons, soil forms, or soil families. Establishing hydropedological behaviour, therefore, relies on linking soil classification principles and conventions to hydrological response and water regimes. In a previous effort, Van Tol and Le Roux (2019) grouped the 73 soil forms from South Africa's previous soil classification system, The Blue Book (Soil Classification Working Group, 1991), into seven hydropedological groups. Since then, a new version of the soil classification system, titled *'Soil Classification: a natural and anthropogenic system for South Africa,'* was published (Soil Classification Working Group, 2018). As with the previous system, the classification of natural soils makes use of two main categories: soil forms (n = 135), which can be further divided into soil families (n = 1 629). For the first time, anthropogenic materials and human-impacted soils are included in the classification. Here, six different classes with 28 families are recognised and described.

The contribution of hydropedological research is evident in shaping the format and structure of the 2018 soil classification system. For instance, hydropedological interpretations influenced the inclusion of descriptions of soils to the bedrock interface (i.e. no depth limit criteria for classification), differentiation between fractured and solid rock, and the recognition of different types of saprolitic weathering at the family level. Additionally, the differentiation between gley and gleyic horizons was also based on improved hydropedological understanding of soil formation and hydrological regimes. For detailed descriptions of the changes between the 1991 and 2018 soil classification systems, see Van Zijl et al. (2020).

With the publication of the new classification system and its strong hydrological emphasis, along with the inclusion of anthropogenic material, it is timely to revisit the hydropedological grouping proposed by Van Tol and Le Roux (2019). In this context, we propose new hydropedological types and aim to group the soil forms and 1 657 (1 629 + 28) families based on their dominant hydrological response. For each hydropedological type, this chapter begins with a brief theoretical description followed by tables (Table 5.1-5.10) that categorise soil forms and families into various hydropedological groups.

5.2 RECHARGE SOILS

5.2.1 Processes, indicators and hydropedological implications of recharge soils

Process: Hydrological recharge involves the replenishment of water, and from a hydropedological perspective, recharge soils facilitate the filling of underlying entities such as groundwater aquifers or downslope wetlands. Infiltration and hydraulic conductivity generally surpass rainfall intensity. Recharge soils are characterised as ‘freely-drained’ soils, indicating the absence of hindrances or layers impeding vertical water movement. However, this does not imply that most of the water will readily exit the profile. In arid and semi-arid regions, a significant portion of infiltrated water is extracted through evapotranspiration (ET). To achieve substantial recharge, the downward water flux in and out of the profile must surpass the upward extraction by evapotranspiration. Hydropedological recharge, therefore, encompasses not only water reaching groundwater aquifers but also includes recharge of wetlands, fractured bedrock flowpaths, and cases where infiltration and ET reach equilibrium.

Indicators: Recharge soil horizons are recognised by their lack of redox or reduction morphology in any part of the profile.

Impacts: Extensive areas of recharge soils enhance the potential water intake by wetlands from their catchments. Diminished infiltration into recharge soils, often coupled with increased overland flow, curtails the hydroperiod (duration of saturation) of wetlands, subsequently reducing stream baseflow. Instances of reduced infiltration involve surface sealing due to structures (primarily roofs) and roads. Alterations in vegetation affect transpiration rates and volumes. Afforestation with deep-rooted trees diminishes the water draining through soils into fractured rock, thus lowering recharge of bedrock, wetlands, and groundwater. Evaluating terrestrial hillslope area and storage volume necessitates considering the vegetation as a factor. Changes in infiltration rate between natural veld and cultivated fields may also influence recharge rates.

5.2.2 Recharge soil groups

5.2.2.1 Recharge (deep)

Recharge (deep) soils are deep, freely drained soils without any indication of saturation, overlying fractured rock or deeply weathered saprolite (Figure 5.1a). In drier areas, the underlying bedrock might not be permeable, and the absence of hydromorphic properties are due to insufficient rainfall to cause saturation for significant periods. *Recharge (deep)* soils contribute significantly to transpiration, but downward ET excess flow is the dominant flowpath.

Table 5.1. Recharge (deep) families of the South African Soil Classification.

Soil form	Families	Remarks
Stanger (Sg)	All families	
Abbotspoort (Ab)	All families	
Inhoek (Ik)	1100; 2100	Families without alluvial wetness
Kranskop (Kp)	All families	

Soil form	Families	Remarks
Longtom (Lg)	1110; 1120; 1210; 1220; 2110; 2120; 2210; 2220	Families without gleylithic
Magwa (Ma)	All families	
Gangala (Ga)	1110; 1120; 1210; 1220; 2110; 2120; 2210; 2220	Families without gleylithic
Inanda	All families	
Henley (He)	1110; 1120; 1210; 1220; 2110; 2120; 2210; 2220	Families without gleylithic
Sweetwater	All families	
Constantia (Ct)	All families	Albic horizons on freely drained horizon will predominantly recharge
Shepstone (Sp)	All families	
Villafontes (Vf)	1110; 1210; 2110; 2210	Aluvic neocutanic
Tsitsikamma (Ts)	1110; 1210; 2110; 2210	Gleying absent below podzol
Houwhoek (Hh)	1111; 1112; 1211; 1212; 1221; 2111; 2112; 2121; 2211; 2212	Families without Ortstein hardening and gleylithic
Concordia (Cc)	1111; 1112; 1211; 1212; 2111; 2112; 2211; 2212	Families without Ortstein hardening
Kinkelbos (Kk)	1111; 1121; 1211; 1221; 2111; 2121; 2211; 2221	Aluvic neocarbonate
Fernwood (Fw)	All families	Check carefully for gleying as described under sandy gley, if gleyed rather *Interflow (soil/bedrock)*
Griffin (Gf)	All families	
Palmiet (Pm)	All families	
Glencoe (Gc)	All families	Considerable lateral flow below hard plinthic possible – verify if not *Interflow (soil/bedrock)*
Clovelly (Cv)	1111; 1121; 1211; 1221; 1311; 1321; 2111; 2121; 2211; 2221; 2311; 2321; 3111; 3121; 3211; 3221; 3311; 3321; 1112; 1122; 1212; 1222; 1312; 1322; 2112; 2122; 2212; 2222; 2312; 2322; 3112; 3122; 3212; 3222; 3312; 3322	All families without gleylithic
Carolina (Ca)	All families	
Ermelo (Er)	All families	
Tongwane (Tg)	All families	
Lichtenburg (Lc)	All families	Considerable lateral flow below hard plinthic possible – verify if not *Interflow (soil/bedrock)*
Nkonkoni (Nk)	1111; 1121; 1211; 1221; 1311; 1321; 2111; 2121; 2211; 2221; 2311; 2321; 3111; 3121; 3211; 3221; 3311; 3321; 1112; 1122; 1212; 1222; 1312; 1322; 2112; 2122; 2212; 2222; 2312; 2322; 3112; 3122; 3212; 3222; 3312; 3322	All families without gleylithic
Vaalbos (Vb)	All families	
Hutton (Hu)	All families	
Magudu (Md)	All families	
Nshawu (Ns)	All families	
Shortlands (Sd)	All families	
Jonkersberg (Jb)	1100; 2100	Gleying absent below podzol
Groenkop (Gk)	1110; 1120; 2110; 2120	Families without Ortstein hardening and gleylithic
Pinegrove (Pg)	1110;1120;2110; 2120	Families without Ortstein hardening
Quaggafontein (Qf)	1111; 1211; 2111; 2211; 3111; 3211	Aluvic neocutanic with dry alluvial
Tubatse (Tb)	1111; 1211; 2111; 2211; 3111; 3211; 1112; 1212; 2112; 2212; 3112; 3212	Aluvic neocutanic with dry lithic
Bethasda (Be)	1111; 1112; 1211; 1212; 2111; 2112; 2211; 2212; 3111; 3112; 3211; 3212	Aluvic neocutanic
Oakleaf (Oa)	1110; 1210; 2110; 2210; 3110; 3210	Aluvic neocutanic
Dundee (Du)	1111; 1121; 1211; 1221; 2111; 2121; 2211; 2221; 3111; 3121; 3211; 3221	Alluvial wetness absent
Namib	All families	

5.2.2.2 Recharge (shallow)

Rechange (shallow) soils are freely drained topsoil horizons overlying fractured rock or saprolite (Figure 5.1b). The contribution of these soils to transpiration is smaller than that of *Recharge (deep)* soils. Due to the relatively short residence time in the biological zone (solum), water exiting *recharge (shallow)* soils have a lower reduction potential (oxygenised).

Table 5.2. Recharge (shallow) families of the South African Soil Classification.

Soil form	Families	Remarks
Mayo (My)	1100; 1200; 2100; 2200	Families without gleylithic
Milkwood (Mw)	1100; 2100	Fractured hard rock
Nomanci (No)	1100; 1200; 2100; 2200	Families without gleylithic
Graskop (Gp)	1100; 2100	Fractured hard rock
Dresden	1000; 2000	Chromic and dark topsoil indicates hard plinthic is permeable
Glenrosa (Gs)	1110; 1210; 2110; 2210; 3110; 3210; 1120; 1220; 2120; 2220; 3120; 3220	Saprolithic and geolithic support recharge
Mispah (Ms)	1110; 1210; 2110; 2210; 3110; 3210	Fractured hard rock

5.2.2.3 Recharge (slow)

In the *Recharge (slow)* group, slow vertical movement is the dominant flowpath. These soils typically have clay rich (luviated) subsoil horizons which act as a store, rather than a conduit of water (Figure 5.1c). ET excess water seldom reaches the bottom of the soil profile and the contribution to transpiration (upward flux) is generally the dominant flowpath. *Recharge (slow)* also includes profiles with ineffective leaching and hence the accumulation and precipitation of bases in the form of lime and gypsum (Figure 5.1d). Hydromorphic properties are absent from these profiles.

Table 5.3. Recharge (slow) families of the South African Soil Classification.

Soil form	Families	Remarks
Darnall (Da)	1110; 1120; 1210; 1220; 2110; 2120; 2210; 2220	Families without gleylithic
Bonheim (Bo)	All families	
Steendal (Sn)	All families	
Immerpan (Im)	All families	
Molopo (Mp)	All families	
Akham (Ak)	All families	
Kimberley (Ky)	All families	
Plooysburg	All families	
Garies (Gr)	All families	
Heilbron (Hb)	All families	
Utrecht (Ut)	1111;1211; 1311; 1411; 1121; 1221; 1321; 1421; 2111; 2211; 2311; 2411; 2121; 2221; 2321; 2421	All families without alluvial wetness
Sandile (Sa)	1111;1211; 1311; 1411; 1121; 1221; 1321; 1421; 2111; 2211; 2311; 2411; 2121; 2221; 2321; 2421; 1112;1212; 1312; 1412; 1122; 1222; 1322; 1422; 2112; 2212; 2312; 2412; 2122; 2222; 2322; 2422	All families without gleylithic
Cookhouse (Ck)	All families	
Sterkspruit (Ss)	All families	

Soil form	Families	Remarks
Queenstown (Qt)	1111;1211; 1311; 1411; 1121; 1221; 1321; 1421; 2111; 2211; 2311; 2411; 2121; 2221; 2321; 2421	All families without alluvial wetness
Swartland (Sw)	1111;1211; 1311; 1411; 1121; 1221; 1321; 1421; 2111; 2211; 2311; 2411; 2121; 2221; 2321; 2421; 1112;1212; 1312; 1412; 1122; 1222; 1322; 1422; 2112; 2212; 2312; 2412; 2122; 2222; 2322; 2422	All families without gleylithic
Spioenberg (Sb)	All families	
Valsrivier (Va)	All families	
Erin (En)	All families	
Makgoba (Mb)	All families	
Etosha (Et)	All families	
Gamoep (Gm)	All families	
Soutvloer (Sv)	All families	
Oudtshoorn (Ou)	All families	
Quaggafontein (Qf)	1121; 1221; 2121; 2221; 3121; 3221	Luvic neocutanic with dry alluvial
Tubatse (Tb)	1121; 1221; 2121; 2221; 3121; 3221; 1122; 1222; 2122; 2222; 3122; 3222	Luvic neocutanic with dry lithic
Bethasda (Be)	1121; 1122; 1221; 1222; 2121; 2122; 2221; 2222; 3121; 3122; 3221; 3222	Luvic neocutanic
Oakleaf (Oa)	1120; 1220; 2120; 2220; 3120; 3220	Luvic neocutanic
Palala (Pl)	All families	
Addo (Ad)	All families	
Prieska (Pr)	All families	
Sendelingsdrif (Sf)	All families	
Trawal (Tr)	All families	
Motsane (Mt)	1111; 1121; 1211; 1221; 2111; 2121; 2211; 2221; 3111; 3121; 3211; 3221	Alluvial wetness absent
Burgersfort (Bg)	1111; 1121; 1211; 1221; 2111; 2121; 2211; 2221; 3111; 3121; 3211; 3221; 1112; 1122; 1212; 1222; 2112; 2122; 2212; 2222; 3112; 3122; 3212; 3222	Dry lithic
Hofmeyer (Hf)	All families	
Augrabies	All families	
Kolke (Ko)	All families	
Olienhout (Oh)	All families	
Koiingnaas (Ks)	All families	
Brandvlei (Br)	All families	
Rooiberg (Ro)	All families	

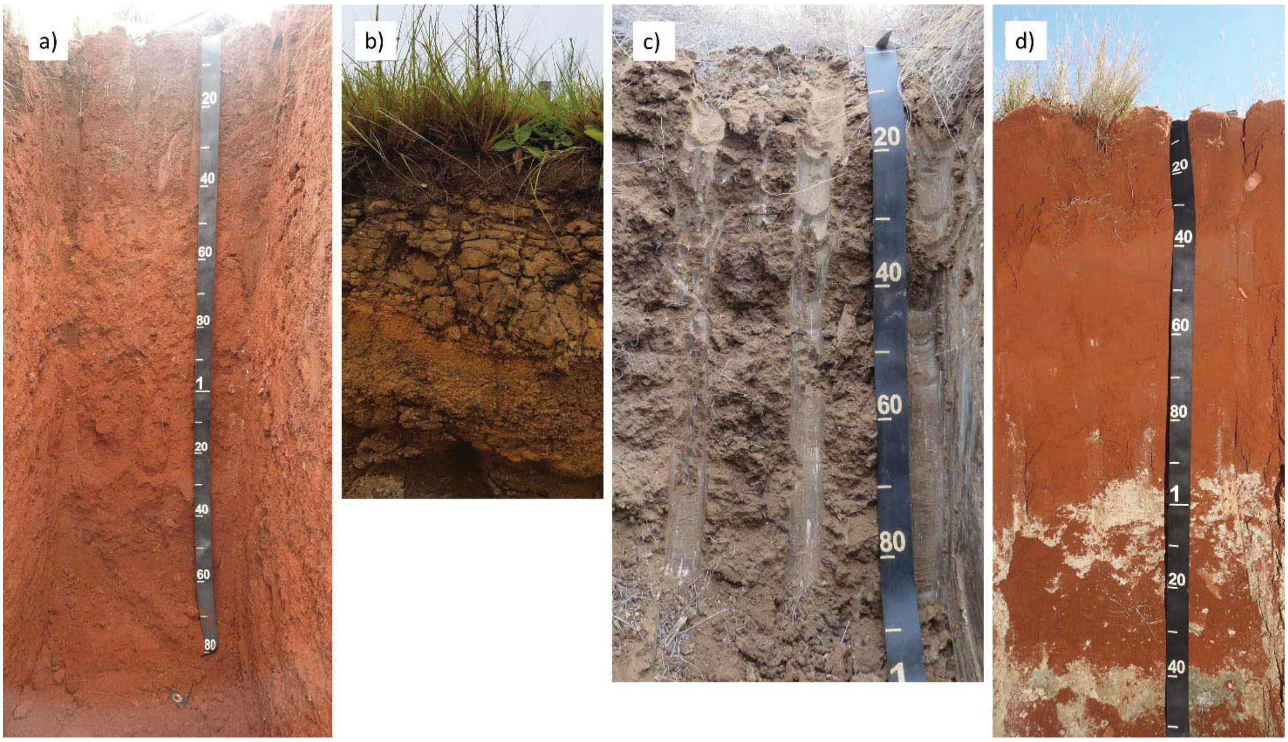

Figure 5.1. Examples of recharge soils: a) Recharge (deep), b) Recharge (shallow), c) Recharge (slow) – high clay contents limit fast vertical drainage and d) Recharge (slow) – lime accumulations indicate insufficient leaching.

5.3 INTERFLOW SOILS

5.3.1 Processes, indicators, and implications of interflow soils

Process: Interflow in soils arises from two primary processes. The first process is attributed to anisotropy in hydraulic conductivity. This occurs when a permeable horizon overlays a less permeable (restrictive) horizon or material, causing vertical draining water to accumulate atop the restricting horizon and subsequently drain laterally downslope. The restrictive horizon can be situated at various depths, such as the topsoil/subsoil interface or the soil/bedrock interface. The second process involves the return of bedrock flowpaths into the soil, saturating the lower part of the profile. These horizons rely on recharge return flows from upslope lands (recharge zones) and, if permeable, could also receive water from overlying horizons. Therefore, it is crucial to analyse the morphology of profiles both higher up the hillslope and downslope from an observation point. The interflow area exhibits variations in slope gradient and fracture systems, and the water content of interflow horizons and soils ranges from periodic to permanent saturation. Flow rates are primarily influenced by slope angle and interflow horizon conductivity (Van Tol et al., 2013a). In interflow soils, the duration of saturation increases vertically in the soil profile and downslope in the hillslope (Van Huyssteen et al., 2005). Sudden increases in deep subsoil moisture content on midslope and lower slopes indicate the return flow from fractured rock to soil saprolite and deep subsoil. This bedrock flowpath can sustain interflow long after the rainy season ends (Le Roux et al., 2011).

Interflow pathways can be categorised as shallow and deep. Shallow flowpaths occur at the topsoil/subsoil interface and generally within 500 mm from the surface. Deep interflows manifest at the soil/bedrock interface, occurring at depths greater than 500 mm from the surface. These pathways typically intersect within wetlands. Shallow interflow is usually event-driven, with flow corresponding to specific rainfall events or a series thereof. Deep interflow hinges on recharge and bedrock flow, exhibiting a seasonal pattern.

Indicators: Shallow and deep interflow soils exhibit morphological evidence of reduction and redox processes in the second and third horizons (evident through grey colours and mottles). When observed in a second horizon, an albic horizon is typically present above the restricting layer.

Impacts: Regardless of whether it occurs in soils or fractured rock, interflow is often within the depth range affected by land-use change activities. The interception of lateral flowpaths due to foundations, pipelines, and open-cast mining can diminish the contribution of these soils to wetland and streamflow water regimes. Surface sealing (such as roofs and pavements) increases overland and peak flow, thereby reducing recharge and negatively affecting the sustained supply of water to wetlands and streams. The hydrological zone sensitive to land-use change extends beyond the typical wetland buffer zone. This extension is determined by the depth of critical flowpaths identified as substantial contributors to wetland hydrology and the potential negative impact of the proposed land-use change.

5.3.2 Interflow soil groups

5.3.2.1 Interflow (soil/bedrock)

In the *Interflow (soil/bedrock)* group, lateral flow is generated, either due to low permeability of the bedrock which restricts vertical drainage, or due to return flow from the bedrock flowpath to the soils (Figure 5.2a). The flowrate via this pathway is determined by the slope and conductivity of the interflow horizon. Flow is normally maintained on a seasonal basis, but it depends on the length and recharge area of the bedrock-return flowpath.

Table 5.4. Interflow (soil/bedrock) families of the South African Soil Classification.

Soil form	Families	Remarks
Stanger (Sg)	1300; 2300	Lateral flow implied by gleylithic
Inhoek (Ik)	1200; 2200	Lateral flow implied by alluvial wetness
Eland (El)	All families	
Longtom (Lg)	1130; 1230; 2130; 2230	Lateral flow implied by gleylithic
Netherley (Ne)	All families	
Gangala (Ga)	1130; 1230; 2130; 2230	Lateral flow implied by gleylithic
Umvoti (Um)	All families	
Henley (He)	1130; 1230; 2130; 2230	Lateral flow implied by gleylithic
Mkuze (Mk)	1200; 2200	Alluvial wetness specified at family level
Tsitsikamma (Ts)	1120; 1220; 2120; 2220	Gleying present below podzol
Lamotte (Lt)	All families	
Houwhoek (Hh)	1113; 1123; 1213; 1223; 2113; 2123; 2213; 2223;	All families with gleylithic
Kransfontein (Kf)	All families	
Avalon (Av)	All families	

Soil form	Families	Remarks
Clovelly (Cv)	1113; 1123; 1213; 1223; 1313; 1323; 2113; 2123; 2213; 2223; 2313; 2323; 3113; 3123; 3213; 3223; 3313; 3323	All families with gleylithic
Bainsvlei (Bv)	All families	
Nkonkoni (Nk)	1113; 1123; 1213; 1223; 1313; 1323; 2113; 2123; 2213; 2223; 2313; 2323; 3113; 3123; 3213; 3223; 3313; 3323	All families with gleylithic
Jonkersberg (Jb)	1200; 2200	Gleying present below podzol
Witfontein (Wf)	All families	
Groenkop (Gk)	1130; 1230; 2130; 2230	All families with gleylithic
Tshiombo (To)	1110; 1210; 2110; 2210; 3110; 3210	Aluvic neocutanic
Quaggafontein (Qf)	1112; 1212; 2112; 2212; 3112; 3212	Aluvic neocutanic with alluvial wetness
Tukulu (Tu)	1110; 1210; 2110; 2210; 3110; 3210	Aluvic neocutanic
Tubatse (Tb)	1113; 1213; 2113; 2213; 3113; 3213	Aluvic neocutanic with Gleylithic
Montagu (Mu)	1110; 1210; 2110; 2210; 3110; 3210	Aluvic neocarbonate
Dundee (Du)	1112; 1122; 1212; 1222; 2112; 2122; 2212; 2222; 3112; 3122; 3212; 3222	Alluvial wetness present
Lepellane (Lp)	1100; 1200; 2100; 2200	Dark or chromic topsoils

5.3.2.2 *Interflow (shallow)*

Interflow (shallow) soils are marked by vertical anisotropy in hydraulic conductivity where a permeable topsoil overlies a restricting subsoil layer (Figure 5.2b). These soils are also termed *Interflow (A/B)*. Lateral flow is generated by specific rain events and the duration of lateral flow in *Interflow (shallow)* soils is relatively short.

Table 5.5. Interflow (shallow) families of the South African Soil Classification.

Soil form	Families	Remarks
Mayo (My)	1300; 2300	Gleylithic indication of interflow/saturation in lithic
Nomanci (No)	1300; 2300	Lateral flow implied by wetness in saprolite
Kroonstad (Kd)	1110; 1120; 1210; 1220	Families with dark/chromic topsoil
Villafontes (Vf)	1120; 1220; 2120; 2220	Luvic neocutanic
Longlands (Lo)	All families	
Wasbank (Wa)	All families	
Estcourt (Es)	All families	
Klapmuts (Km)	All families	
Kinkelbos (Kk)	1112; 1122; 1212; 1222; 2112; 2122; 2212; 2222	Luvic neocarbonate
Cartref (Cf)	All families	
Iswepe (Is)	All families	
Westleigh (We)	1100; 1200; 2100; 2200	Families with dark and chromic topsoils
Lepellane (Lp)	3100; 3200	Bleached topsoil
Concordia (Cc)	1121; 1122; 1221; 1222; 2121; 2122; 2221; 2222	Families with Ortstein hardening
Houwhoek (Hh)	1121; 1122; 1222; 2122; 2221; 2222	Families with Ortstein hardening without gleylithic
Wasbank (Wa)	All families	
Groenkop (Gk)	1210; 1220; 2210; 2220	Families with Ortstein hardening without gleylithic

Soil form	Families	Remarks
Pinegrove (Pg)	1210; 1220; 2210; 2220	Families with Ortstein hardening
Glenrosa (Gs)	1130; 1230; 2130; 2230; 3130; 3230	Gleylithic indication of interflow/saturation in lithic

5.3.2.3 Interflow (slow)

The *Interflow (slow)* hydropedological group comprises of soils with high clay contents at the soil/bedrock interface (Figure 5.2c). Although they could be saturated for long periods, their contribution to streamflow is relatively small because of the low hydraulic conductivity. In some cases, they act primarily as a store of water and not a conduit.

Table 5.6. Interflow (slow) families of the South African Soil Classification

Soil form	Families	Remarks
Lauriston (Lr)	All families	
Potsdam (Pd)	1120; 1220; 2120; 2220	Slow conductivity of pedocutanic with wet alluvium
Darnall (Da)	1130; 1230; 2130; 2230	Slow conductivity through pedocutanic with gleylithic
Dartmoor (Dm)	All families	
Highmoor (Hm)	All families	
Pinedene (Pn)	All families	
Bloemfal (Bd)	All families	
Idutywa (Id)	All families	
Utrecht (Ut)	1112;1212; 1312; 1412; 1122; 1222; 1322; 1422; 2112; 2212; 2312; 2412; 2122; 2222; 2322; 2422	Families with alluvial wetness present
Sandile (Sa)	1113;1213; 1313; 1413; 1123; 1223; 1323; 1423; 2113; 2213; 2313; 2413; 2123; 2223; 2323; 2423	Interflow implied by gleylithic
Sepane (Se)	All families	
Queenstown (Qt)	1112;1212; 1312; 1412; 1122; 1222; 1322; 1422; 2112; 2212; 2312; 2412; 2122; 2222; 2322; 2422	Families with alluvial wetness present
Swartland (Sw)	1113;1213; 1313; 1413; 1123; 1223; 1323; 1423; 2113; 2213; 2313; 2413; 2123; 2223; 2323; 2423	All families with gleylithic
Tukulu (Tu)	1120; 1220; 2120; 2220; 3120; 3220	Luvic neocutanic
Tshiombo (To)	1120; 1220; 2120; 2220; 3120; 3220	Luvic neocutanic

Soil form	Families	Remarks
Quaggafontein (Qf)	1122; 1222; 2122; 2222; 3122; 3222	Luvic neocutanic with alluvial wetness
Tubatse (Tb)	1123; 1223; 2123; 2223; 3123; 3223	Luvic neocutanic with gleylithic
Montagu (Mu)	1120; 1220; 2120; 2220; 3120; 3220	Luvic neocarbonate
Motsane (Mt)	1112; 1122; 1212; 1222; 2112; 2122; 2212; 2222; 3112; 3122; 3212; 3222	Alluvial wetness present
Burgersfort (Bg)	1113; 1123; 1213; 1223; 2113; 2123; 2213; 2223; 3113; 3123; 3213; 3223	All families with gleylithic

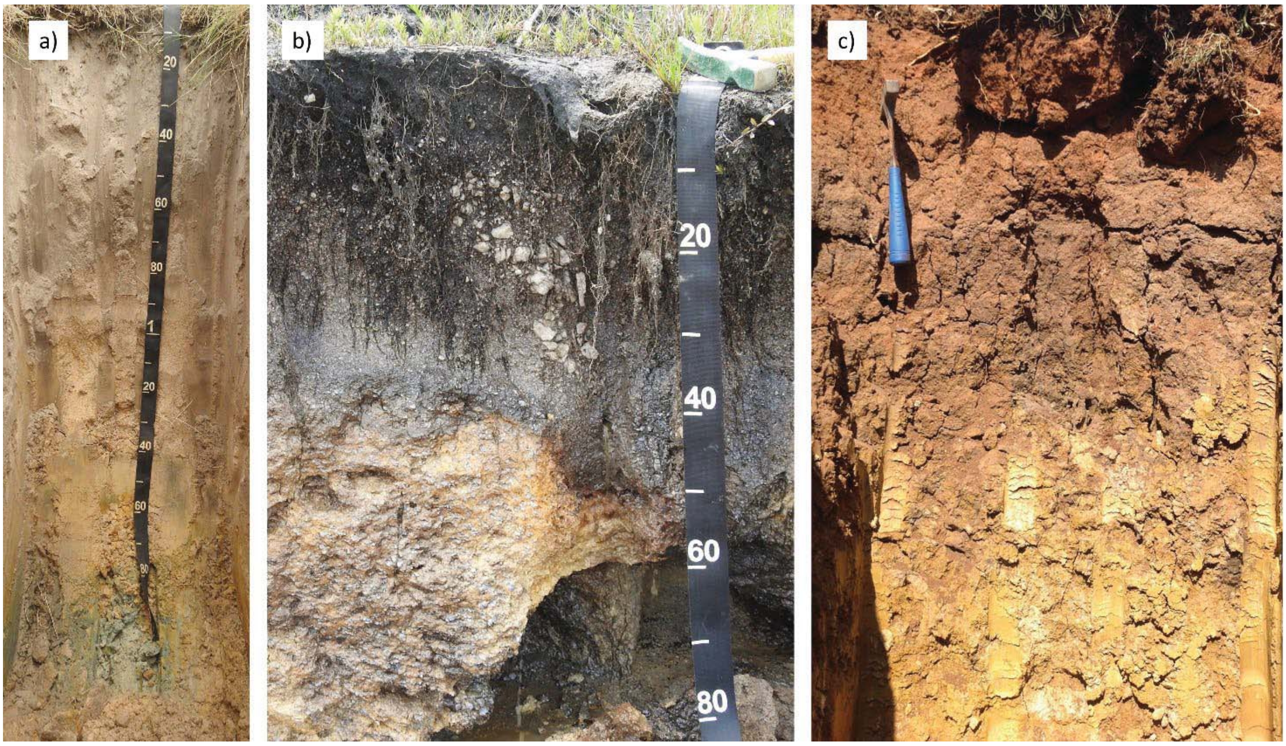

Figure 5.2. Examples of interflow soils: a) Interflow (soil/bedrock) – notice grey colours at the bottom of the profile, b) Interflow (shallow) – water exiting in grey albic between 300 and 500 mm and c) Interflow (slow) – morphological properties of saturation are present but high clay contents limit lateral flow.

5.4 RESPONSIVE SOILS

5.4.1 Processes, indicators, and implications of responsive soils

Process: Responsive soils are characterised by their swift reaction to precipitation events, resulting in the generation of overland flow. Overland flow originates from three main mechanisms:

- Shallow soils overlaying relatively impermeable bedrock lead to overland flow due to their limited storage capacity, which quickly becomes exceeded after typical rainfall events.
- Soils experiencing prolonged saturation generate overland flow due to saturation excess.
- Soils with low surface infiltration rates trigger overland flow through infiltration excess (Hortonian flow). This phenomenon is evident in soils with high 2:1 clay content, as well as soils that have undergone physical (compaction or crust formation) or chemical (sodicification) degradation.

Indicators: Bleached topsoil horizons in shallow soils serve as reliable indicators of shallow responsive soils. The presence of hydromorphic properties near the surface and high organic carbon content (peat and organic horizons) suggests a saturation excess response. Topsoils exhibiting physical activity (vertic properties) expand during the wet season, causing a significant decrease in infiltration rates. Indicators of overland flow dominance and soil responsiveness include sodicity and degradation, such as sheet and rill erosion.

Implications: Overland flow contributes to the peak flow phase of the hydrograph (see Figure 2.5). In areas dominated by responsive soils, a considerable portion of rainfall fails to infiltrate, and water is not retained for plant uptake. The occurrence of overland flow can result in flooding and infrastructural damage. While overland flow might be prevalent in higher elevation regions within a landscape, this water could eventually re-infiltrate and contribute to lateral or recharge flowpaths. In exceptionally wet years, entire landscapes might become ''responsive'' although such occurrences are rare.

5.4.2 Responsive soil groups

5.4.2.1 Responsive (shallow)

Responsive (shallow) soils are soils with limited depth and hence small storage capacity. The underlying rocks are slowly permeable and rapid recharge of bedrock flowpaths is not likely (Figure 5.3a). When significant rainfall is received, the storage capacity of the soil is exceeded, and overland flow is then generated. *Responsive (shallow)* soils respond quickly to rain events.

Table 5.7. Responsive (shallow) families of the South African Soil Classification.

Soil form	Families	Remarks
Milkwood (Mw)	1200; 2200	Solid rock
Graskop (Gp)	1200; 2200	Solid rock
Dresden	3000	Bleached topsoil indicate hard plinthic is slowly permeable
Coega (Cg)	All families	

Soil form	Families	Remarks
Knersvlakte (Kn)	All families	
Mispah (Ms)	1120; 1220; 2120; 2220; 3120; 3220	Solid rock

5.4.2.2 Responsive (wet)

Responsive (wet) soils are marked by saturation close to the surface layers for extended periods, especially during the wet season. Additional precipitation will not infiltrate but overland flow will be generated (Figure 5.3b). Soils therefore respond quickly to rain events, resulting in high peak flows.

Table 5.8. Responsive (wet) families of the South African Soil Classification.

Soil form	Families	Remarks
Mfabeni (Mf)	All families	Long periods of saturation implied by presence of peat horizon
Nhlangu (Nh)	All families	
Muzi (Mz)	All families	
Kromme (Kr)	All families	
Champagne (Ch)	All families	
Manguzi (Mg)	All families	
Makhasana (Mh)	All families	
Didema (Dd)	All families	
Rensburg (Rg)	All families	Vertic horizon would limit infiltration, still be responsive
Willowbrook (Wo)	All families	
Katspruit (Ka)	All families	
Kroonstad (Kd)	2110; 2120; 2210; 2220	Families with bleached topsoil indicate saturation close to surface
Westleigh (We)	3100; 3200	Families with bleached topsoil indicate saturation close to surface

5.4.2.3 Responsive (Hortonian)

Responsive (Hortonian) soils are soils with vertic horizons that will swell closed during wet periods. The hydraulic conductivity or infiltration rate of these soils with high 2:1 clay content is less than the rainfall intensity and will therefore generate overland flow due to infiltration excess. This is often referred to as Hortonian overland flow. Degraded soils with surface crusting or sodic soils will behave similarly (Figure 5.3c).

Table 5.9. Responsive (Hortonian) families of the South African Soil Classification

Soil form	Families	Remarks
Glen (Gl)	All families	Vertic horizons will have low conductivity when saturated /swell
Zondereinde (Zo)	All families	
Dwaalboom (Dw)	All families	
Bakwena (Bk)	All families	
Waterval (Wv)	All families	
Mkuze (Mk)	1100; 2100	
Arcadia	All families	
Rustenburg	All families	

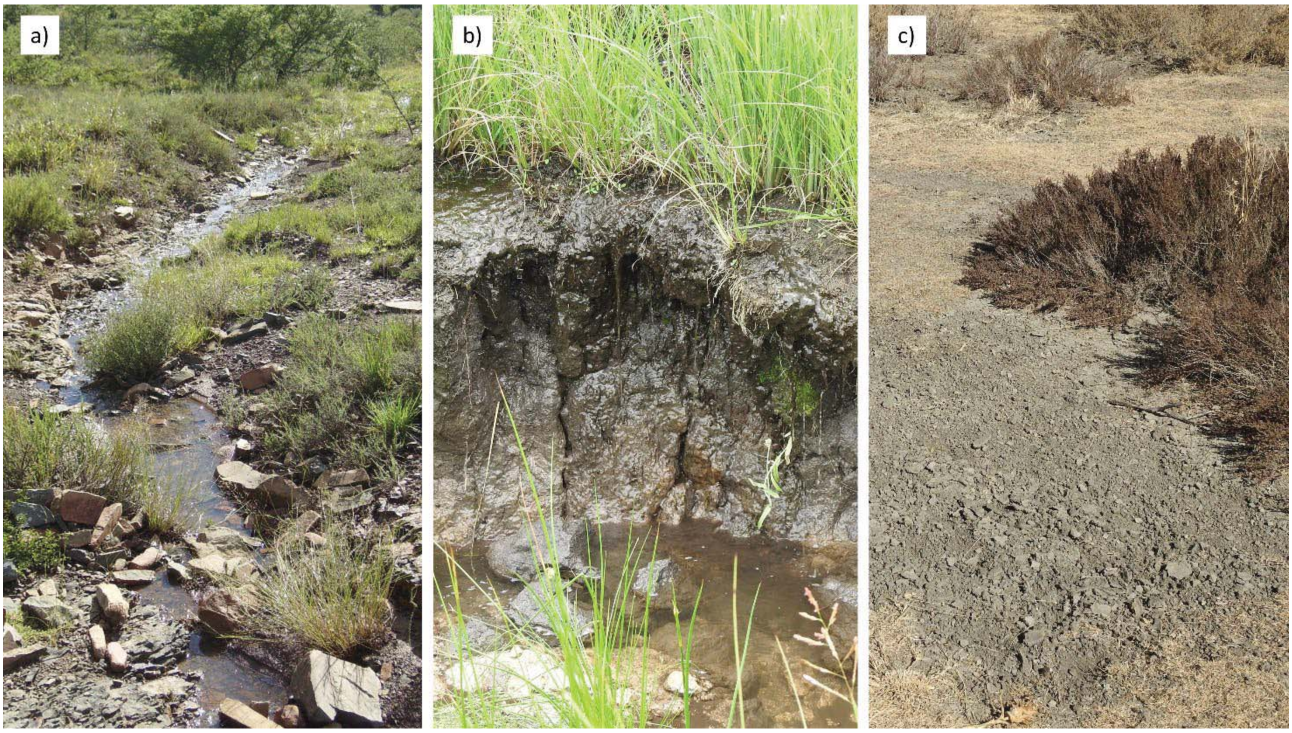

Figure 5.3. Examples of responsive soil: a) Responsive (shallow) – overland flow is generated due to low storage capacity, b) Responsive (wet) – overland flow is generated by saturation excess and c) Responsive (Hortonian) – overland flow will be generated due to crusting and low infiltration rates.

5.5 ANTHROSOLS AND TECHNOSOLS

As per the defined criteria, anthrosols and technosols have undergone such extensive human-induced alterations that their physical, chemical, and hydrological functions have been transformed, rendering their original natural soil form indiscernible (Soil Classification Working Group, 2018). The classification system makes a distinction between materials that have undergone inadvertent modifications (anthrosols) and those that have been deliberately transported through human intervention (technosols). When observable impacts are present, a thorough depiction of the nature and extent of the disturbance is necessary. When evaluating these soils, it is very important to consider the new physical properties. Properties like crusting on exposed subsurface horizons and compaction associated with rehabilitated soils need to be considered. In certain scenarios, identifying the impact might be unfeasible, as is the case with radioactive pollution. Table 5.10 offers guidance on the hydropedological categorisation of anthrosol and technosol families or classes.

Table 5.10. Hydropedological grouping of anthrosols and technosols.

Soil form	Family	Description	Hydropedology group
Grabouw	1000	Some original horizons remain, but in a disturbed state.	Check properties of original soil and group according to natural soils.
	2000	Original horizons overturned and irreversibly mixed (dorbank, hard plinthite, hard carbonates, lithic,	Recharge (shallow)

Soil form	Family	Description	Hydropedology group
		prismacutanic, hard rock) for agricultural purposes.	
	3000	Physically degraded and disturbed due to water actions (water erosion caused by anthropogenic activities).	Responsive (Hortonian)
	4000	Physically disturbed due to aeolian actions (wind erosion instigated by anthropogenic activities).	Recharge (deep)
	5000	Natural soil horizons severely compacted without any removal or overturning of original horizon.	Responsive (Hortonian)
Witbank	1100	Ex-natural soils covering natural soils.	Classify and group as natural soils
	1200	Ex-natural soils covering anthropogenic materials.	Responsive (shallow)
	1300	Ex-natural soil cover as fill material in excavated areas.	Responsive (shallow)
	2100	Anthropogenic materials covering undisturbed natural soils.	Responsive (shallow)
	2200	Anthropogenic materials covering anthropogenic materials.	Responsive (shallow)
	2300	Anthropogenic materials covering excavated areas.	Responsive (shallow)
Industria	1100	Chemical pollution of natural soils.	Classify and group as natural soils.
	1200	Chemical pollution of anthropogenic materials.	Classify and group as natural soils.
	2100	Radioactive natural and anthropogenic materials.	Classify and group as natural soils.
Stilfontein	1100	Natural soils saturated by natural quality water.	Responsive (wet)
	1200	Anthropogenic materials saturated by natural quality water.	Responsive (wet)
	2100	Natural soils saturated by polluted water.	Responsive (wet)
	2200	Anthropogenic materials saturated by polluted water.	Responsive (wet)
	3100	Natural wetland soils drained and irreversibly altered	Interflow (soil/bedrock)

Soil form	Family	Description	Hydropedology group
		by clearly identified human-induced action.	
	3200	Natural wetland soils drained and burnt.	Interflow (soil/bedrock)
Cullinan	1000	Large, exposed excavations without backfilling.	Responsive (Hortonian)
Maropeng	1100	Exposed archaeological material.	Responsive (Hortonian)
	1200	Sub-surface archaeological material.	Classify and group as natural soils.
Johannesburg	1100	Uncovered urban waste.	Responsive (Hortonian)
	1200	Urban waste covered with ex-natural topsoil.	Responsive (shallow)
	1300	Urban waste covered with liners and topsoil.	Responsive (Hortonian)
	2100	Cemeteries and grave sites.	Classify and group as natural soils.
	2200	Other urban uses.	Describe according to use – typically Responsive (Hortonian).

CHAPTER 6: HYDROPEDOLOGY OF HILLSLOPES

6.1 INTRODUCTION

The hillslope is widely recognised as a fundamental unit within the landscape (Weiler and McDonnell, 2004; Lin et al., 2006). The interplay of topography, soils, climate, and vegetation gives rise to discernible, repeating patterns and laws that offer valuable insights into their functioning (Sivapalan, 2003a). These components exert significant control over hydrology, and their relationships with water distribution serve as valuable indicators of hydrological response (Le Roux et al., 2011; Van Tol et al., 2010a, 2010b; Kuenene et al., 2011). Understanding and simulating hydrological processes depend on comprehending the hillslope, which acts as a critical building block in this regard (Tromp-Van Meerveld and Weiler, 2008). The hydrological response of catchments is determined by the collective hydrological response of the hillslopes within a specific catchment (Sivapalan, 2003b).

6.2 HILLSLOPE-WETLAND CLASSIFICATION

The characteristic organisation and symmetry of hillslopes provides a basis for constructing a classification system. Van Tol et al. (2013b) classified South African hillslopes into six distinct classes, basing their classification on the sequence and distribution of hydropedological soil types along the hillslope. Their hypothesis posits that soil properties governing current, and future, hydrology, as well as properties indicative of ancient hydrological behaviour, are scientifically sound and can serve as criteria for defining functional units within hydrological hillslopes. The control exerted by parent material, encompassing lithology and weathering patterns, as well as climate, finds representation in the distribution of soils across the landscape and effectively shapes the hydrology of hillslopes.

Recent advancements in understanding of the hydrology of soil formations, as discussed in the previous chapter, necessitate a reassessment of the existing six hillslope classes. Consequently, we have introduced new classes that encompass slopes dominated by groundwater, as well as those where recharge (slow) and interflow (slow) soils prevail. As a result, we now propose 12 hillslope-wetland response classes. These classes, each representing a broadly defined hydrological response, provide standardised representations of the dominant mechanisms through which water is delivered from hillslopes to wetlands. However, it is important to note that the relative presence of different soil forms within an individual hillslope can vary, and a combination of several flow directions may occur at a given site.

Flow recharge typically occurs on the crest, deep interflow on the midslope and return to the topsoil and surface in the valley bottom. Generally, convex profile curvatures (Figure 6.1) recharge the hillslope and may limit the interflow zone to a small fraction. Concave slopes (Figure 6.1) generally have more interflow. These flowpaths may be deep. The impact of profile curvature on flowpaths is increased by planform curvature in the order of *concave* > *linear* > *convex*, and this relationship improves with a wetter climate.

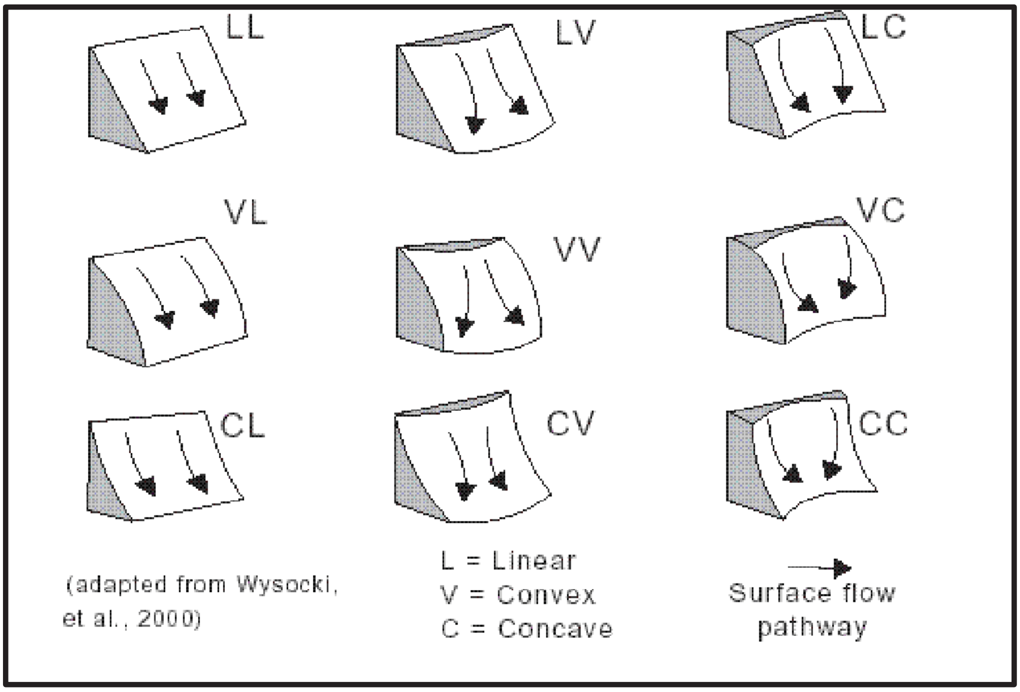

Figure 6.1. Profile and planform terrain forms (Schoenenberger et al., 2002).

The size and ensuing hydroperiod of wetlands are also influenced by factors such as the contributing storage volume (including the length and depth of the slope), prevailing climate, and the characteristics of the soil or rock. These factors, including the presence of fractures, connectivity, and hydraulic conductivity, collectively influence the rate of water movement. The review and development of these proposed classes is still ongoing and will continue to be improved over time.

6.3 RIVER INFLOWS AND GEOMORPHIC CONTROLS ON WETLAND HYDROPERIOD

As collections of one or more hillslopes, wetland catchments may similarly be characterised according to a combination of prevailing geology, climate and morphologically characteristic hillslopes. Our premise is that wetland hydroperiod (saturation or inundation volume, timing, duration) reflects the hydrological response of the wetland catchment. Characterising the wetland catchment as supporting one (or several) hillslopes allows the wetland catchment to be placed into one of a selected number of classes which function in a similar, predictable way in terms of geomorphic context and dominant flowpaths.

Rivers as a water source to wetlands are not discussed in detail in this document, which is focused on the fate of rainwater once it infiltrates and moves through the vadose zone to sustain wetlands. However, river and stream inflows are recognised as important contributors to wetland hydrology for a significant proportion of South Africa's wetlands. It is widely recognised that wetland hydrology and functions vary according to the hydrogeomorphic (HGM) wetland classification system, developed in the USA by Brinson (1993), which defines wetlands based on their landscape position, dominant water source, and direction(s) of water movement (hydrodynamics). The "*Classification system for wetlands and other aquatic ecosystems in South Africa"* (Ollis et al., 2013) follows this HGM approach to wetland classification, and describes five main wetland types in South Africa. Of these, floodplain wetlands and channelled valley-bottom wetlands undoubtedly receive their dominant water inputs from river flows, as do unchanneled valley-bottom wetlands.

However, particularly in the case of unchanneled valley-bottom wetlands, supplementary lateral flows from the vadose zone or regional groundwater often contribute significantly. These contributions should be noted as they may play a cumulatively important role and may be a significant source of base flow which sustains the hydrology of the overall wetland, even though it is situated within a fluvial context. The relative role of hillslope versus river water in a valley-bottom wetland may be partially revealed through observation of the river water level in comparison with the prevailing water level within the wetland, especially if the river water level is far below that of the wetland. Similarly, depressional wetlands receive much of their water from rain and overland flow, however, subsurface lateral flows from the wetland catchment may also play a significant role in a subset of wetland depressions.

The remaining HGM type, namely seep wetlands, is dominated by lateral inflows from the local wetland catchment, unless the inflow source is groundwater (see Section 6.4), which may extend beyond the local catchment.

Importantly, in addition to considering water inflows to wetlands, the presence of additional controls on wetland hydroperiod which influence the accumulation and retention of water within a wetland, should be taken into consideration. In these cases the inflow of water into the wetland is amplified, for example reflecting not only the expected hillslope outputs, but leading to wetland conditions that may be wetter than expected. Documented controls on water retention and wetland formation include but are not limited to: the development of wetlands within faulted basins McCarthy et al. (1997); wetland occurrence on valley floors developed through planing by rivers of easily eroded lithologies, forming a basin (such as Karoo Supergroup sedimentary rocks) upstream of a more resistant lithology (such as a dolerite dyke) (Grenfell et al., 2019; Tooth et al., 2004; Tooth and McCarthy, 2007); depression wetlands in areas created through deep weathering and volume loss of volcanic rocks (Edwards, 2009; Alistoun, 2013); accumulation of sediment within trunk or tributary streams leading to the formation of a wetland conditions behind the sedimentation; or wetlands occurring upstream of the presence of biological or “ecosystem engineers” such as rhizomatous and clonal palmiet plants which form a dense wall of plants (Job, 2014; Sieben, 2012).

6.4 GROUND-WATER DEPENDENT WETLANDS

6.4.1 Class 1: *Recharge (deep)* soils dominant, wetlands are permanent and groundwater-dependent

The climate is moderate, characterised by sandy coastal plains, topography is steep to moderate hills and dunes (Figure 6.2). The dominant direction of water recharge is vertical, moving down through highly permeable deep recharge sandy soils to regional groundwater. Wetlands occur where the coastal aquifer intersects lower-lying areas and are sustained by the regional aquifer[11]. Wetland hydroperiod shows a flat, long tail indicating the seamless link between the wetland and the unconfined, highly transmissive groundwater aquifer. Wetland soils in this class are homogenous, with diffuse transitions in colour or the absence of distinct horizons, evidence of the stable water regime and continuous saturation. Permanently saturated sands are low chroma grey or white, or blue-green gleys, or else peat may occur. Examples include the Cape Flats aquifer (Adelana et al., 2010), Maputaland coastal plain (Kelbe et al., 2016; Pretorius et al., 2020; Grundling, 2014), Atlantis, Sedgefield and Woody Cape regions.

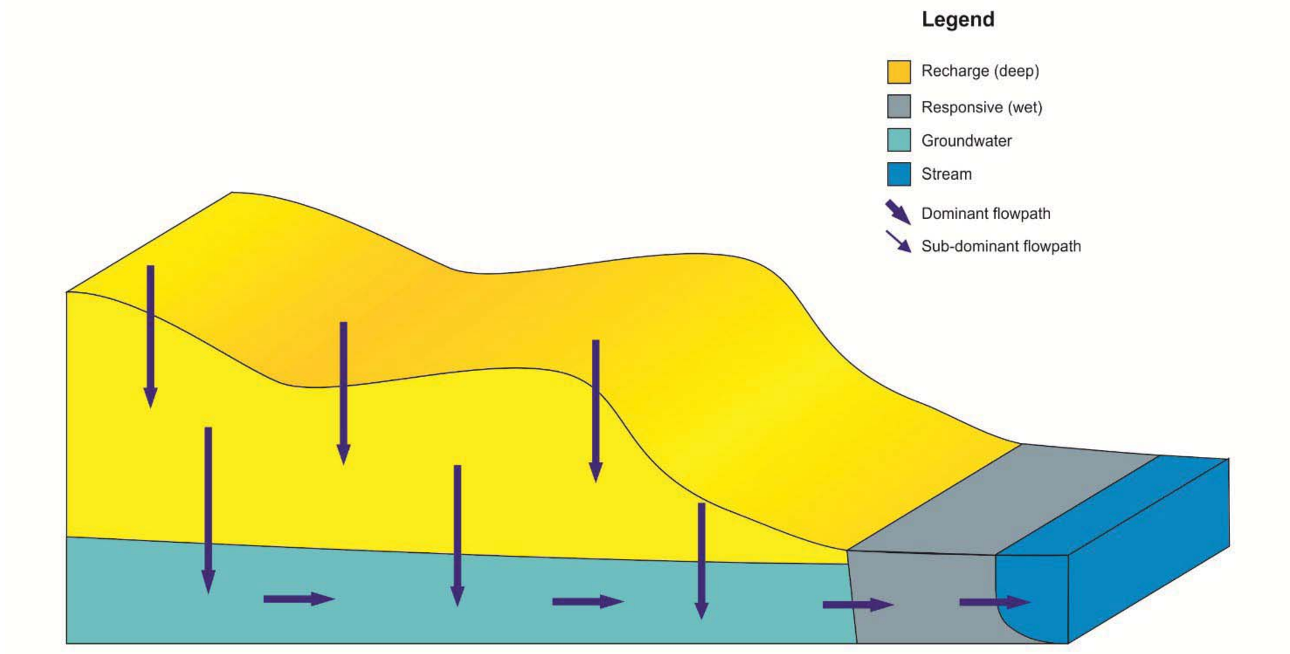

Figure 6.2. Conceptual hydrological response of a Class 1 hillslope.

Risk to wetland from catchment development (hydropedological perspective): These permanently saturated wetlands are stable relative to other wetlands, fed by a sustained water source. They are, however, vulnerable to broadscale artificial drawdown as a result of high levels of groundwater abstraction or regionally extensive water-reduction activities within the aquifer catchment, such as commercial plantations, as well as to pollution of the aquifer.

6.4.2 Class 2: *Recharge (deep)* soils dominant, wetlands are permanent and groundwater-dependent

The climate is moderate to dry, underlying lithology is limestone or dolomite (calcium/magnesium carbonate), topography is undulating hills. The dominant direction of water recharge is vertical, moving down through porous, fractured dolomite to regional groundwater (Figure 6.3). In these karst landscapes, fissures and caves have evolved over millions of years through the dissolution of bedrock to form a strongly connected regional aquifer (Meyer, 2014). Wetlands are not common in this landscape but can occur where low-lying topography intersects the karst aquifer. The wetland hydroperiod is visualised as a flat, long tail to indicate the continuous,

[11] Note that some wetlands in this landscape may also be perched above the regional aquifer on a less permeable material such as unfractured calcrete or subsoil clay, and completely disconnected from the regional groundwater, maintained by vadose zone flow from within the wetland's catchment, and, therefore, placing them in a different wetland class.

connected feed of water from groundwater. Wetland soils are homogenous gleyed clays or peat soils, formed and maintained in a state of continuous saturation. A stable base flow to streams and rivers is also characteristic of this class. Karst terrain which supports wetlands in South Africa stretches from Delmas to Johannesburg to the Botswana border (Schrader et al, 2015).

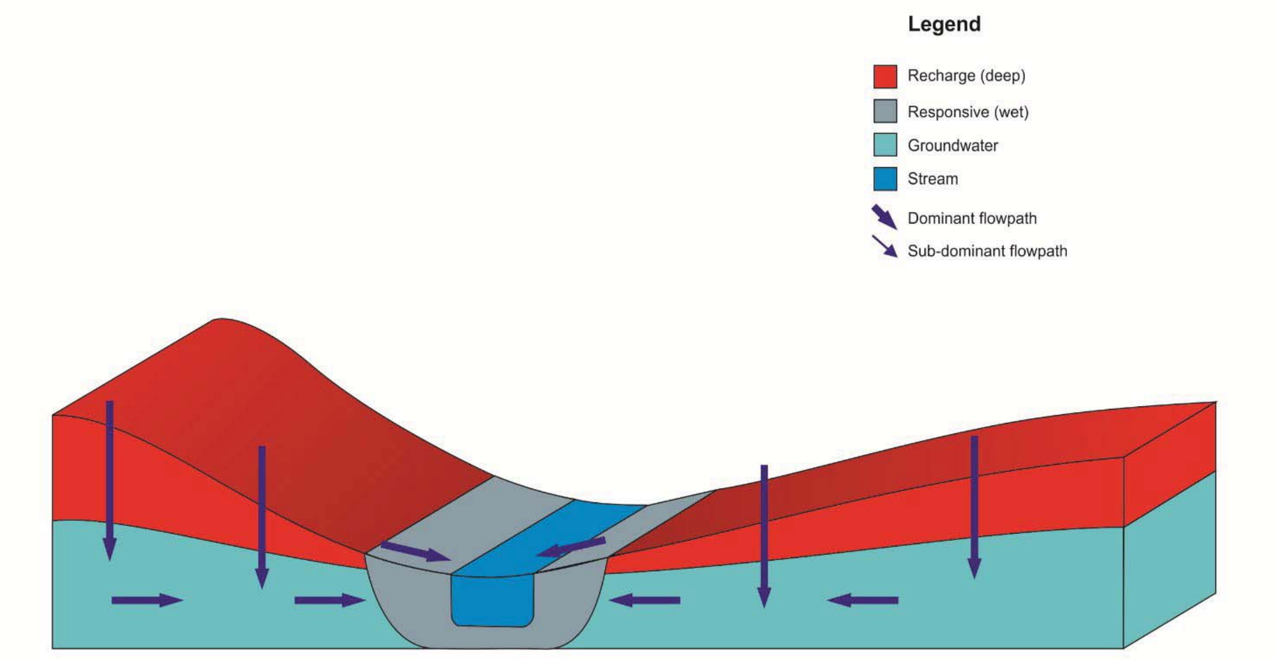

Figure 6.3. Conceptual hydrological response of a Class 2 hillslope.

Risk to wetland from catchment development: These permanently saturated wetlands are stable relative to other wetlands, fed by a sustained water source. They are, however, vulnerable to artificial lowering of the regional aquifer as a result of high levels of abstraction or diversion, or to high intensity uses that cause pollution of the aquifer, such as from acid mine drainage.

6.4.3 Class 3: *Recharge (shallow)* soils dominant, wetlands are permanent and groundwater-dependent

The climate is moderate, underlying lithology is fractured, topography is characterised by hills or mountains. The dominant direction of water is vertical, with water moving quickly after rain events through the shallow recharge soils to fractured bedrock, shielding the water from the effects of evapotranspiration and interception. Water then moves slowly down through the fractured rock (months to years) to the regional groundwater, which in this case is connected to the wetland (Figure 6.4). Wetlands in this class are, therefore, considered groundwater-dependent ecosystems, formed where the hillslope intersects the regional groundwater, and groundwater daylights either as a spring or seep wetland. The wetland hydroperiod may show a small response following rain events but overall has a relatively flat, long tail to indicate the slow flow, long duration and continuous feed of water from the regional aquifer. Wetland soils in this class are endosaturated (wetting from below) and the sustained inflow of water from the regional aquifer creates conditions of permanent saturation ideal for the formation of peat soils or permanently wet mineral soils such as gleyed clays.

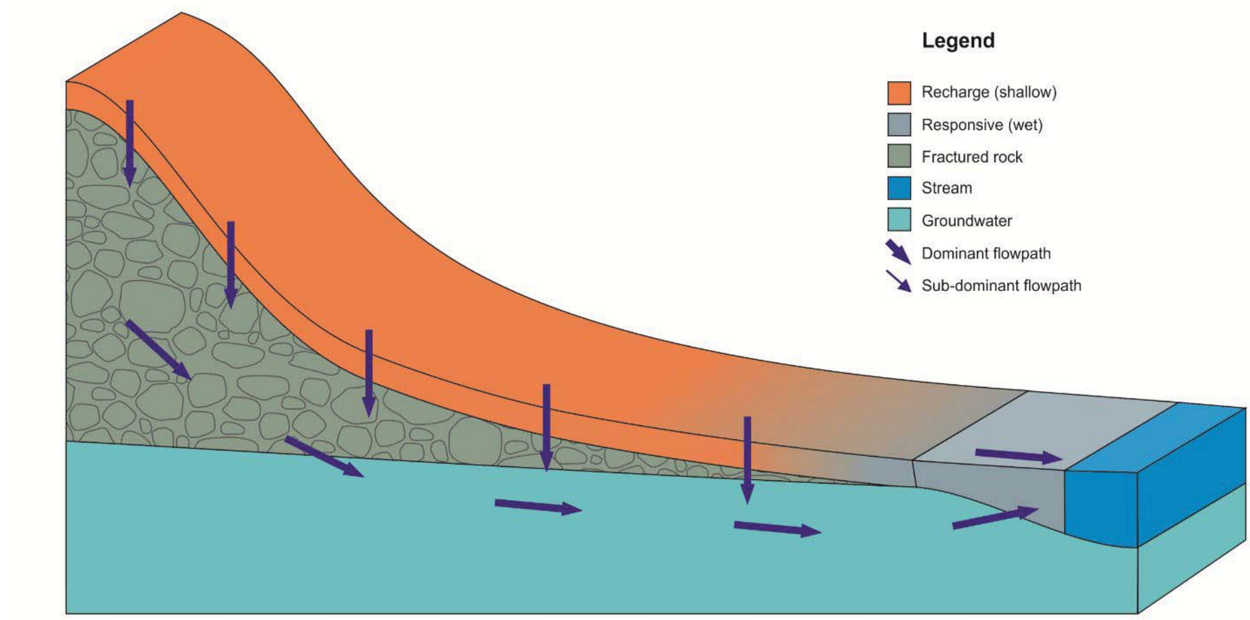

Figure 6.4. Conceptual hydrological response of a Class 3 hillslope.

Risk to wetland from catchment development: These permanently saturated wetlands are stable relative to other wetlands, fed by a sustained water source. They may be vulnerable to activities which impact recharge, such as surface sealing or water-intensive woody alien invasive species, which will be felt over the long term if replenishment of the aquifer is impacted. However, overall, the water flowpaths to the wetland are relatively well-protected from surface anthropomorphic activities.

6.5 HILLSLOPE-DEPENDENT WETLANDS

6.5.1 Class 4: *Recharge (shallow)* soils dominant, wetlands are typically permanent

The climate is moderate, underlying lithology is fractured, topography is characterised by steep to moderate hills and mountains. The dominant direction of water is vertical, with water moving quickly after rain events through the shallow recharge soils to fractured bedrock, effectively removing the water from the effects of evapotranspiration and interception (Figure 6.5). Water then moves slowly down through the fractured rock (months to years). The restricted permeability of a deeper rock layer causes water to accumulate within the overlying fractured rock and gravity influences the overall downslope movement of water, especially within lateral rock fractures. Ultimately, some water also moves very slowly vertically through the slowly permeable deeper rock to contribute to regional groundwater, which in this case is well below, and not connected to, the wetland. Wetlands in this class are, therefore, not considered groundwater-dependent ecosystems.

Wetland formation is influenced by underlying slowly permeable rock, with hillslope water accumulating in valley floor positions and creating permanently waterlogged conditions. Water enters the wetland either where major lateral rock fractures intersect the hillslope or at the contact zone of the fractured with the less permeable geology, and where the underlying, less permeable, rock intersects the hillslope or valley floor. In the case of the geological contact, the underlying barrier of impermeable rock impedes vertical recharge and water daylights into the wetland. The wetland hydroperiod shows a small response following rain events but overall has a relatively flat, long tail indicating a continuous feed of water from the fractured rock storage to the wetland. Wetland soils in this class are typically endosaturated (wetting from below). The sustained inflow of water from the fractured rock store creates conditions of permanent saturation ideal for the formation of peat soils[12], or permanently wet mineral soils (gleyed clays, sometimes together with and flanking the organic soils). A stable base flow to streams and rivers is also characteristic of this class. Since the wetland soils are already saturated, additional precipitation cannot infiltrate and some saturation excess flow will be generated from the wetland. However, the wetlands are expected to also have a buffering effect on the streams, thus the generalised hydrograph for the stream associated with a wetland is depicted as relatively flat and sustained. Wetlands overall may be rare in these landscapes, especially where slopes are very steep. Nevertheless, many of South Africa's peat wetlands across the country, from the southern and eastern Cape (Smit and Van Tol, 2022; Tanner, 2022; Job, 2014) to Limpopo province (Bootsma, 2019), occur at the foot of these large, fractured rock mountain water storage areas, which are covered by skeletal soils.

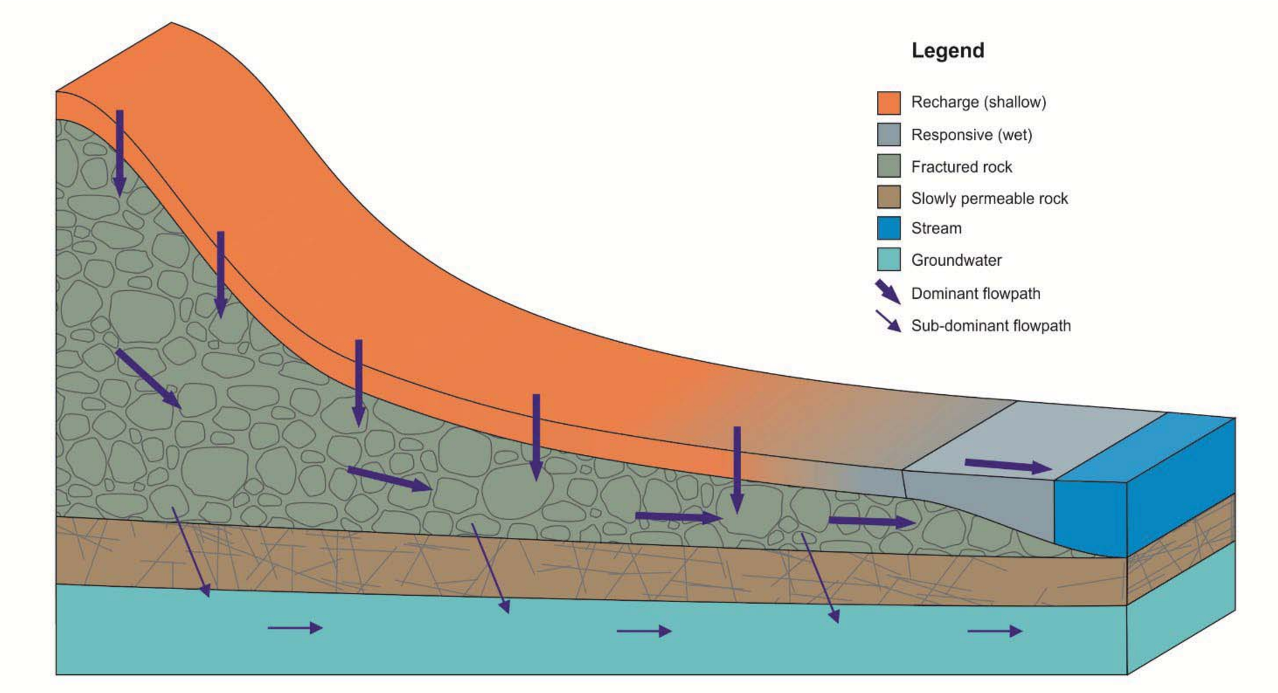

Figure 6.5. Conceptual hydrological response of a Class 4 hillslope.

Risk to wetland from catchment development: These permanently saturated wetlands are stable relative to other wetlands, fed by a sustained water source. Overall, the water flowpaths to the wetland are relatively well-protected from surface anthropomorphic activities. Broadly, water-intensive woody alien invasive species will have a lower impact on shallow recharge soils than on deep recharge soils, as water reaches fractured rock relatively rapidly in this class. Wetlands in this class may, however, be vulnerable to surface sealing impacts on shallow recharge which will impact the wetland hydroperiod over the long term if replenishment of fractured rock water storage is impacted. If the permanently saturated nature of these wetlands has been altered due to drought conditions or within wetland impacts, such as drainage ditches or woody invasive alien

[12] Note that sand horizons or lenses if present within the peat were likely deposited as sediment pulses during peak river flows and suggest a wetland predominantly fed by river flows (a class not discussed further in this document).

species, all of which cause the wetland water table to drop below the surface, then these wetlands become much more vulnerable to anthropogenic activities. For example, through improperly-sized road culverts, which concentrate flows to the wetland during the extreme peak rainfall events characteristic of these landscapes. This can cause a threshold to be breached and major erosion events within the wetland.

6.5.2 Class 5: *Recharge (shallow)* to fractured aquifer, wetlands are temporary to permanent

The climate is moderate, underlying lithology is fractured but underlain with repeating steps of more slowly permeable rock, topography is characterised by moderate hills. Dominant water direction is vertical, interrupted by lateral rocky outcrops or shallow rock shelves forming recurring steps downslope (Figure 6.6). Water moves quickly after rain events through shallow recharge soils to fractured bedrock, effectively removing the water from the effects of evapotranspiration and interception. The hydrology of this class is controlled by permeable fractured rock with underlying impermeable layers forcing fractured rock return flow in the midslope and lower slopes and feeding lower lying soils via the fractured rock flowpath. Temporary wetlands may form where local water shows confined characteristics and travels below a low permeability material, such as rock outcrop, becoming phreatic as it emerges as a spring or seep during high rainfall years. In the upper and middle midslope, relatively shallow depth to bedrock impedes recharge and supports lateral flow, becoming return flow from fractured rock to the saprolite, subsoil and even to the soil surface visible as redox morphology in bleached topsoils and even local patches of Fe and Mn accumulation as hard plinthite. Bleached topsoils on saprolite or solid rock on the hillslope crest are interpreted as event driven saturation of saprolite or soil with an impermeable layer of solid rock underneath. An albic horizon (see Section 4.5) and bleached topsoil horizon in the footslope position is evidence of a shallow flow path returning to soil. Ultimately, some water also moves very slowly through the slowly permeable rock to contribute to regional groundwater, which in this case is well below, and not connected to, the wetland. Wetland soils in this class are endosaturated (wetting from below) and are generally subject to seasonal water table fluctuations, with midslope wetlands more likely to be temporary to seasonal.

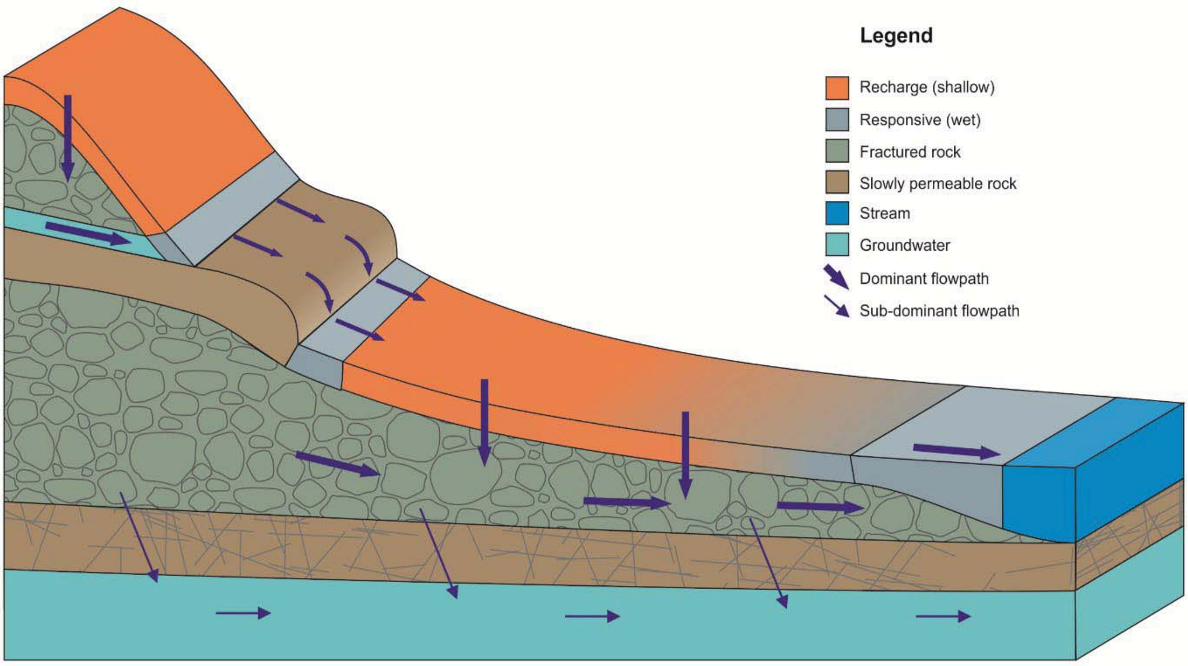

Figure 6.6. Conceptual hydrological response of a Class 5 hillslope.

Risk to wetland from catchment development: These temporary to seasonal wetlands are vulnerable to surface sealing which prevents infiltration of recharge water.

6.5.3 Class 6: *Recharge (deep)* soils dominant, wetlands are typically wet seasonal to permanent

The climate is moderate, underlying lithology is fractured, topography is characterised by steep to moderate hills. The dominant direction of water recharge is vertical (Figure 6.7). The infiltration rate of these soils exceeds rainfall intensity and moves down through the deep recharge soils to fractured bedrock, exposed, however, to some interception and evapotranspiration while moving through the soil. Water then moves down through the fractured rock (months to years). The restricted permeability of a deeper rock layer causes water to accumulate within the overlying fractured rock and, driven by gravity, influences the overall downslope movement of water, especially within lateral rock fractures. Ultimately, some water also moves very slowly through the slowly permeable deeper rock to contribute to regional groundwater, which in this case is well below, and not connected to, the wetland. Wetlands in this class are, therefore, not considered groundwater-dependent ecosystems.

Horizontal, slowly permeable rock layers are increasingly close to the surface downslope, and wetlands form on the valley floor where the underlying, less permeable, rock intersects the hillslope, at the contact zone of the fractured and less permeable geologies, or where major lateral rock fractures intersect the hillslope. In the case of the geological contact, the underlying barrier of impermeable rock impedes vertical recharge and accumulated water daylights, wetting from below (endosaturated) across the wetland at this contact, at times developing a significant piezometric head, causing soil pits to fill with water over time when left open. In the case of water entering the wetland through lateral rock fractures, the wetland wets predominantly from this location, often seen as patches of wetter zones within the overall wetland, especially for seasonally wet wetlands (resulting from smaller overall hillslope storage). The sustained inflow of water from the fractured rock store can create conditions of permanent saturation ideal for the formation of peat soils, or permanently wet mineral soils (gleyed clays). The wetland hydroperiod is visualised as a small response following rain events but with a relatively flat, long tail to indicate the slow flow, long duration and continuous feed of water from the fractured rock storage to the wetland. A stable base flow to streams and rivers is also characteristic of this class. Since the wetland soils are already saturated, additional precipitation cannot infiltrate and some saturation excess flow will be generated from the wetland. However, the wetlands are expected to have a buffering effect on the streams, thus the generalised hydrograph for the stream associated with the wetland is depicted as relatively flat and sustained.

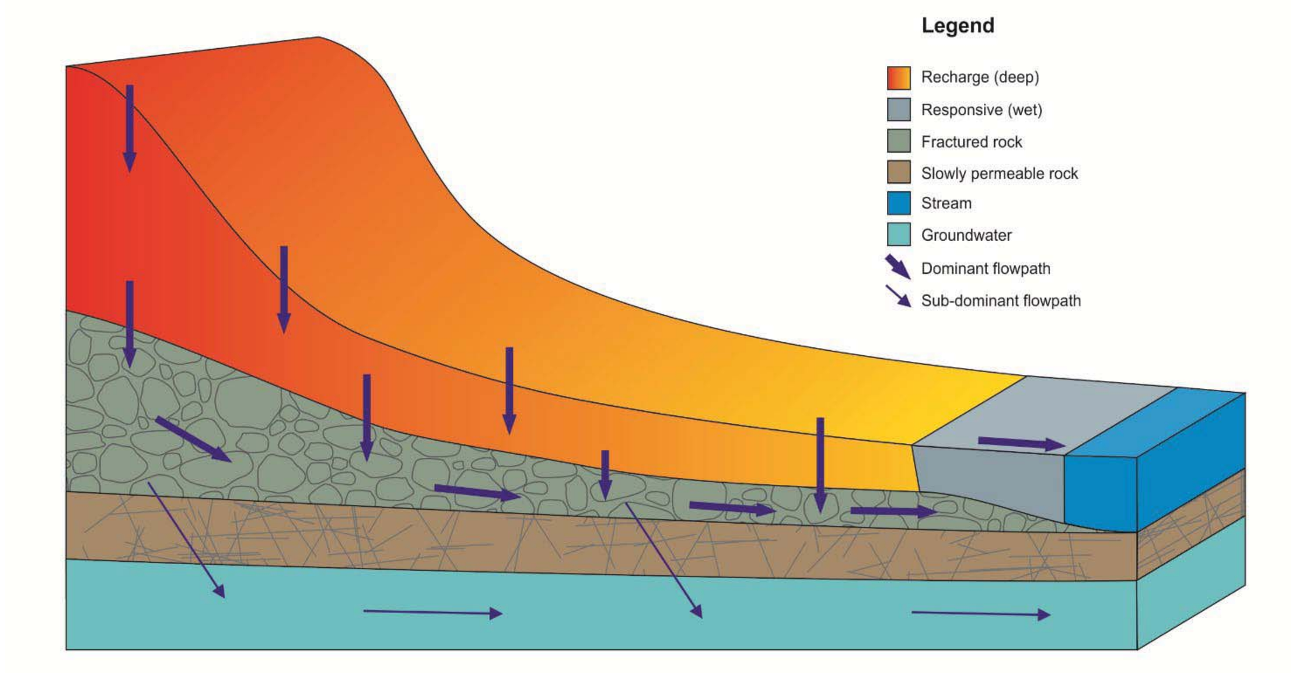

Figure 6.7. Conceptual hydrological response of a Class 6 hillslope.

Risk to wetland from catchment development: These wet-seasonal to permanently saturated wetlands are vulnerable to activities within the wetland catchment, such as surface sealing from buildings, parking lots and roads, which decrease the amount of recharge-derived water available to the wetland. Water-intensive woody alien invasive species will have a high impact, increasing the volume that has to be recharged before the water reaches the fractured rock and reducing the contribution of these soils to wetlands. Changes in the infiltration rate between natural veld and cultivated fields could also alter the recharge rates. Reduction of infiltration into recharge soils is often combined with increased overland flow. Wetlands that are already in poor condition have increased vulnerability to within-wetland erosion caused by unnatural, concentrated flows from the wetland catchment.

6.5.4 Class 7: *Recharge (slow)* soils dominant, wetlands absent, streams are typically non-perennial

In addition to the two recharge hillslopes already described (shallow recharge and deep recharge), two further generalised depictions of recharge hillslopes may be encountered, where wetlands are absent or rare. In Class 7 (Figure 6.8), the climate is dry to moderate, underlying lithology is fractured, topography is characterised by moderate hills to low gradient slopes. These hillslopes have deep recharge soils throughout, typically with clay-rich subsoil horizons which impede water movement and temporarily store water. The direction of water recharge is vertical, moving slowly down through the deep recharge soils to fractured bedrock. However, water seldom reaches the bottom of the soil profile and transpiration (upward flux) becomes the dominant flowpath. These hillslopes generate some infiltration excess overland flow towards the downslope non-perennial streams, but this is limited, especially where the gradient is low, and water is intercepted downslope and lost to evapotranspiration. At a secondary level, some water moves into the fractured rock and underlying slowly permeable rock. In this case, the soil-rock interface is well below, and not in contact with, the wetland and does not directly influence the wetland. Streams, where present, are, therefore, ephemeral, and are fed by overland flow, which is short in duration, slightly more when accumulated from several upstream catchment hillslopes. Wetlands are largely absent from this hillslope class. A typical example is the basalt landscape of the Kruger National Park (Riddell et al., 2020; Van Tol et al., 2015).

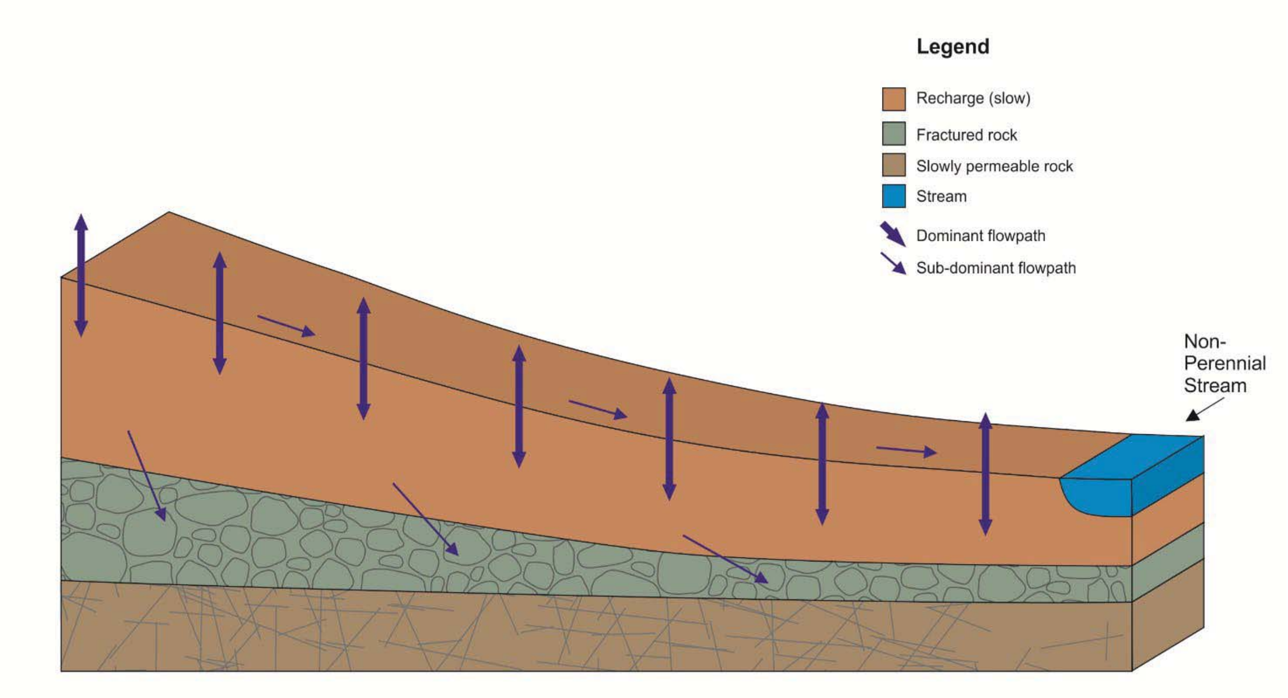

Figure 6.8. Conceptual hydrological response of a Class 7 hillslope.

Risk to wetland from catchment development: Not applicable.

6.5.5 Class 8: *Recharge (deep)* soils dominant, wetlands absent, streams are typically non-perennial

The climate is dry to moderate, underlying lithology is fractured, topography is characterised by moderate hills to low gradient slopes. These hillslopes have deep recharge soils throughout that are typically coarse in texture, for example, inland Kalahari sands. The dominant direction of water recharge is vertical, moving moderately quickly down through the deep recharge soils to fractured bedrock to replenish groundwater (Figure 6.9). Wetlands are typically absent or rare. Streams, where present, are ephemeral, and are fed by short duration overland flow from upstream contributing catchments and are generally not in contact with the regional groundwater table.

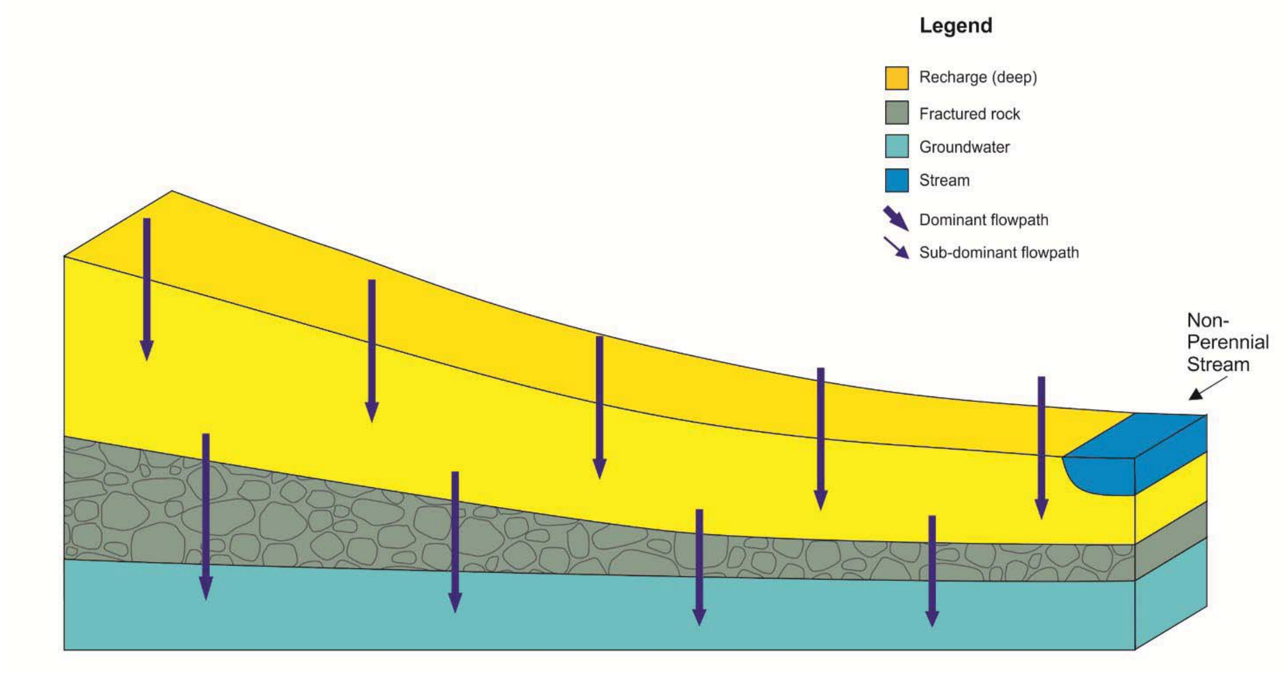

Figure 6.9. Conceptual hydrological response of a Class 8 hillslope.

Risk to wetland from catchment development: Not applicable.

6.5.6 Class 9: *Responsive (shallow)* soils dominant, wetlands are rare and when present are temporary

The climate is typically arid to semi-arid, with steep to moderate slope topography. An abrupt transition to slowly permeable rock controls the hydrological response in this hillslope class, promoting rapid excess flow of storage capacity following rain events. The dominant direction of flow, therefore, is downslope and overland (Figure 6.10). A small amount of water moves vertically and slowly (months to years) through the slowly permeable rock to contribute to the regional groundwater, which is well below and not connected to the wetland.

Wetlands form in low-lying, low gradient positions in the landscape, where water accumulates over the slowly permeable rock, typically as depressional (pan) wetlands. The hillslope response to rain is quick ("flashy") over a short time period during rain events, with water reaching the wetland through overland flow and wetting the wetlands from above. The wetland hydroperiod is visualised as small in volume and short in duration. Wetland soils are mostly very shallow over ferricrete or bedrock, but may be sandy clays where soils have accumulated from upslope sediments and water is retained for slightly longer, such as on the Nieuwoudtville Plateau, which supports a diversity of depression wetlands (Helme, 2013). Wetland soils typically lack redoximorphic features or have low chroma surface horizons evident of surface wetting and evapotranspiration. Slightly deeper, more developed profiles may support bleached surface horizons due to reduction in the saturated surface horizon, with evidence of downward transported, oxidised iron and manganese in underlying unsaturated horizons. There is no saturation excess generated at the wetland, water is mostly lost to evapotranspiration. Streams in this landscape, therefore, are not commonly supported by wetlands. The streams are non-perennial or ephemeral and have a similar, quick flow response curve from overland flow during rain events. This class also represents landscapes where no wetlands are present, exemplified by Van Tol et al. (2010b) for the Bedford catchment and much of the Karoo.

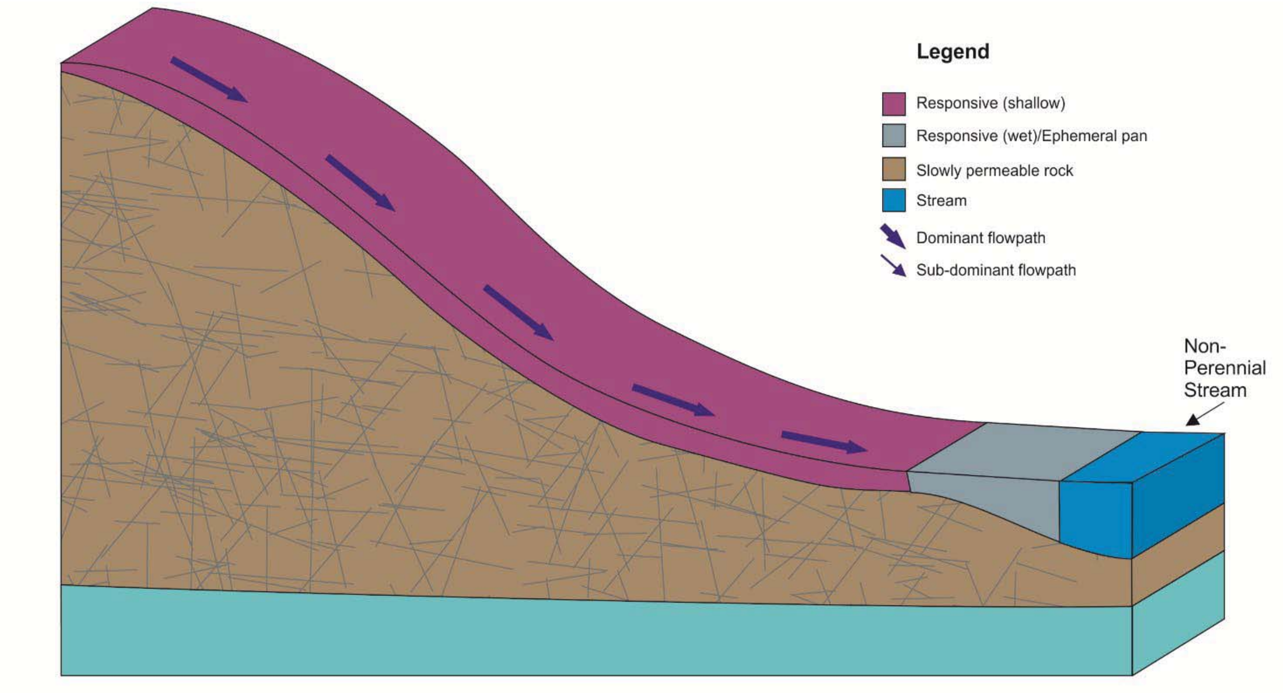

Figure 6.10. Conceptual hydrological response of a Class 9 hillslope.

Risk to wetland from catchment development: These are generally low risk hillslopes as wetlands predominantly have short hydroperiods and are relatively self-contained. Depression wetlands often also generally have small wetland catchments, limiting the potential cumulative intensity of impacts. However, natural overland flow does contribute to the hydroperiod of wetlands in this class. Wetlands may be rich in biodiversity in wet years, although they may lie dormant for many dry years in between. Increased overland flow in a fully developed catchment can completely change the hydroperiod of a naturally seasonal or temporary wetland to more permanent.

6.5.7 Class 10: *Recharge (deep)* soils to *interflow* soils, wetlands are seasonal to permanent

The climate is moderate, underlying lithology is fractured, topography is characterised by moderate hills. These hillslopes have deep recharge soils at the crest, grading into interflow soils downslope, with a wetland comprising the lower slope or valley floor (Figure 6.11). The dominant direction of water in the upslope portion of the hillslope is vertical, moving down through deep recharge soils to fractured bedrock. Underlying the fractured rock is a less permeable rock layer. The restricted permeability of this layer influences the overall downslope movement of water within the fractured rock. Ultimately, some water moves from the overlying fractured rock through the slowly permeable rock to support regional groundwater, which in this case is well below, and not connected to, the wetland. Interflow at the soil/rock interface dominates in the downslope soils. The water that infiltrates into the saprolite and fractured rock deep flow paths within the hillslope over months and years converges in the lower slope, wetting the wetland from below, and is highly important in sustaining wetland hydroperiod, maintaining seasonal to permanent saturation in these ecosystems. Multiple shallow flow paths are also present within the hillslope as albic and plinthic horizons (see Section 4.5). These respond quickly to rain events and are responsible for a variation in seasonally fluctuating water tables of the wetlands. Wetlands are common in such landscapes.

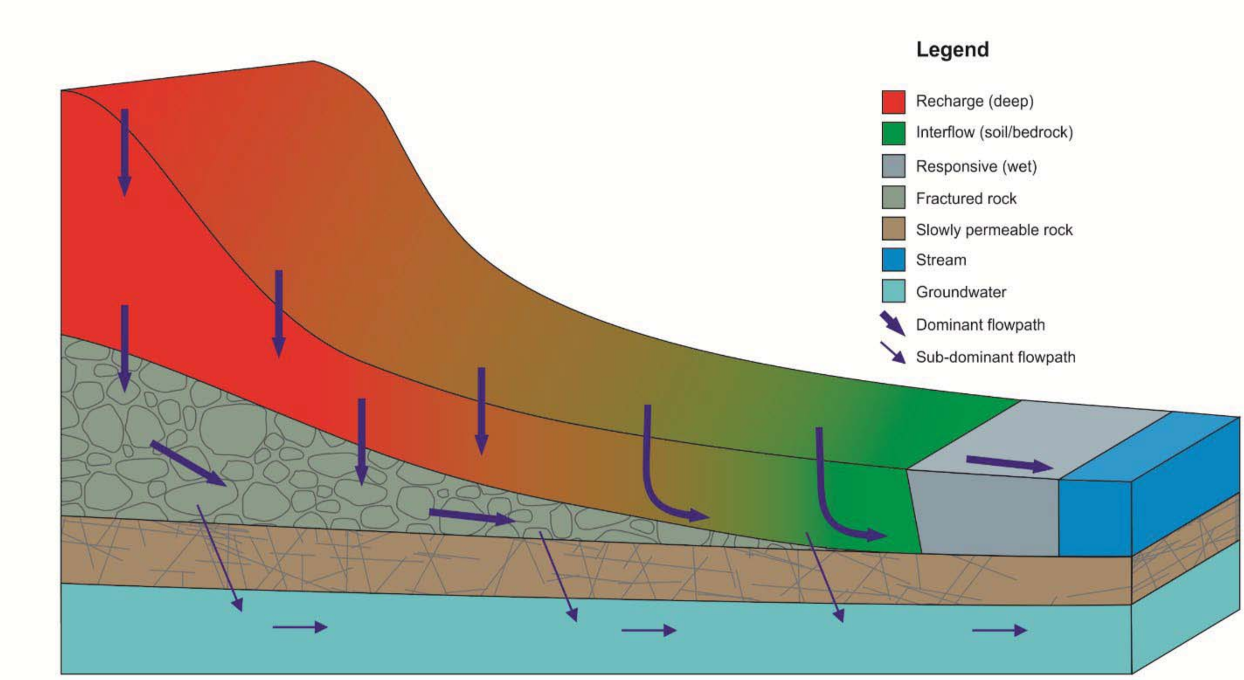

Figure 6.11. Conceptual hydrological response of a Class 10 hillslope.

Risk to wetland from catchment development: Interception or disruption of flowpaths pose a moderate to high risk, especially where areas of return flow from soft plinthic soils are present or where development impacts areas of interflow in deep subsoils which has a knock-on impact reducing or preventing returning flows to the subsoil and wetland.

6.5.8 Class 11: *Interflow (slow)* soils are dominated by evapotranspiration, wetlands are seasonal

Climate is moderate to low rainfall, underlain by slowly permeable lithology, in low gradient areas and poorly drained clay-rich soils. Rainwater infiltrates and drains vertically at a high rate in the topsoil horizon and infiltration is retarded by the clay horizon (Figure 6.12). Although hillslope soils could be saturated for long periods, their potential contribution to wetland hydroperiod is relatively small because of low hydraulic conductivity and they may act primarily as a store of water and not a conduit. Evapotranspiration (upward flux) of water is significant, both from the hillslope and wetlands. When present, wetlands occur in low positions in the landscape due to short duration ponding accumulating over underlying slowly permeable rock. Wetland soils in this class support redoximorphic features, evidence of a seasonally fluctuating water table. Base flow to streams is limited but wetlands, where present, may play a positive role in extending river seasonal flows. Examples of this landscape include areas of the central and eastern Free State.

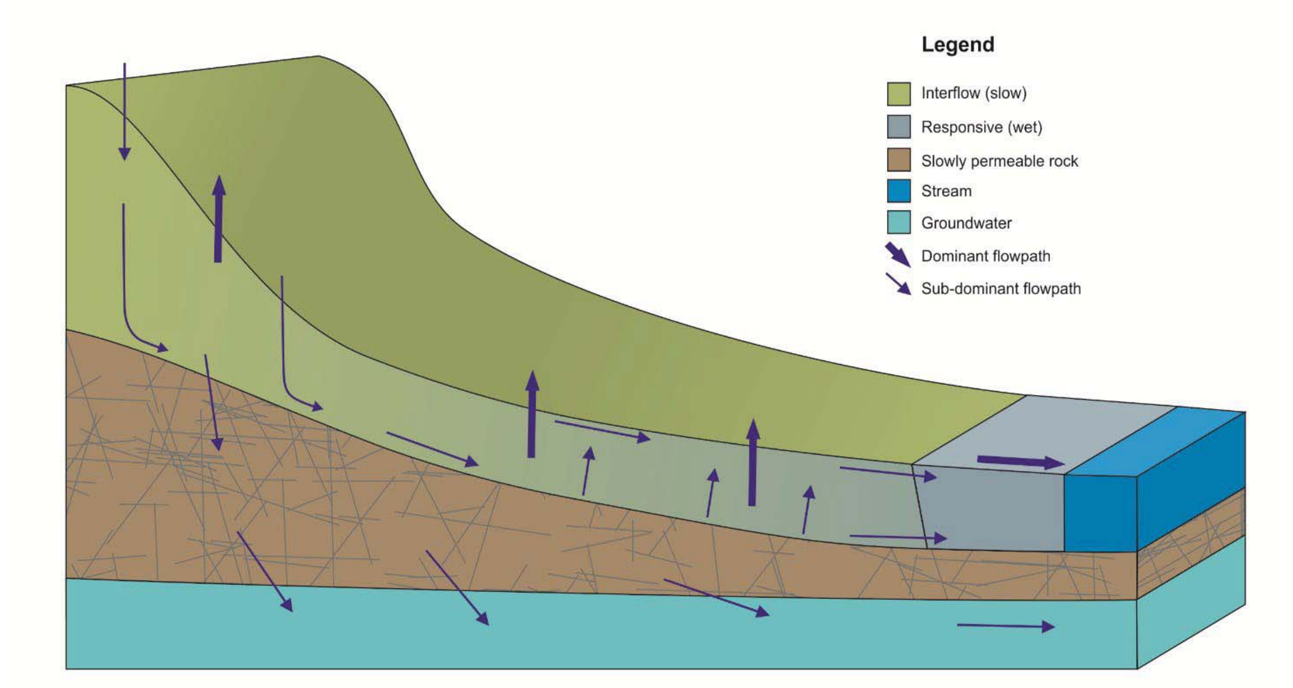

Figure 6.12. Conceptual hydrological response of a Class 11 hillslope.

Risk to wetland from catchment development: Moderate risk posed by the interception or disruption of flowpaths in shallow interflow areas, diverting flows away from the wetland.

6.5.9 Class 12: *Interflow* soils dominant, wetlands are seasonal

Climate is moderate, underlain by slowly permeable lithology, in low gradient areas. The dominant direction of water recharge is downslope through gravity, at the soil/rock interface (Figure 6.13). The restricted permeability of an underlying slowly permeable rock layer influences the overall downslope movement of water at the interface. Ultimately, some water moves through the slowly permeable rock to the regional groundwater, which in this case is well below, and not connected to, the wetland. Lateral flow is also generated through downslope return flow via the bedrock flowpath to the soils. The combination of the underlying barrier of impermeable rock that impedes vertical recharge, and the gravity-fed downslope movement of water especially as return flows to downslope soils, leads to the accumulation of water and formation of wetland conditions at the low point of the landscape. Wetlands are common in such landscapes but whether they are temporary or seasonally wet[13], depends on the hillslope storage length and storage area as well as the conductivity of the interflow soil horizon. The wetland hydroperiod is visualised with an initial peak, followed by a second, smaller peak generated from saturation excess in the subsoil horizon. Wetland soils in this class support extensive redoximorphic features, evidence of a seasonally fluctuating water table.

[13] Note that sometimes the presence of a downstream control, such as a dolerite dyke, can increase the accumulation of water, influencing the overall hydroperiod and amplifying the hillslope affect to deliver a wetter hydroperiod.

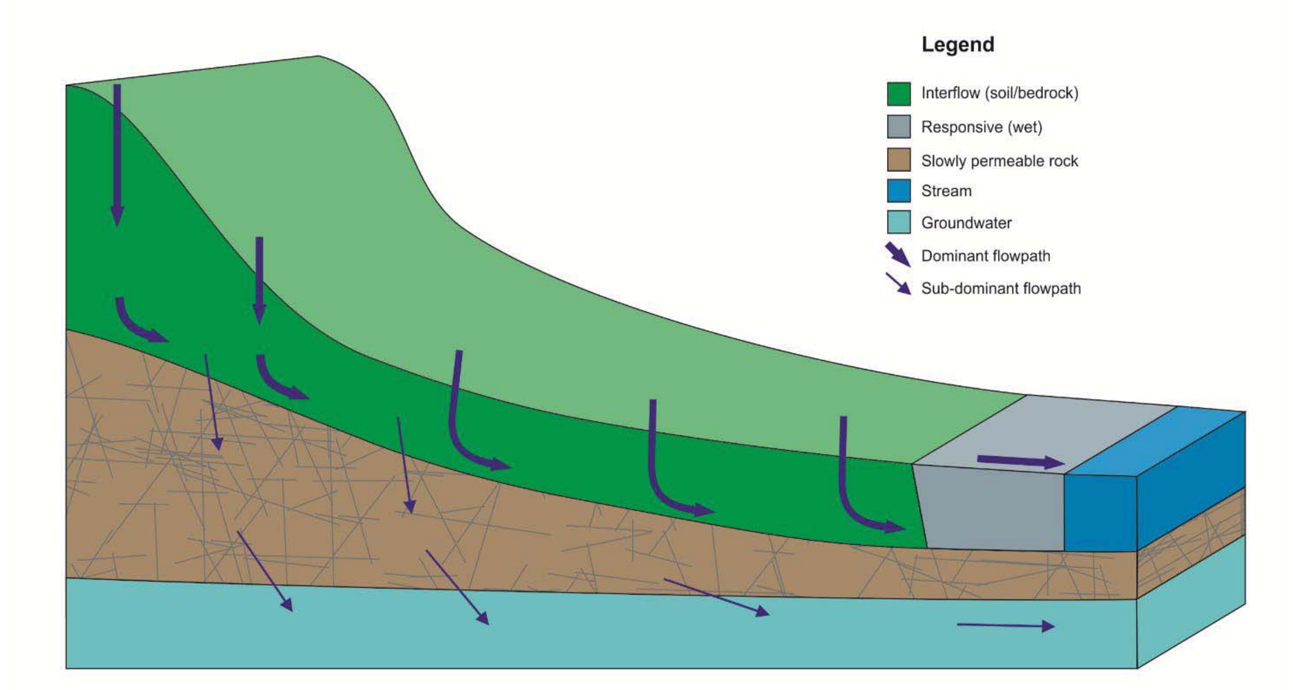

Figure 6.13. Conceptual hydrological response of a Class 12 hillslope.

Risk to wetland from catchment development: Moderate risk posed by the interception or disruption of flowpaths in shallow interflow areas, diverting flows away from the wetland.

SECTION B:

PRACTICAL GUIDELINES FOR PRACTITIONERS AND DECISION MAKERS

CHAPTER 7: WETLAND MANAGEMENT CONTEXT

7.1 INTRODUCTION

To develop defensible land-use decisions and best manage South Africa's wetlands, it is necessary to draw from a comprehensive suite of tools. Not doing so can lead to incomplete understanding of the issue at hand, and result in incorrect decision-making, contributing to the ongoing degradation of these important ecosystems. South Africa has made significant progress over more than 20 years to develop the necessary range of tools, predominantly funded through the Water Research Commission. Each assessment tool has a specific purpose, for example, the purpose of wetland delineation is to identify the outermost boundary of a wetland, and it does not tell us much about hydrological or other drivers of wetland presence. Wetland delineation is a fundamental first step that needs to be undertaken in a defensible manner, but needs to be packaged together with several other assessments before an informed management or water resource regulatory decision can be developed.

Similarly, a hydropedological study can add much useful information on the drivers of wetland hydrology and how land use within the wetland's hydrological catchment may alter the hydrological characteristics of the ecosystem, but does not provide wholistic information on the overall ecological state of the wetland and how other biophysical characteristics may be altered, nor on the ecosystem services the wetland may provide, or its relative importance, among other things. It is, therefore, acknowledged that a comprehensive suite of assessments is required in support of wetland management and regulatory decisions, as outlined by Ollis et al. (2014) in Figure 7.1.

A hydropedological assessment of the hillslopes comprising a wetland catchment, is a critical new tool in the wetland assessment toolbox. It is a relevant addition at Step 2 of Figure 7.1 to classify wetland hillslopes. At Step 3 (see also Section 7.1), hydropedological assessment can contribute to the understanding of wetland hydrology. With respect to Step 3, the current hydropedological guidelines are focussed on wetland hydrology, however, wetland-hillslope hydropedological understanding can certainly also contribute to assessment of wetland water quality impacts, a topic for a future guideline. At Step 5, a hydropedological assessment can help to formulate ecosystem protection measures (see also Section 7.3 on buffer guidance and Section 7.4 on identifying sensitivity zones).

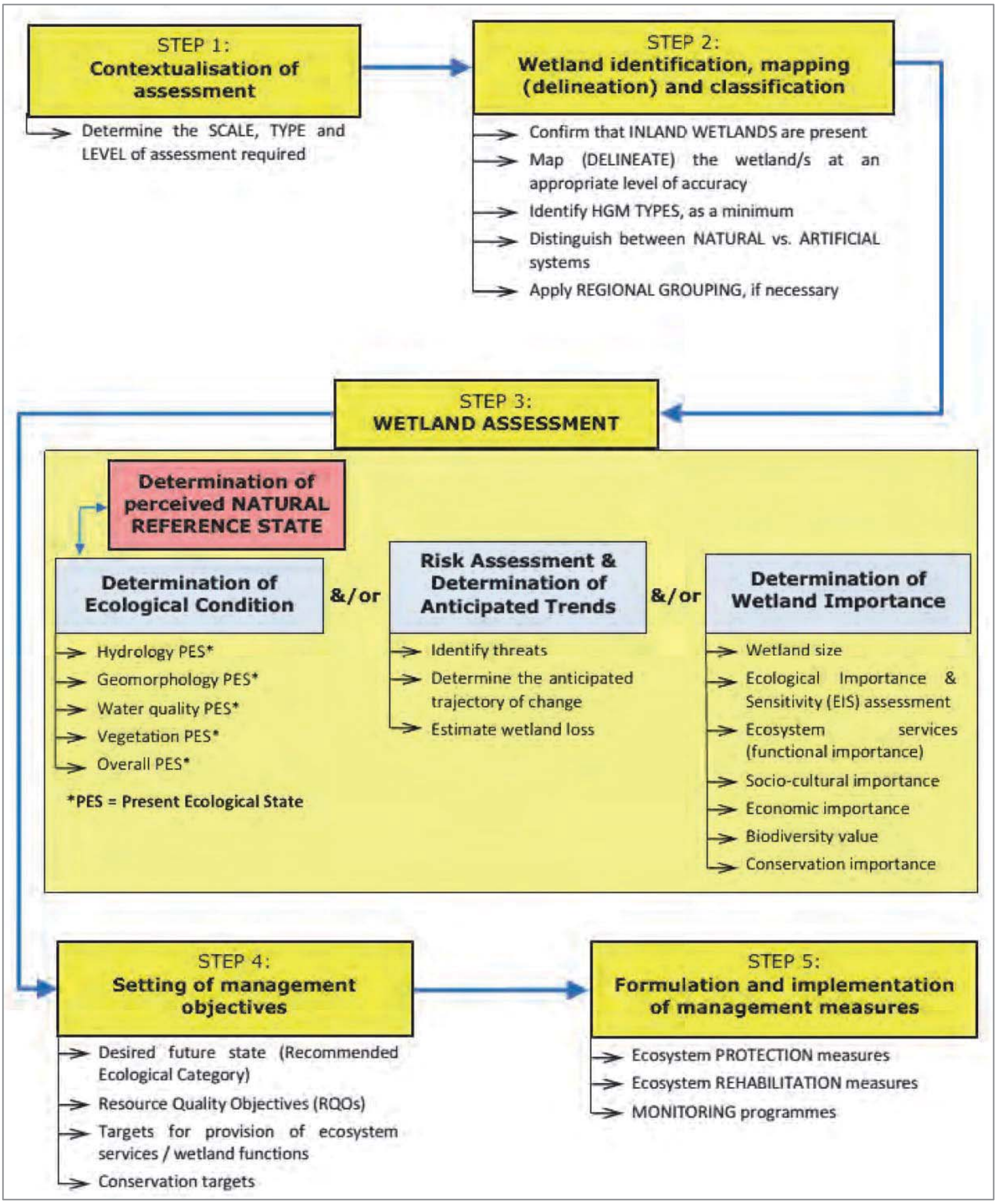

Figure 7.1. Decision-support framework for wetland assessment in South Africa (Ollis et al., 2014).

7.2 STATE OF WETLAND HYDROLOGY

South Africa has adopted a standardised method for the assessment of impacts to wetlands. The WET-Health Manual (MacFarlane et al., 2020) outlines a comprehensive methodology in support of assessing wetland condition. This is carried out according to four main components or modules, namely geomorphology, hydrology, vegetation and water quality (Figure 7.2).

Figure 7.2. Four modules to assess wetland present ecological status using the WET-Health method (MacFarlane et al., 2020)

Since water is a primary determinant of wetland structure and function, it is useful to consider the present (impacted) quantity, distribution and timing of water coming into a wetland against the estimated quantity, distribution and timing of water delivery in an unimpacted state (MacFarlane et al., 2020). WET-Health, therefore, bases the assessment of wetland hydrological condition on quantifying changes to those hydrological factors that underpin the wetland ecosystem, such as timing and quantity. These hydropedological guidelines provide an expanded assessment, intended to complement the component of WET-Health focussed on wetland hydrology assessment, through providing more in-depth assessment and supporting information to characterise, manage and conserve hillslope water resources and the wetlands they supply.

When preparing to undertake a WET-Health assessment, the following is recommended to incorporate a hydropedological assessment:

1. **Wetland catchment mapping**: Both WET-Health and hydropedological assessments acknowledge the importance of assessing a number of elements within the wetland catchment. While WET-Health discriminates two areas of influence, a) an area of high influence, within 200 m of the wetland, and b) the remainder of the wetland catchment, which can be either a local catchment or distant (in the case of wetlands influenced by rivers, which may originate many kilometres away), the critical contribution of the hydropedological assessment is to assess the full local (wetland) catchment for key water contribution zones. In many cases, these may be key water recharge areas at the crest of the wetland or important interflow areas within one hillslope of the catchment. If impacted, these critical areas may have a significant impact on wetland hydrology. Thus, in addition to assessing the land use within the wetland catchment, the step of classifying and characterising the representative hillslopes present in the wetland catchment, and identifying key water source and water delivery areas as part of a hydropedology study, is recommended. This is important because in the current WET-Health assessment, the assessment weights each HGM type according to the conceptual understanding of the relative impact from the two areas of influence. An improved conceptual understanding of hillslope-influenced wetlands should guide adjustments in these weightings, so that, for example, the relative impact of surface sealing in the critical recharge zone of a wetland is given sufficient weighting to acknowledge the influence it has on wetland condition. A similar approach can be used to predict the

potential impact of a proposed land use on the wetland, as hydropedological assessments are most commonly applied to assess new land use applications.

2. **Hydrogeological setting:** As part of catchment assessment, WET-Health recommends contextualising the hydrogeological setting of the wetland and provides the options of karst, coastal aquifer and other, mentioning the fractured aquifers of Table Mountain Sandstone as one of several additional groundwater-influenced situations. It is recommended that this be expanded to consideration of CHAPTER 6: of these hydropedological guidelines, namely, the twelve wetland-hillslope classes. This is the point where a hydropedological study could be commissioned, noting that the study generates information that is useful more widely across the wetland condition assessment process.
3. **Catchment landcover assessment:** The state of wetland hydrology can be interpreted partially as a response to catchment activities. This allows management recommendations to be developed specifically to address those activities. An unnatural increase or decrease in the quantity of water entering a wetland may be linked to land use changes in the wetland catchment. WET-Health methodology (MacFarlane et al., 2020) evaluates the effect that land use changes across the catchment are likely to have on wetland condition. Using the wetland catchment as the study boundary, each land use is assessed, initially by allocating a default impact intensity score. The WET-Health methodology provides a list of land uses (Table 7.1) grouped according to whether they lead to an increase in water reaching the wetland, for example sewerage discharges, storm water and irrigation return flows, and inter-basin transfer schemes; or a decrease in water reaching the wetland, for example abstraction of water for irrigation and dams, timber plantations, sugarcane and other perennial crops, and woody alien plants, and rates them according to the significance of their effect on water quantity. Rating of high to low of different plant species differs depending on their rates of water consumption and transpiration, which is affected by their growth form, root depth, location/access to the water, among other factors. This leads to less recharge and can especially affect interflow in the case of shallow flowpaths. The methodology calculates the proportion of the wetland catchment affected by each land use activity, with extent of impact expressed as a percentage of the total area of the wetland catchment. In this regard, the WET-health methodology provides significant additional information to a hydropedological assessment, which assesses the storage and movement of water within a wetland catchment and its inflow into the wetland. WET-Health offers a standardised, rapid approach to quantifying how land cover changes contribute to the relative amount of water inflow to the wetland. WET-Health considers these impacts in light of change to water inputs [EXT-MAR], to seasonality of wetland hydroperiod [EXT-Seas] and to peak flows of within wetland stream channels. However, once wetland-hillslopes within the wetland catchment have been classified through a hydropedological study, it is likely that the association of particular land covers within a particular topographic location of a particular hillslope-wetland class, would support the motivation for an adjustment of the weighting of the assigned impact within WET-Health.

Table 7.1. Default impact intensity scores assigned to specific catchment land cover categories affecting wetland hydrology (MacFarlane et al., 2020).

	EXT_MAR[14]	EXT_Seas	EXT_Peak
Open water – natural	0	0	0
Water supply dam	-8	3	-9
Aquaculture dams/ponds	-8	3	-9
Natural / minimally impacted	0	0	0.5
Semi-natural	0	0	1.5
Moderately degraded land	1	1	3
Orchards and vineyards	-5	4	2
Sugar cane	-4	1	2
Commercial annual crops (irrigated)	-5	4	3
Commercial annual crops (non irrigated)	-2	1	3
Subsistence crops	-2	1	3
Tree plantations	-7.5	0	2
Dense infestations of invasive alien plants	-5.5	0	0
Quarrying (sand, stone, diamonds)	-1	1	4
Coal mining	-4	2	5
Ore mining	-5	2	5
Eroded areas (and heavily degraded lands)	2	0	5
Urban industrial / commercial	2	1	9
Urban informal	2	1	7
Urban residential – high density	2	2	7
Urban residential – low density	2	1	5
Urban open space	-1	1	3
Livestock feedlots (cattle and pigs)	1	1	4
Chicken farms	-2	2	2
Planted pastures	-4	3	2

4. **Additional catchment hydrology-related questions:** In addition to assessing the impact of catchment land cover, WET-health methodology proposes a number of additional questions (Table 7.2). A hydropedological study, which delivers a classification of the one or more wetland-hillslopes comprising the wetland catchment, complements and supports answering these questions. The hydropedological study calls for looking beyond the 200 m "area of influence" and provides a number of additional factors to consider, including overall storage and timing of water delivery within the respective wetland-hillslopes, as well as the depth and nature of the dominant or multiple flow paths within the wetland-hillslope.

[14] EXT_MAR = change in mean annual runoff; EXT_Seas = change to seasonality of wetland hydroperiod; EXT-Peak = change in peak stream flows

Table 7.2. In addition to the detailed assessment, a number of general catchment hydrology-related questions are proposed in the WET-Health methodology (MacFarlane et al., 2020)

Wetland catchment
Average slope of the catchment
Inherent runoff potential of soils in the catchment
Within 200 m buffer of wetland
Average slope of the buffer
Soil permeability
Location of largely untransformed, vegetated land (natural and near-natural areas) within the buffer, upslope of the wetland
Structural characteristics of the dominant vegetation in the buffer
Concentration of flows

7.3 WETLAND BUFFERS TO MITIGATE IMPACT ON WETLAND HYDROLOGY

There is no single best design for wetland buffers, as the relative impact of the proposed land use, as well as the nature of the receiving ecosystem all need to be taken into account. South Africa does have a methodology in place for this (MacFarlane and Bredin, 2017). This component of wetland assessment falls within Step 5 – ecosystem protection measures – of the suite of tools for a comprehensive assessment in support of decision-making (Figure 7.1). MacFarlane and Bredin (2017) acknowledge that buffer zones do not address all water resource related problems. From a water quantity perspective, the interactive relationship between soils and water (hydropedology) influences how water moves through the landscape (surface flows, sub-surface flows and groundwater flows). Buffer zone guidelines are developed from the perspective of mitigating diffuse surface runoff and do not consider sub-surface flow interactions in the determination of buffer width (Browne et al., 2020). Although they can be effective in addressing diffuse source pollution in storm water run-off, for example, it is noted that buffer zones can do little to address impacts such as hydrological changes in the wetland catchment, for example, stream flow reduction as a result of afforestation. Buffer zones also do not address contamination of vadose zone water or groundwater or impacts on the quantity of water reaching the wetlands via these sources. Complementary approaches to address these impacts are, therefore, needed.

Browne et al. (2020) piloted an approach to delineate watercourse buffers within sugarcane cultivation landscapes which takes into account hillslope characteristics. In the proposed approach, the hillslope class is taken as the primary determinant of buffer width. Each hillslope class is associated with a specific buffer width, as the hillslope class changes across the landscape, the recommended buffer width changes. The recommended buffer width is, therefore, variable across the landscape, but within a recommended range, in relation to the hillslope class.

The Browne et al. (2020) study made use of Land Type (Land Type Survey Staff, 1972-2006) information to interpret a hydropedological response from the broad land type categories. The range in buffer widths recommended by this study are outlined in Table 7.3.

Table 7.3. Hillslope class and buffer width range, for modifying the proposed buffer width based on higher or lower threat to the wetland (Browne et al., 2020)

Hillslope class	**Buffer width (m)**		
Class	Narrow	Moderate	Wide
Class 3 – Recharge (not connected)	10	15	30
Class 4 – Recharge to wetland	15	30	50
Class 1 – Interflow (soil / bedrock)	30	50	75
Class 2 – Shallow responsive	50	75	90

These hydropedological guidelines recommend caution when applying the broad land type categories. A hydropedology assessment of the wetland catchment is necessary to establish the wetland-hillslope classes as a basis for applying the proposed buffer widths.

7.4 CATCHMENT SENSITIVITY ZONES BASED ON HYDROPEDOLOGY

Relatively large areas of homogeneous hillslope may be expected to have a degree of homogeneity in hydrological response. The range of anticipated hillslope hydrological responses across South Africa have been generalised into a set of classes (CHAPTER 6:). Based on this, the wetland catchment can be divided into morphologically similar hillslopes. Several hydrological hillslope classes may occur in one wetland catchment, and these may be rated according to their varying contribution to a wetland. This implies that several, often different, types of hillslopes contribute to a wetland. In Figure 7.3, this is presented both in terms of percentage spatial cover of the catchment and associated percentage of affected wetland, as well as broad quantity of hydrological contribution.

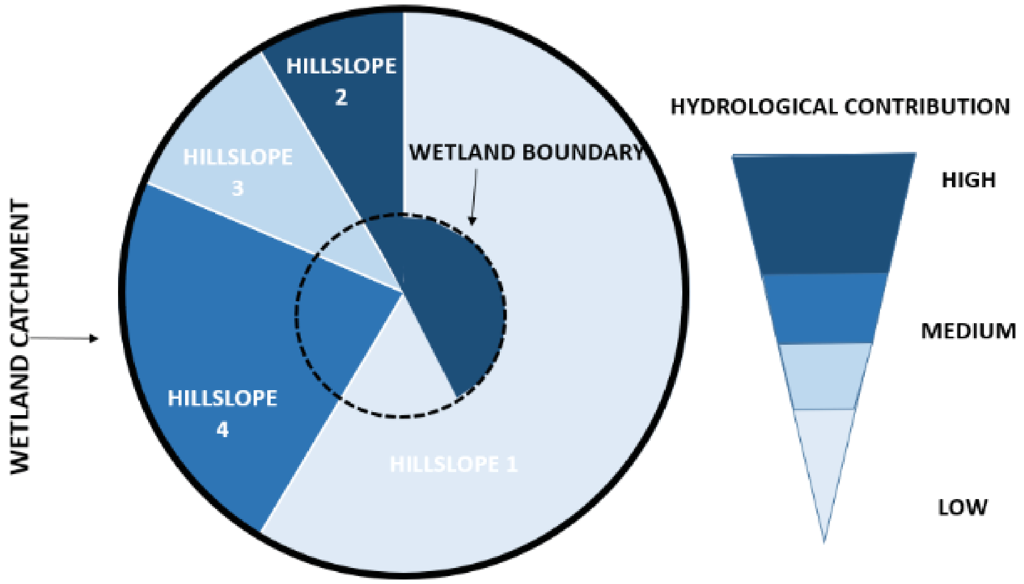

Figure 7.3. A generalised wetland catchment, divided into hillslopes, and depicting both the wetland (within the wetland boundary) and terrestrial components of the hillslopes. Hillslopes are rated according to their hydrological contribution.

A combined interpretation of land use activities, extent of land cover types, and relative cover of hydrological hillslope response types can support a matrix of sensitivity zones. New land use change activities can be interpreted against the list of activities impacting wetland hydrology (Table 7.1) and assessed against the presence of hydrological soil types. The risk posed by a potential land use impact is estimated by evaluating the degree of hydrological alteration that results from a given activity, considered against the degree to which the water source (recharge area) or flow path has been impacted (Table 7.1).

Risk, therefore, can be measured against:

- The default impact land use list provided by WET-Health.
- The hillslope hydrological response class, i.e. water delivery systems to the wetland, on which the land use occurs (certain hillslope hydrological classes are more or less vulnerable to certain land use impacts).
- Vulnerability of the HGM wetland type to the land use (based on water input source and local climate broadly divided by WET Health into five groups).

Catchment hardening increases runoff and affects timing of water to a wetland. The greater the extent of hardened surfaces (e.g. roofs, parking lots, etc.) or areas of bare soil in the wetland catchment, the lower the infiltration of storm water, and therefore the greater the surface runoff and increase in flood peaks. This has an especially negative effect on the water source areas, preventing recharge and ultimately reducing input to the wetland or delivered it in a point source manner, often at too high a velocity. Table 7.4 highlights that the key impacts to flag within the hillslopes of a wetland catchment are those proposed changes in land use which will seal recharge zones, or disturb interflow zones.

Approaching an assessment in this way links wetland degradation to specific causes and locations within the wetland catchment, leading to informed decisions and selection of management interventions. The approach outlined throughout this document is useful preparation for a further step of modelling of water inputs (CHAPTER 10:), which may require more resources and time, but offers a more accurate assessment of the hydrological impacts.

Table 7.4. Risk of local activities impacting on the functions of wetlands, based on hydropedological hillslope types (Section 6.4 and 6.5).

Wetland group	Wetland-hillslope class (Figure A)	High-impact activities		Risk zone	Risk to wetland	Potential contribution of hydropedological assessments[1]
		Hydrological impact	Activities			
Groundwater-dependent, permanent	**1**: Recharge deep soils dominant	Abstraction (broadscale lowering of regional aquifer from groundwater abstraction)	boreholes	Anywhere within the wetland catchment	Moderate	**Low**: Groundwater driven
		Reduction (regionally extensive water-reduction activities)	commercial plantations	Anywhere within the wetland catchment	Moderate	**Low**: Groundwater driven
Groundwater-dependent, permanent	**2**: Recharge deep soils dominant	Abstraction (broadscale lowering of regional aquifer from groundwater abstraction)	boreholes	Anywhere within the wetland catchment	Moderate	**Low**: Groundwater driven
Groundwater-dependent, permanent	**3**: Recharge shallow soils dominant	Surface sealing and diversion (prevents infiltration of recharge water, changes recharge infiltration rates, diverts and converts water into peak flows and concentrated runoff)	urbanisation: buildings, roofs, roads	Anywhere within the wetland catchment	Low	**Low**: Groundwater driven
		Reduction (interception and extraction of available recharge volumes)	water-intensive woody alien invasive species	Anywhere within the wetland catchment	Low	**Low**: Groundwater driven
Hillslope—dependent, permanent	**4**: Recharge shallow soils dominant	Surface sealing and diversion (prevents infiltration of recharge water, changes recharge infiltration rates, diverts and converts water into peak flows and concentrated runoff)	urbanisation: buildings, roofs, roads	Anywhere within the wetland catchment	Moderate	**High:** Identifying and characterising recharge zones
Hillslope—dependent, temporary to permanent	**5**: Recharge shallow, to fractured aquifer	Surface sealing and diversion (prevents infiltration of recharge water)	urbanisation: buildings, roofs, roads	Midslope, fractured rock recharge as well as soil return flow areas	Moderate	**High:** Identifying and characterising recharge zones
Hillslope—dependent, seasonal to permanent	**6**: Recharge deep soils dominant	Surface sealing and diversion (prevents infiltration of recharge water, changes recharge infiltration rates, diverts and converts water into peak flows and concentrated runoff)	urbanisation: buildings, roofs, roads; land use conversion	Recharge area, typically at hillslope crest	Moderate to high	**High:** Identifying and characterising recharge zones
		Reduction (interception and extraction of available recharge volumes)	alien invasive plants	Recharge area, typically at hillslope crest	Moderate to high	**High:** Identifying and characterising recharge zones
Wetlands rare or absent	**7**: Recharge slow soils dominant	Not applicable		Not applicable	Low	**Low:** Limited lateral landscape connectivity
Wetlands rare or absent	**8**: Recharge deep soils dominant	Not applicable		Not applicable	Low	**Low:** Limited lateral landscape connectivity
Hillslope—dependent, temporary	**9**: Responsive shallow soils dominant	Surface sealing and diversion (increased, concentrated overland flow can change hydroperiod of a naturally seasonal or temporary wetland to more permanent)	urbanisation: buildings, roofs, roads; mining	Anywhere within the wetland catchment	Low	**Low:** Overland flow dominant
Hillslope—dependent, seasonal to permanent	**10**: Recharge deep soils to interflow soils	Surface sealing and diversion (prevents infiltration of recharge water, changes recharge infiltration rates, diverts and converts water into peak flows and concentrated runoff)	urbanisation: buildings, roofs, roads	Fractured rock recharge area, areas of return flow from interflow	High	**High:** Identify and characterising recharge and interflow zones
Hillslope—dependent, seasonal	**11**: Interflow (slow) soils dominated by evapotranspiration	Limited risk		Hillslope has limited flow generation	Moderate to low	**Low:** Lateral connectivity limited
Hillslope—dependent, seasonal	**12**: Interflow soils dominant	Surface sealing and diversion (interception or disruption of shallow flowpaths, diverting flows away from the wetland)	urbanisation: buildings, roofs, roads; mining	Bedrock interflow areas	High	**High:** Identifying and characterising interflow zones

[1]The contribution of hydropedological assessments to understand the hydrological behaviour of the landscape and contribute to protecting the wetland and manage the water resources more sustainably
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CHAPTER 8: GENERAL REQUIREMENTS AND CONSIDERATIONS

8.1 INTRODUCTION

Hydropedological assessment plays a crucial role in understanding the flow of water across landscapes, from surface and sub-surface pathways to wetlands, streams, and groundwater. The purpose of these guidelines is to provide decision makers and practitioners with clear directions on the following aspects:

- **Determining the necessity of hydropedological surveys:** The guidelines offer guidance on when it is necessary to conduct hydropedological surveys, helping decision makers determine whether such assessments are required for a particular project.
- **Identifying the level of hydropedological assessment required:** The guidelines outline the different levels of assessment that may be needed based on the specific project or development. This ensures that practitioners can tailor their survey efforts to match the requirements of the situation.
- **Standardising survey methodology:** The guidelines establish a standardised approach to conducting hydropedological surveys. By following these methods, practitioners can effectively identify the dominant hydrological drivers and responses of landscapes, allowing for a quantification of the impact that new developments may have on water resources.
- **Enabling informed decision making:** By providing a comprehensive understanding of the hydrological system, the guidelines assist decision makers in making informed choices regarding sustainable water management. This ensures that decisions align with the principles of responsible resource usage.

It is important for practitioners to read these guidelines in conjunction with the theoretical background (Section A). The development of these guidelines was based on numerous scientific and consultancy projects, as well as incorporating existing guidelines (Job and Le Roux, 2018; Van Tol et al., 2021a). The input and feedback gathered from workshops and stakeholder engagements during the ongoing WRC project have also been taken into account.

8.2 MINIMUM REQUIREMENTS OF PRACTITIONERS

According to South African legislation, all professional practitioners consulting in the natural sciences must be registered with the South African Council for Natural Scientific Professions (SACNASP) in their relevant field. The Natural Scientific Professions Act (Act 27 of 2003) prohibits individuals from practicing in a professional consulting capacity without appropriate SACNASP registration, ensuring compliance with the code of conduct. Candidate Natural Scientists may work under the supervision of a Professional Natural Scientist, however, the professional must be physically present during the field survey and must include a signed declaration in the report, confirming that all aspects of the work performed by the candidate were adequately supervised.

Registration alone does not guarantee the necessary qualifications for wetland delineation or conducting a hydropedological survey. The specialist responsible for the field survey and reporting must possess relevant experience and qualifications to perform these tasks. The specialist's curriculum vitae should clearly highlight their pertinent expertise.

Conducting a comprehensive hydropedological assessment requires the practitioner to classify South African soils up to the soil family level. This classification is the minimum requirement for practitioners, as it facilitates interpretations of soil and hillslope hydropedological behaviour. Evidence of this capacity could be in the form of a tertiary degree in soil science, accredited short courses in soil classification, and/or accredited short courses on hydropedology.

Hydropedology, by definition, is an interdisciplinary science. Embedding hydropedological interpretations in wetland management necessitates collaboration among a team of experts, such as a soil scientist, wetland ecologist, freshwater specialist, and hydrologist. While it is possible for one person to possess all these capabilities, the team of practitioners should have the ability to classify soils up to the family level and delineate wetlands based on interpretations of soils, hydrology, and vegetation.

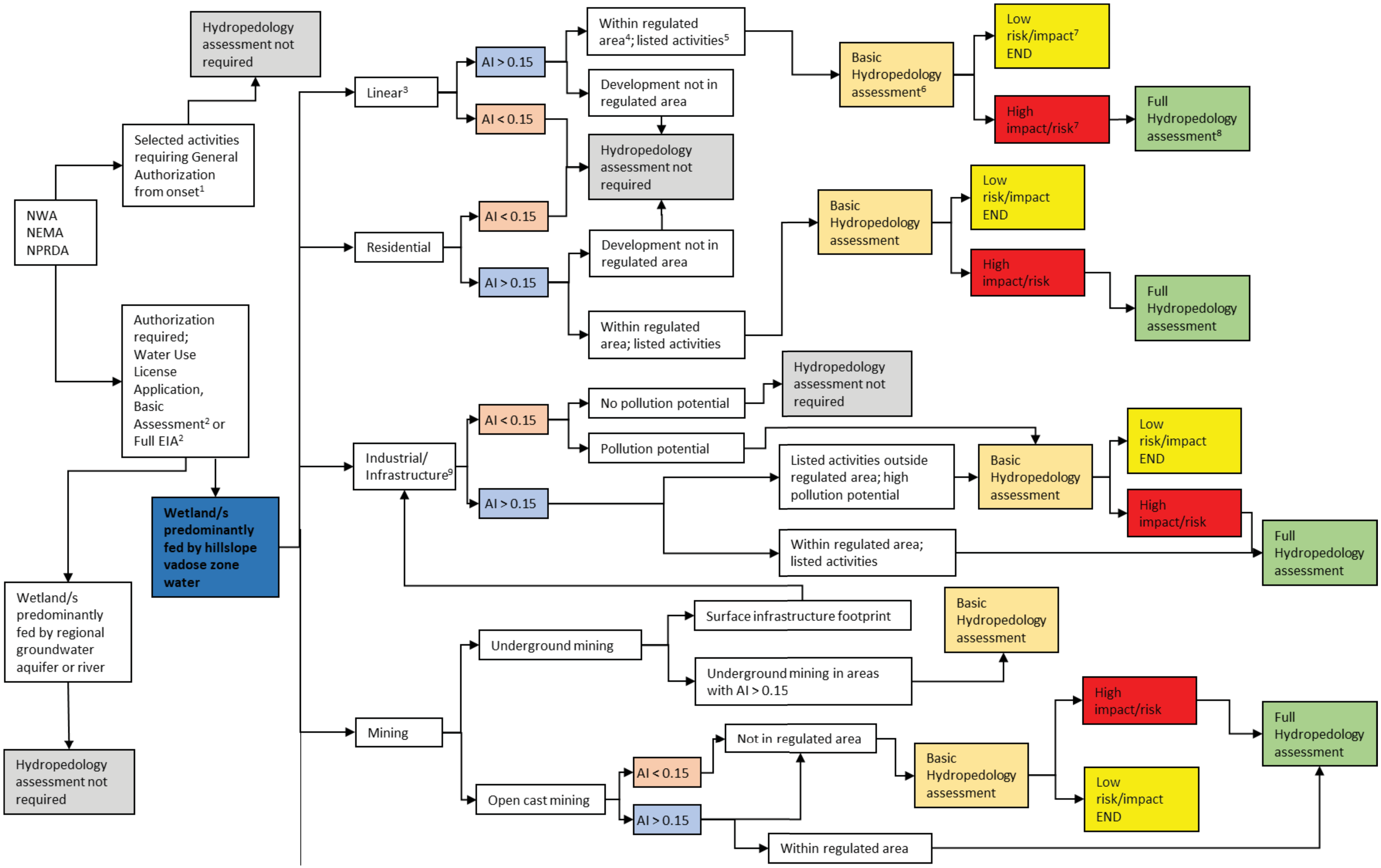
8.3 WHEN IS A HYDROPEDOLOGICAL ASSESSMENT REQUIRED?

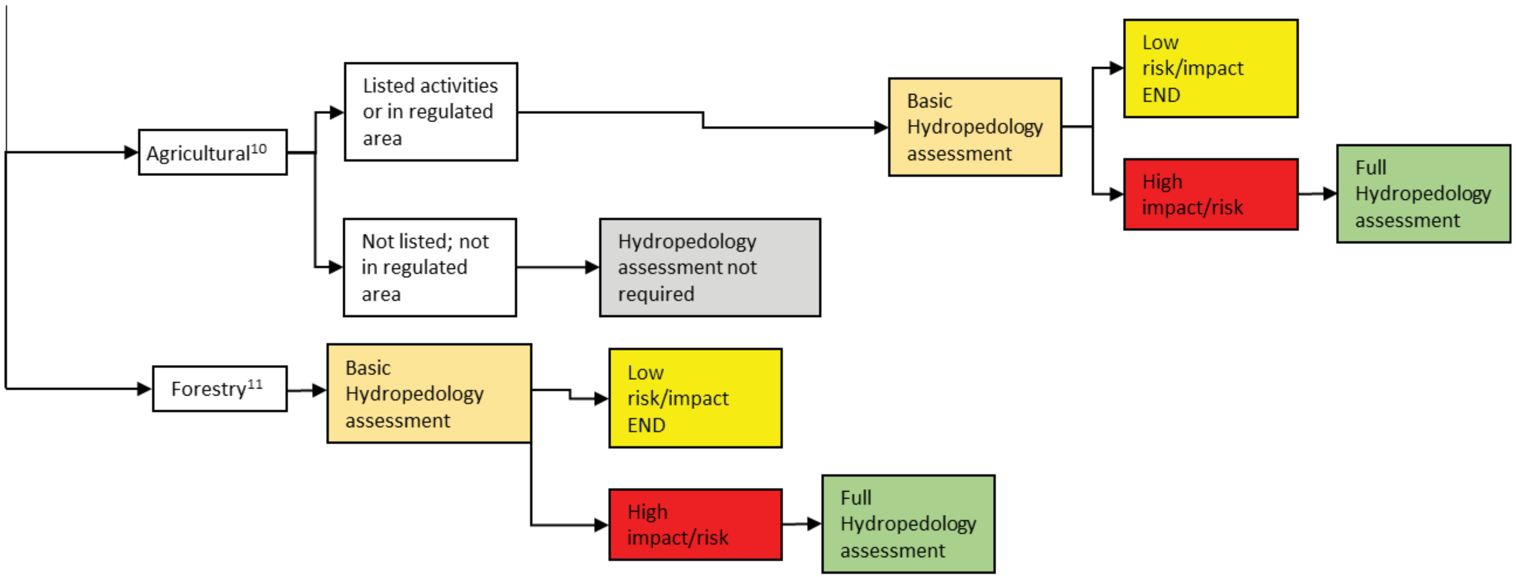
Hydropedological assessments are required when a change in land use will likely result in an alteration of hydropedological processes. The need for a hydropedological assessment and the type of assessment can be determined from the decision tree (Figure-8.1). Certain activities by individuals and institutions will only require a General Authorisation and a hydropedological assessment is not required (Table 8.1)[15]. This decision tree (Figure 8.1). distinguishes between six land use impacts namely *linear, residential, industrial, mining, agriculture* and *forestry*. In each of these cases, the climate, as depicted through the aridity index (*AI*), serves as the primary criterion for determining the necessity and type of hydropedological assessment required. The *AI* is calculated using:

$$AI = \frac{Annual\ Rainfall}{Potential\ Evaporation}$$

The lower the *AI* the more arid the climate. In more arid climates (<0.15), with limited lateral flows and hillslope responses, hydropedology studies are required only when the impact is significant and full assessments only when high impacts are anticipated. For industrial developments, especially when pollution potential is high, a full assessment is required. For open cast mining activities, a full assessment is always required. When there is a significant development footprint associated with underground mining, the infrastructure branch of the decision tree should be used instead of the mining branch.

[15] Full list of activities requiring only a General Authorisation available from Department of Water and Sanitation.


NWA
NEMA
NPRDA
Selected activities requiring General Authorization from onset[1]
Hydropedology assessment not required
Authorization required; Water Use License Application, Basic Assessment[2] or Full EIA[2]
Wetland/s predominantly fed by hillslope vadose zone water
Wetland/s predominantly fed by regional groundwater aquifer or river
Hydropedology assessment not required
Linear[3]
AI > 0.15
AI < 0.15
Within regulated area[4]; listed activities[5]
Development not in regulated area
Hydropedology assessment not required
Basic Hydropedology assessment[6]
Low risk/impact[7] END
High impact/risk[7]
Full Hydropedology assessment[8]
Residential
AI < 0.15
AI > 0.15
Development not in regulated area
Within regulated area; listed activities
Basic Hydropedology assessment
Low risk/impact END
High impact/risk
Full Hydropedology assessment
Industrial/ Infrastructure[9]
AI < 0.15
AI > 0.15
No pollution potential
Pollution potential
Hydropedology assessment not required
Listed activities outside regulated area; high pollution potential
Basic Hydropedology assessment
Low risk/impact END
High impact/risk
Within regulated area; listed activities
Full Hydropedology assessment
Mining
Underground mining
Surface infrastructure footprint
Underground mining in areas with AI > 0.15
Basic Hydropedology assessment
Open cast mining
AI < 0.15
AI > 0.15
Not in regulated area
Within regulated area
Basic Hydropedology assessment
High impact/risk
Low risk/impact END
Full Hydropedology assessment



Notes:

12) Activities that are generally authorised for any person, institution and / or SOCs subject only to conditions of the General Authorisation for Section 21 (c) and (i) water uses do not require any level of hydropedological assessment (see examples in Table 8.1)
13) See triggering actions in listing notices in Appendix A
14) Linear in the context of the decision tree refers to belowground linear development (e.g. pipes and drains) and roads. Aboveground linear developments do not require hydropedological assessment as they do not significantly alter flow paths. However, authorities may request hydropedological assessment based on the specific development, method statement and expected impacts.
15) Regulated area as defined in the National Water Act (1998) – see definition under terms and definitions
16) Activities listed in Appendix A which will require basic or full Environmental Impact Assessment
17) Basic assessment focus only on conceptual description of pathways and connectivity (flow drivers) and the potential impact of the development on these
18) Risk/impact is based on risk matrix associated with different hillslope types (Section 6.4 & 6.5 and Table 7.4)
19) Full assessment: Include quantification of fluxes and loss/gain of different water balance components
20) Includes renewable solar energy projects. Wind farms typically excluded.
21) Agricultural activities include dams, planting in water source areas and changes from rainfed to irrigation agriculture. Water quality impacts (pesticides, herbicides and nutrients) should also be considered.
22) Changing of natural vegetation or cultivated agriculture to commercial plantations.

Figure 8.1. Decision tree for when and the type of hydropedological assessment required.

Table 8.1. Examples of activities only requiring General Authorisation without considering decision tree (full list to be gazetted).

Responsible	Activity
Any person	Construction of a single residential house and associated infrastructure.
Any person	Maintenance to private roads and river crossings with limited footprint.
Any person	Erection of fences which will not impede or divert flow, or affect resource quality.
Any person	Emergency river crossings for vehicles to gain access to livestock, crops or residences.
ESKOM and other institutions	Construction of new overhead transmission and distribution power lines outside the active channel of a river and/or outside the extent of a wetland.
ESKOM and other institutions	Minor maintenance of roads, river crossings, towers and substations where the footprint will remain the same.
Water provisioning institutions	Maintenance of existing water pipelines and construction of new raw and drinking water pipelines.

8.4 LEVELS OF DETAIL

The level of assessment should be in accordance with the anticipated intensity and scale of land use change impacts (Figure 8.1). The anticipated impact on hydropedological behaviour is also specific to the hydrological hillslope types. From the decision tree there are three possible scenarios; 1) hydropedological survey is not required, 2) basic assessment is sufficient, and 3) a full assessment is required.

The *Basic* assessment will include:

1. Identification of dominant hillslopes.
2. Description and classification of dominant soils based on soil morphology.
3. Conceptualising hillslope hydropedological responses and grouping into hillslope class.
4. Discussion on the impact of the land use change on hydropedological behaviour and wetland function.

The *Full* assessment will include the above as well as:

5. Quantification of hydraulic properties of representative soil horizons.
6. Quantification of hydropedological fluxes and the impact of the land use change on wetland hydroperiod and fluxes.

8.5 HYDROPEDOLOGICAL ASSESSMENT REPORT

The hydropedological assessment report will accompany other reports in the Environmental Impact Assessment and Water Use Licence Application and will adhere to the standards and requirements of these reports. Below are the minimum requirements of what should be contained in a hydropedological assessment report, these include the description of the sampling campaign, observations for each TMU, description of each of the observations (with photograph), soil type, and a map of observations.

8.5.1 Description of sampling effort

Specialists are required to present information on the intensity of the survey. This should be quantified in some manner as the amount of effort spent according to the type of sampling performed, for example:

- Number of plots per unit area (ha or km^2).
- Number of plots per TMU.
- Duration of sampling time per sample plot, site, transect or meander.
- Distance walked or driven while sampling.

Sampling plots should be mapped in relation to the proposed development footprint and area of influence. Where possible, GPS tracks of the survey conducted by the specialist should be included on the map to show coverage of the area of influence, including the start and end point of plots or transects. Representative photographs of each sampling location should be provided.

8.5.2 Description of sampling limitations

Limitations to both the desktop and fieldwork studies must be carefully described in the specialist report and accompanied by photographic evidence where possible (for example, impassable road or fence preventing access to an important portion of the survey area). Limitations include but are not limited to:

- Lack of sufficient time for the survey to be adequately representative of the area of influence.
- Restricted access to the area of influence or topographically diverse and large study areas.
- Adverse weather conditions.
- Security threats.

It is also important to describe the effects that such limitations have on the data quality and to suggest corrective measures. For example: “The survey took place in April after a relatively high rainfall season and some of the profiles in lower lying positions were filled with water”.

8.5.3 Photographic evidence

Photographic evidence that is provided in a report must be obtained from within, or verified to originate from, the area of influence and from the fieldwork or historical images acquired from landowners or staff. If a photograph is included in the report which was not taken under these circumstances, then this must be clearly stated in the caption and all relevant metadata for the image (for example, date, location, photographer) must also be provided.

Soil profiles should be photographed together with a measuring tape or object that provides a scale reference. It is advisable that morphological properties of interest are also photographed (Figure 8.2).

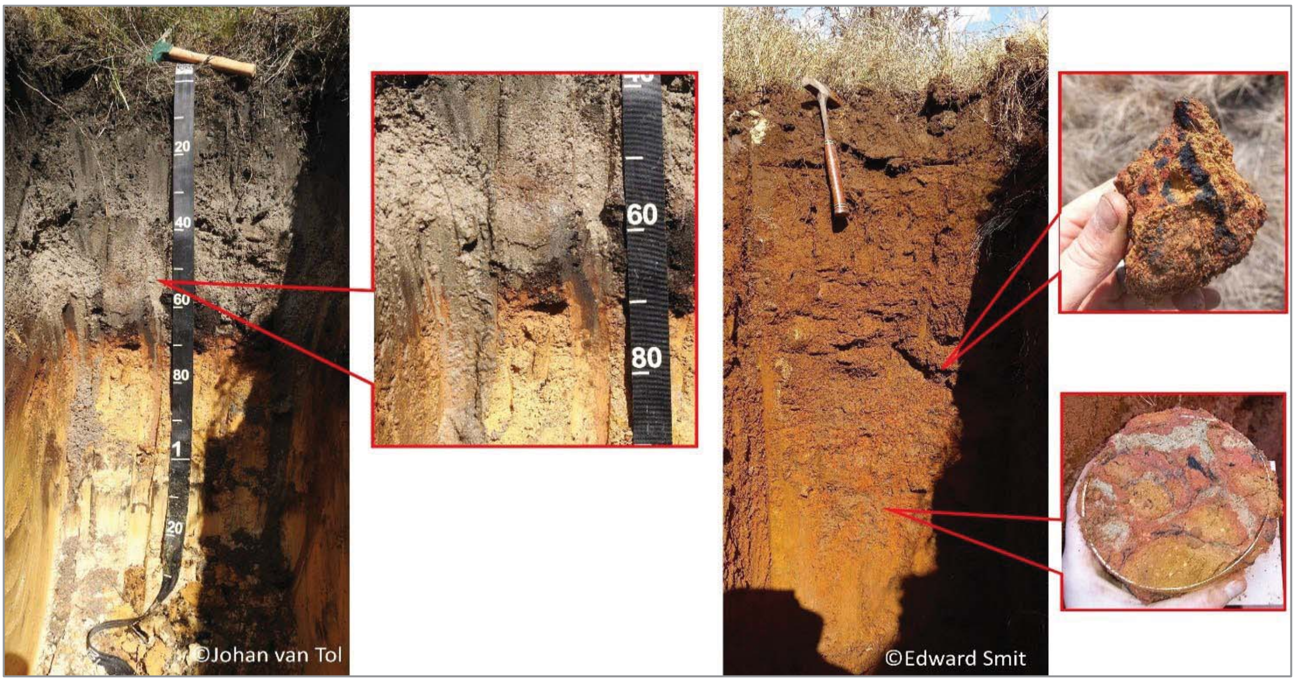


Figure 8.2. Clear photographs with scale and focussing on morphological properties of interest adds value to the report.

8.5.4 Mapping standards

All specialist studies should contain maps showing, at a minimum, the following information where relevant:

- Proposed development footprint and defined area of influence.
- Observation points and type (e.g. profile, soil auger, surface observation).
- Locality map showing the general location of the area of influence in relation to nearby features such as urban centres, roads, protected areas, provincial boundaries, etc.
- All biodiversity priority areas and other sensitive features.
- Terrestrial and aquatic ecosystem types that fall within the area of influence, as per current datasets available via the screening tool.
- Terrestrial and aquatic ecosystem types as delineated in the field, based on the descriptions of such ecosystems.
- Any recommended mitigation measures and proposed project design alternatives.

A map should always include the following:

- A directional indicator, usually provided as an arrow indicating north.
- A scale bar with suitable units and precision in metric scale for measuring distances and areas on the map.
- A legend with clearly identifiable colours and readable fonts for all of the displayed spatial information.
- Tick marks in geographic co-ordinates (WGS84) of sufficient precision along the X (longitude) and Y (latitude) axes, preferably with markers inside the map area to assist in the evaluation of the precise location.
- A national or provincial context map.

8.6 WETLAND DELINEATION REPORT

Hydropedological surveys aim to characterise dominant surface and sub-surface flowpaths of water through the landscape to wetlands. Although wetland field delineation is noted as one of the steps in the step-by-step guidelines (CHAPTER 9:), it should be noted that these guidelines do not provide full coverage of the topic. The practitioner should therefore be familiar with the DWS delineation manual (DWAF, 2005). Further useful references include USDA-NRCS, 2010; USACOE, 2006; SAWS, 2014; Job, 2008; Kotze et al., 1996.

However, it is noted that overall, the standard of wetland delineation reporting has frequently been poor. Often, little or no data is presented to support a particular finding and the fieldwork is undertaken with insufficient rigour. Job (2008) and the KwaZulu-Natal Wetland Community of Practice (Cowden et al., 2011) offer recommendations on how to improve the quality of wetland delineation practice and reporting. These recommendations were supported by the wetland delineation working group of the South African Wetland Society (SAWS, 2014). The reporting should be comprehensive enough to allow an independent wetland specialist reviewer to provide comment on the study without needing to visit the site.

In addition to improved rigour in describing how and when the delineation was undertaken, wetland delineation reports should also include a review of historical imagery and anecdotal evidence. Field datasheets should be provided with a description of site conditions of representative sample points that adequately describe the full delineation. Particularly for difficult sites, the sample points should be described from both inside and outside the delineated wetland boundary. Site maps should be included identifying the boundary of the wetland within the study area, plus an indication if the wetland extends outside the site boundary, *albeit* only at a desktop level if access is restricted or difficult in those areas. The location of all data collection points recorded during the study should be provided. In the case of wetlands, both wetland and non-wetland habitat should be depicted in photographic evidence to support a delineation.

Wetland delineation alone does not tell us much about the hydrological or other drivers of wetland presence. While it can provide an indication of the wetting regime of a wetland system, it does not provide information on the ecological state of the wetland, ecosystem services it may provide, wetland importance or how land use within the wetland or its hydrological catchment may alter the biophysical characteristics, ecosystem processes and functionality of the wetland. Buffers cannot be set following delineation alone, and a delineation alone is not sufficient to answer land or water resource regulatory decisions. Delineation is, however, a fundamental first step that needs to be undertaken in a defensible manner. For this reason, DWS requests both a wetland delineation and a wetland assessment report[16] to be submitted as part of the Water Use License Application.

[16] To understand the conditions of the wetland (PES, EIS, how water moves in the landscape, etc.) and the impact/risk posed to the wetland due to the proposed activity/development.

CHAPTER 9: STEP-BY-STEP GUIDE FOR INTEGRATING HYDROPEDOLOGY IN WETLAND ASSESSMENT AND MANAGEMENT

9.1 INTRODUCTION

This chapter offers a comprehensive, step-by-step guide on conducting hydropedological assessments and integrating them into wetland delineation, assessment, and management. Throughout the steps, reference is made to background documentation or relevant sections in these guidelines. It is essential for the practitioner to have a thorough understanding of the theoretical and practical foundations upon which these steps are constructed. The steps are:

- **Step 1:** Delineate wetland boundary on desktop.
- **Step 2:** Delineate wetland catchment boundary on desktop.
- **Step 3:** Identify influence of regional groundwater or rivers.
- **Step 4**: Characterise the wetland catchment environment.
- **Step 5:** Identify representative hillslopes.
- **Step 6:** Delineate wetland in the field.
- **Step 7:** Conduct hydropedology transect survey.
- ***Step 8:*** *Conduct hydraulic measurements; in-situ and in lab.*
- **Step 9**: Regroup soil observations into hydropedological groups.
- **Step 10:** Conceptualise hillslope hydrological responses.
    - Hillslope classes
    - Contribution to wetlands
- **Step 11:** Describe impacts on processes and wetland responses.
- ***Step 12:*** *Quantify hydropedological fluxes.*
- **Step 13**: Develop mitigation and management plans to reduce or avoid impacts.

Note: Step 8 and 12 are only for *Full* hydropedological assessments.

9.2 HYDROPEDOLOGICAL ASSESSMENT PROCEDURE

9.2.1 Step 1: Delineate wetland boundary on desktop

Wetland delineation includes confirmation of the presence (and size) of the wetland; and an approximate determination of the outermost edge (boundary) of the wetland. Wetland delineation should result in three things: 1) a wetland boundary indicated on a map, and where necessary, in the field; 2) a map that clearly identifies data collection points and the boundaries of the delineated wetland (topographic and aerial site maps are very helpful); and 3) a report that explains how the boundary was determined. Before going to the field, map the wetland on desktop in GIS and Google Earth, using multiple imagery resources (such as the historical view on Google Earth, orthorectified aerial photography if available in high resolution and other satellite-derived imagery. Ideally, review imagery across both wet and dry seasons, from recent to historical.

References: Guidance on how to identify and map a wetland: Job et al., 2018.

9.2.2 Step 2: Delineate wetland catchment boundary

Map the wetland catchment on desktop based on topographic contours or a digital elevation model. Joining all the highest elevation points around a particular wetland typically delineates the catchment boundary. For large study areas with multiple wetlands, consider the multiple wetland catchments within the larger area.

References: Contour lines to help identify watersheds and the head of drainage initiation areas are available from: Chief Directorate: National Geospatial Information. Guidance on how to identify and map the catchment of a wetland is provided in: Russel, 2009.

9.2.3 Step 3: Identify influence of groundwater or rivers

If the dominant wetland water source is potentially a stream, river or regional groundwater, the assessment and resulting conceptual model must be widened beyond these guidelines, which only consider hillslope interflow inputs. Substantive guidance on groundwater and river contributions is not in the scope of these guidelines.

Drawing from topographic maps, Google Earth and aerial imagery, as well as geological information for the area, identify the presence of rivers or streams flowing into the wetland. In the field, check the stream level relative to the prevailing wetland water level. Wetland water levels higher than stream level are more likely indicative of a hillslope contribution, and vice versa. Groundwater contribution to wetlands is difficult to verify without detailed investigation. Where possible, incorporate information on the depth to regional groundwater from a nearby borehole or geotechnical report. The presence of wetland field indicators signifying stable and sustained waterlogging (such as gleying or peat soils) may flag potential groundwater contribution, although these indicators may equally occur when groundwater is absent, driven rather by a favourable climate, the presence of downstream wetland controls, or several other factors.

References: Guidance related to identification of wetland water sources can be found in: Colvin et al., 2007; Ellery et al., 2009.

9.2.4 Step 4: Characterise the wetland catchment environment

Describe and map environmental properties such as geology, land cover and vegetation. Also provide long term average climatic parameters (at least rainfall).

9.2.5 Step 5: Identify representative hillslopes

9.2.5.1 Identify land types within the study area.

Identify land types (Land Type Survey Staff, 1972-2006) within the study area. If no existing hydropedological soil map is available, it is possible to approximate dominant responses through disaggregation of Land Type data (Van Zijl et al., 2013) **(NB this does not replace the hydropedological survey and the land type data has inherent flaws as discussed in Van Tol and Van Zijl, 2020).** The catena properties of the Land Type inventory makes them suitable for rapid identification of hydrological hillslopes from the inventory (Figure 9.1).

Reference: Approach to disaggregation of Land Type data is available in: Van Zijl et al., 2013.

9.2.5.2 Identify dominant hillslopes

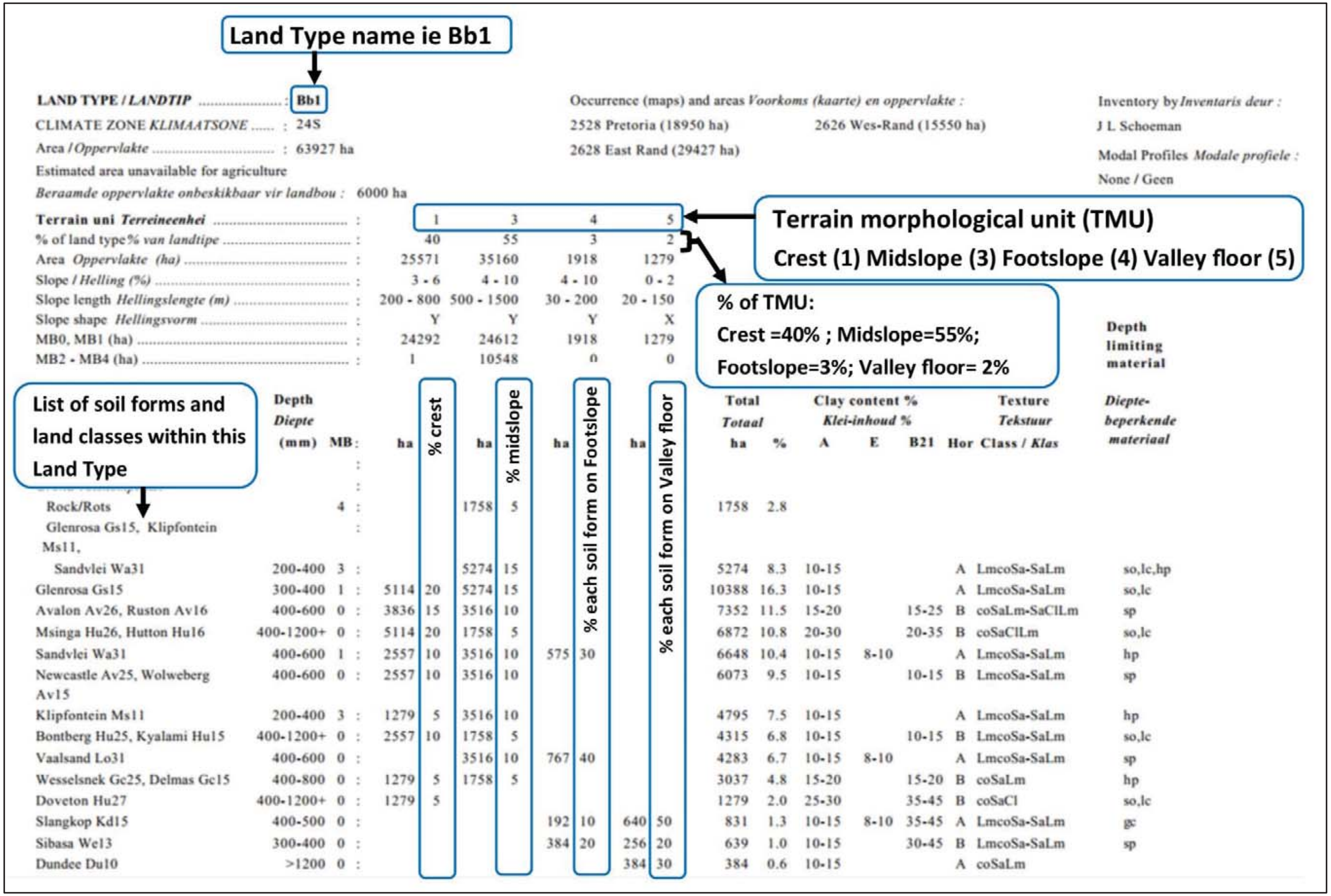
Identify dominant hillslopes (from crest to stream) of the study area using terrain analysis, for example, with software such as ArcGIS, SAGA or QGIS and the nationally available 30 m digital elevation model. For non-GIS users, it is possible to interpret contour lines of a hardcopy topographic map. There should be at least one hillslope in each land type of the study area. Hillslopes should be representative of the topography (e.g. slope, aspect and curvature) and land types. Where the site is divided by a stream, a representative hillslope should be identified on both sides of the stream.

The wetland catchment can be divided into morphologically similar hillslopes through applying the shape of the terrain morphological units (TMU)(see TERMS AND DEFINITIONS). These typically include crest, slope (upper, mid and foot) and valley floor, but may be further sub-divided. The relationship to hydrology can be further allocated to hillslopes according to the degree of soil development and wetness. Soils of the different TMUs can be assessed for the role they play in hillslope hydrology using soil morphological indicators. The impact of slope and relief should be taken into account (CHAPTER 6: and Table 9.1). Curvature from crest to valley bottom of the typical hillslope is expressed in the terrain sketch of the Land Type inventory (Figure 9.1). These are not to scale and are generalised for the whole area, thus need to be adjusted in the field for the specific site. The use of Land Type data is limited to desktop study and small-scale assessments, as the country is mapped on a scale of 1:250 000. The main value of Land Type maps is that the soils are allocated to terrain morphological units.

Table 9.1. Impact of slope shape on the interpretation of flowpaths

Profile curvature	Characteristics of soils	Typical flowpaths
Convex	Shallow soils, few horizons.	Recharge saprolite and fractured rock.
Concave	Receive water from up slope via fractured rock return flow. Deeper soils and more horizons. Redox morphology (increased wetness) down slope.	Preferable flowpaths return to saprolite, deep subsoils to shallow soil flow.
Straight	Moderate number of soil horizons.	Homogeneous diffuse flow, distributed through fracture system.

References: Selected terrain analysis and digital soil mapping references include: Jenness et al., 2013, Schoenenberger et al. 2005; Van Zijl et al., 2013.



LAND TYPE / *LANDTIP* .... : Bb1
CLIMATE ZONE *KLIMAATSONE* ...... : 24S
Area / *Oppervlakte* .... : 63927 ha
Estimated area unavailable for agriculture
Beraamde oppervlakte onbeskikbaar vir landbou : 6000 ha

Occurrence (maps) and areas *Voorkoms (kaarte) en oppervlakte :*
2528 Pretoria (18950 ha) 2626 Wes-Rand (15550 ha)
2628 East Rand (29427 ha)

Inventory by *Inventaris deur :*
J L Schoeman
Modal Profiles *Modale profiele :*
None / Geen

Terrain uni ***Terreineenhei***	1	3	4	5
% of land type *% van landtipe*	40	55	3	2
Area *Oppervlakte (ha)*	25571	35160	1918	1279
Slope / *Helling (%)*	3 - 6	4 - 10	4 - 10	0 - 2
Slope length *Hellingslengte (m)*	200 - 800	500 - 1500	30 - 200	20 - 150
Slope shape *Hellingsvorm*	Y	Y	Y	X
MB0, MB1 (ha)	24292	24612	1918	1279
MB2 - MB4 (ha)	1	10548	0	0

	Depth *Diepte* (mm)	MB	ha	%	ha	%	ha	%	ha	%	Total *Totaal* ha	%	Clay content % *Klei-inhoud %* A	E	B21	Hor	Texture *Tekstuur* Class / *Klas*	Depth limiting material *Diepte-beperkende materiaal*
Rock/Rots		4			1758	5					1758	2.8						
Glenrosa Gs15, Klipfontein Ms11, Sandvlei Wa31	200-400	3			5274	15					5274	8.3	10-15			A	LmcoSa-SaLm	so,lc,hp
Glenrosa Gs15	300-400	1	5114	20	5274	15					10388	16.3	10-15			A	LmcoSa-SaLm	so,lc
Avalon Av26, Ruston Av16	400-600	0	3836	15	3516	10					7352	11.5	15-20		15-25	B	coSaLm-SaClLm	sp
Msinga Hu26, Hutton Hu16	400-1200+	0	5114	20	1758	5					6872	10.8	20-30		20-35	B	coSaClLm	so,lc
Sandvlei Wa31	400-600	1	2557	10	3516	10	575	30			6648	10.4	10-15	8-10		A	LmcoSa-SaLm	hp
Newcastle Av25, Wolweberg Av15	400-600	0	2557	10	3516	10					6073	9.5	10-15		10-15	B	LmcoSa-SaLm	sp
Klipfontein Ms11	200-400	3	1279	5	3516	10					4795	7.5	10-15			A	LmcoSa-SaLm	hp
Bontberg Hu25, Kyalami Hu15	400-1200+	0	2557	10	1758	5					4315	6.8	10-15		10-15	B	LmcoSa-SaLm	so,lc
Vaalsand Lo31	400-600	0			3516	10	767	40			4283	6.7	10-15	8-10		A	LmcoSa-SaLm	sp
Wesselsnek Gc25, Delmas Gc15	400-800	0	1279	5	1758	5					3037	4.8	15-20		15-20	B	coSaLm	hp
Doveton Hu27	400-1200+	0	1279	5							1279	2.0	25-30		35-45	B	coSaCl	so,lc
Slangkop Kd15	400-500	0					192	10	640	50	831	1.3	10-15	8-10	35-45	A	LmcoSa-SaLm	gc
Sibasa We13	300-400	0					384	20	256	20	639	1.0	10-15		30-45	B	LmcoSa-SaLm	sp
Dundee Du10	>1200	0							384	30	384	0.6	10-15			A	coSaLm	

Figure 9.1. An example of a Land Type inventory (Land Type Bb1; Land Type Survey Staff, 1972-2006).

9.2.6 Step 6: Delineate wetlands in the field

Current legislation in South Africa requires that wetlands be identified and afforded specific protection measures. Wetlands occur where soil is saturated close to or at the surface for long enough to support a wetland ecosystem. Wetlands are identified through interpretation of the same set of pedofeatures that are used to identify flowpaths in hydropedology. They must, however, occur sufficiently close to the surface to influence the wetland ecosystem, in particular, the biota.

To document a wetland soil in the field, auger a hole and describe the soil profile, removing successive cores to a depth of approximately 50 cm. Describe successive cores in the same sequence as removed from the hole. Soil colour is quantified with a Munsell Colour Chart (Munsell Color Firm, 2010). For wetlands, the colour is most easily recorded in a moist state, with the addition of a few drops of water where necessary. Observe changes in soil colour and texture and presence of redoximorphic features, and record these in the datasheet (Figure 9.2), noting the depth at which each change occurred. Based on the completed soil morphology description, specify which, if any, of the soil indicators of wetland hydrology have been met. Deeper examination of soil may be required where field indicators are not readily apparent within 50 cm of the surface. It is always recommended that soils be excavated and described as deep as necessary to make reliable interpretations. It is often necessary to make exploratory observations to a depth of 1 m or more to understand the influence of underlying horizons and impermeable layers. These observations should be made with the intent of documenting and understanding the variability in soil properties and hydrologic relationships on the site, as significant changes in parent material or lithological discontinuities in the soil can affect its hydrological properties. As recommended by the USACOE (2006) methodology, once the number of exploratory observations are sufficient for an understanding of the soil-hydrologic relationships at the site, subsequent excavations may then be shallower if continued identification of appropriate indicators allow. The shape of the local landform can also affect the movement of water through the landscape and should be noted in the datasheet (see Step 5).

Internationally, a multiple parameter approach is applied when delineating wetlands, collecting information on hydrology, soil morphology and vegetation. Although vegetation is often the most readily observed parameter, *"sole reliance on vegetation or either of the other parameters as the determinant of wetlands can sometimes be misleading"* (USACOE, 1987). It is recommended that a datasheet (Figure 9.2) be filled out for each representative investigation plot, recording vegetation, soil, topography and visible hydrology. The presence of all three wetland hydrology indicators provides a logical, defensible and technical basis of evidence in support of the presence of wetlands. If possible, several non-wetland datasheet plots should also be prepared to further support the presence of wetland as distinguished from non-wetland characteristics on the site.

WETLAND DELINEATION DATA SHEET

Project/Site: ____________________ **Sample Plot #:** __________
Applicant/Owner: ____________________ **Sample Date:** __________
Investigator(s): ____________________ **GPS coordinates:** ____________________
Are normal circumstances present on the site? ☐ Yes ☐ No (explain) ____________________

Are climatic / hydrologic conditions on the site typical for this time of year? ☐ Yes ☐ No (explain) ____________

Is ☐ vegetation ☐ soil or ☐ hydrology significantly disturbed?

Is ☐ vegetation ☐ soil or ☐ hydrology naturally problematic?

SUMMARY OF FINDINGS *(attach a site map showing sampling points, transects, important features etc.)*

Hydrology indicators present? ☐ Yes ☐ No

Vegetation indicators present? ☐ Yes ☐ No

Soil morphology indicators present? ☐ Yes ☐ No **Therefore, is this sampling plot within a wetland? ☐ Yes ☐ No**

Remarks:

HYDROLOGY

☐ Inundated - Depth of inundation:__________cm ☐ dry season / ☐ rainy season
☐ Saturated - Depth to saturated soil:________cm Depth to free water:________cm
☐ Recent sediment deposits ☐ Salt crust ☐ Algal mat ☐ Aquatic invertebrates ☐ Water-stained leaves ☐ Water marks
☐ Shallow bedrock/dense clay/other impeding layer Depth to impeding layer: _____ cm
Landform (hillslope, basin, valley floor etc.):
Local relief (concave, convex, straight): ____________________Slope (%):______

VEGETATION INDICATOR

Dominant or indicator plant species within sample plot		**WIS**	**% Cover**
1 ______________________	OBL/FACW/FAC		
2 ______________________	OBL/FACW/FAC		
3 ______________________	OBL/FACW/FAC		
4 ______________________	OBL/FACW/FAC		
5 ______________________	OBL/FACW/FAC		
6 ______________________	OBL/FACW/FAC		
7 ______________________	OBL/FACW/FAC		
8 ______________________	OBL/FACW/FAC		

Are more than 50% of dominant species (> 50% cover) obligate, facultative wetland or facultative? ☐ Yes ☐ No

---

SOIL MORPHOLOGY INDICATOR *(this data sheet represents one soil plot and associated veg and hydrology)*

Depth (cm)	Horizon	Matrix colour (moist)	Redoximorphic features		Soil texture
			Colour	Abundance/Contrast	

Figure 9.2. Example of a wetland delineation datasheet.

References: DWAF, 2005; Kotze et al., 1996; USACOE, 2006; USDA-NRCS, 2010.

9.2.7 Step 7: Conduct hydropedology transect survey

9.2.7.1 Transect survey

Confirm hydrological hillslopes mapped on desktop. The wetland catchment may be made up of multiple hydrological hillslopes. Walk the wetland catchment to ensure a representative of each hydrological hillslope has been characterised. Make enough observations in the wetland catchment to ensure representation of hydrological hillslopes has been characterised.

- A transect soil survey should be conducted on each of the identified hillslopes (Step 5) (Le Roux et al., 2011).
- Soil observations should be made at regular intervals to capture the variation in topography and associated soil distribution.
- Profile pits[17] of representative soil forms should be opened to provide proper description, photographs and collection of undisturbed samples.
- Observation depth should be until refusal (soil/bedrock interface). Where the soil depth exceeds 2 m, auger observations must be made in the bottom of the pit in order to describe soil/saprolite/bedrock transition.

Soil maps are the basis of hydropedological interpretation. Basic soil formation leaves signatures representative of the general conditions of formation (CHAPTER 3:). These signatures are commonly used to infer soil conditions. In the field, soil properties are exposed in soil profile pits and with hand or mechanical augers. A transect from the hill crest to within the wetland is required. All pedofeatures, some of which are not diagnostic in the soil classification system, should be recorded in hydropedology surveys. Pedofeatures commonly include individual soil properties, e.g. soil texture, colour, etc., and combinations of properties, e.g. cutans, horizons and distribution patterns. Pedofeatures should be recorded at all depths and in all horizons. Depth to refusal, indications of deep flow, character of the soil/rock transition and signs of return flow must be recorded (irrespective of depth) to confirm the soil hydrological class. In the past, most soil maps were prepared with a depth limitation (only the top 1.2 m was investigated). However, in order to expose critical flowpaths, observations must reach refusal and the transition between soil and bedrock must be described adequately.

The transition to rock is important and the depth of this transition should be recorded. In aeolian, alluvial and colluvial deposits, and deep soils in moist areas, observation depth depends on site characteristics, but could extend beyond 2 m. If refusal is not reached, it must be taken into account during interpretation. Soil pits aim to expose soil to 1.5 m depth or refusal, with deeper observations continued with an auger.

[17] Soil auger observations can be used where it is not feasible to open profile pits in *Basic* assessments. Opening of profile pits are however strongly recommended.

9.2.7.2 Soil description and classification

Soils should be described and classified in accordance with the South African Soil Classification system up to family level (Soil Classification Working Group, 2018). The following morphological properties should be described:

- Thickness of horizons
- Structure (size, grade, type)
- Estimated texture
- Matrix Munsell colour (moist and dry)
- Mottles (colour, size, frequency, prominence and type)
- Concretions (colour, size, frequency, prominence and type)
- Precipitation of carbonates, gypsum or salts
- Roots (abundance)
- Macropores (frequency and size)
- Nature of transition between horizons/bedrock/saprolite

Reference: Methodology can be found for hydropedological surveys in: Le Roux et al., 2011; Van Tol et al., 2013b; Le Roux et al., 2015: Soil Classification Working Group, 2018.

9.2.8 Step 8: Conduct hydraulic measurements; *in-situ* and in lab

From the transect survey (Step 7), it is important to identify representative soil forms and horizons. This involves carefully observing and documenting the different soil types and their vertical arrangement along the transect. Once representative horizons have been identified, it is necessary to measure their soil physical and hydraulic properties using standard procedures. These measurements should encompass various factors, such as:

- **Particle size distribution:** Analyse the proportions of different particle sizes (e.g. sand, silt, clay) within the soil samples (The Non-affiliated Soil Analysis Work Committee, 1990).
- **Porosity/bulk density:** Using undisturbed core samples or clod method (see Section 10.2).
- **Hydraulic conductivity/permeability:** *In-situ* or on undisturbed core samples using for example the falling head method (Philip et al., 1992). This to assess the soil's ability to transmit water by measuring its conductivity or permeability and is also used to parameterise the hydrological model.

Subsequently, the measured soil properties should be related to the conceptualised hydropedological response model. This step involves establishing quantitative relationships between the measured properties and the expected flow rates and storage capacity within the soil system. By integrating the measurements with the hydropedological response model, a more comprehensive and quantitative description of flow rates and storage dynamics can be achieved. This enables a deeper understanding of how water moves through the soil, the rates at which it is transported, and the capacity of the soil to store water.

9.2.9 Step 9: Regroup soil observations into hydropedological groups

Following Steps 7 and 8, each soil profile should then be re-grouped into one of the nine hydropedological groups (CHAPTER 5:). To assign a hydrological soil type, soils are classified into hydropedological classes. For increased detail, the results can be improved further by applying the interpretation of individual diagnostic horizons (CHAPTER 4:). At an even higher level of detail, individual soil properties are interpreted. CHAPTER 5: provides a full list of South African soil forms and families, each allocated to one of the hydrological soil classes. If an existing soil map is already available, group the soil forms into hydropedological classes.

References: Further guidance on hydrological soil classes is available in CHAPTER 5:.

9.2.10 Step 10: Conceptualise hillslope hydropedological responses

The occurrence, sequence and coverage of the different hydropedological groups on a transect must then be used to describe the hydrological behaviour of the hillslope (CHAPTER 6:). A graphical representation of the dominant and sub-dominant flowpaths at hillslope scale prior to development. This could show:

- Overland flow.
- Subsurface lateral flow.
- Bedrock flow.
- Return flow.
- Storage mechanisms.

9.2.11 Step 11: Describe impacts on processes and wetland responses

Based on Step 10, the conceptual impact of the development on wetland and water resources should then be discussed in detail (CHAPTER 6:). The risk of different kinds of developments on different types of hillslopes are discussed in CHAPTER 7: (see Section 7.4 and especially Table 7.4). The impact of the proposed development on the hydropedological behaviour should also be graphically presented. This should typically include the location of the development on the hillslope and the anticipated impact of the development on water flows.

9.2.12 Step 12: Quantify hydropedological fluxes

Sections 10.3 and 10.4 emphasise the objectives and considerations when conducting modelling for hydropedological assessments. Hydropedological fluxes of water before and after development can be quantified using:

- Long term hydrometric measurements.
- Modelling/simulations of the hydropedological response.

When the fluxes will be quantified using modelling, it is important that the selected model is capable of reflecting hydropedological processes (especially lateral fluxes) at hillslope scale. Suggested models are:

- SWAT+ (Bieger et al., 2017; Van Tol et al., 2020a).
- Catchment Modelling Framework (Kraft et al., 2011; Van Tol et al., 2020b).

- Hydrus 2/3D for small hillslopes (Simunek et al., 2006; Van Zijl et al., 2020).

The model should be configured using the actual soil distribution and parameterised using measured properties (step 3) under realistic climatic scenarios. Model runs should include a pre-development set-up (baseline) as well as one or more runs where the proposed development is included in the model configuration (post-development). Post-development modelling should preferably consider more than one scenario such as different size buffers or more than one developmental layout.

Model outputs that should be considered and compared to the baseline include (but not limited to):

- Impact on streamflow.
- Impact on wetland water regimes.
- Impact on lateral flow to the wetland.
- Impact on overland flow and associated risk of water erosion.

See Section 10.5 for common mistakes made in modelling approaches and *mis*interpretations of modelling results.

References: Examples of hydropedological modelling: Van Tol et al., 2020a; Van Tol et al., 2020b; Van Zijl et al., 2020; Smit et al., 2023; Van Tol and Van Zijl, 2022; Smit and Van Tol, 2022; Harrison et al., 2022; Van Tol et al., 2021.

9.2.13 Step 13: Develop mitigation and management plans to reduce or avoid impacts

The foundation of mitigation and management plans should prioritise the preservation and assurance of hydropedological flowpaths to the wetland, endeavouring to keep them intact to the greatest extent possible. This will clearly necessitate site-specific recommendations. For instance, in a Class 12 hillslope where lateral flows predominate, residential development should contemplate using pillar foundations to minimise the disruption of the flowpath. Furthermore, expanding the buffer zone will help minimise impacts on the wetland hydroperiod.

Conversely, a Class 6 hillslope, characterised by wetland recharge through a bedrock flowpath, demands dedicated efforts to reduce surface sealing within the wetland catchment and to facilitate exfiltration from the soil into the fractured rock, maintaining the natural hydrological balance. Expanding the buffer zone in this type of hillslope is unlikely to yield significant benefits.

Collaboration with various experts, such as civil engineers and surface water hydrologists, is essential in the development of comprehensive mitigation and management plans. Maintaining the hydropedological integrity of the landscape opens new opportunities for bioengineering research and development that have not yet been fully capitalised upon.

CHAPTER 10: QUANTIFYING HYDRAULIC PROPERTIES AND MODELLING HYDROPEDOLOGICAL PROCESSES

10.1 INTRODUCTION

Developments that are expected to have significant impacts on wetland and water resources require a comprehensive hydropedological assessment (Van Tol et al., 2021a). The interpretation of morphological properties provides a qualitative conceptual understanding of flowpaths, connectivities, storage mechanisms, and hydroperiods of wetlands, as discussed in previous chapters. In order to fully assess the impacts of the development, it is necessary to quantify the hydraulic properties and flow rates, as they directly influence fluxes and hydrological processes. This quantification is crucial for understanding the magnitude of the development's effects on hydropedological processes. Ideally, such quantification would rely on long-term monitoring and measurements of water levels in various parts of the catchment and wetland. However, practical limitations, such as time and financial constraints, make continuous monitoring infeasible in most instances. Therefore, the quantification heavily relies on modelling to assess the impacts of the developments on hydrological processes.

10.2 QUANTIFICATION OF HYDRAULIC PROPERTIES

Quantifying hydraulic properties is essential for determining flow rates and setting parameters for hydrological models, as detailed in Section 3.3. When measuring these properties, it is important to consider representative horizons. The minimum set of measurements should include:

- **Particle size distribution:** This should be determined in a laboratory using standard methods such as the pipette or hydrometer method, based on Stokes Law. Field estimations of texture classes alone are not sufficient.
- **Bulk density:** Measurement should be conducted on undisturbed cores or undisturbed soil aggregates (clod method). Laboratory estimations based on disturbed samples or inferences from texture are generally unrealistic and should be avoided.
- **Saturated hydraulic conductivity:** Measurements should be conducted in-situ or on undisturbed core samples. Acceptable methods include the double ring constant- or falling head method, as well as geulph permeameter measurements.

Using PedoTransfer Functions (PTFs) derived from soil texture to estimate bulk density and saturated hydraulic conductivity results in considerable modelling errors (see CHAPTER 12:). While the absolute difference in generated streamflow may not be substantial, the processes through which water reaches the stream can differ significantly, leading to inaccurate process simulations.

Ideally, water retention characteristics, such as the *drained upper limit* (DUL) and *lower limit* (LL) of *plant available water* (PAW), should also be measured on undisturbed samples. These measurements are required by several hydrological models. DUL is similar to the concept of *field capacity*, while LL is similar to the *permanent wilting point*. The difference between these two represents the PAW. Additionally, measurements of flow rates and porosity should be used to improve the conceptual hydropedological response model by providing quantitative descriptions of flow rates and storage volumes.

10.3 OBJECTIVE OF MODELLING

In hydropedological assessments, the primary goal of modelling is to provide estimates of the impact of developments on hydropedological processes. The purpose is not to approve or disapprove the conceptual model derived from morphological properties. Instead, modelling should primarily be used to determine changes in hydrological processes associated with different land use scenarios. These scenarios typically include:

- **Before scenario:** This represents the hydrological response prior to development, serving as a baseline for comparison.
- **After scenario:** This quantifies the response based on a modelling setup that mimics the preferred development footprint. It allows for evaluating the specific impacts of the proposed development.
- **Alternative scenarios:** These scenarios reflect different development layouts or sizes of development footprints, enabling the assessment of different possibilities and their respective impacts.

Modelling also enhances our understanding of the relative importance of different water balance components, which may not always be apparent from soil morphology alone. For instance, in semi-arid to arid landscapes, evapotranspiration (ET) typically accounts for more than 70% of the water balance (approximately 90% in arid landscapes). On the other hand, lateral flows and water storage are subdominant processes that should be acknowledged and reported accordingly in the assessment.

By utilising modelling in hydropedological assessments, we can gain insights into the potential changes in water balance components and their relative significance, providing a more comprehensive understanding of the hydrological implications of the proposed developments.

10.4 SUITABLE MODELS

Given the dynamic nature of the modelling field, it is important not to enforce a specific software requirement[18]. However, certain minimum requirements should be considered when selecting suitable models for hydropedological assessments. These requirements include:

- **Process-based modelling:** Models should be based on well-defined processes to accurately represent the behaviour of the system.

[18] SWAT+, MikeShe, ACRU-Int, Hydrus 2D are examples of models meeting the minimum requirements for hydropedological assessments.

- **Soil routine based on solid soil hydraulic/physical properties and theories:** The model should incorporate reliable soil hydraulic and physical properties, such as hydraulic conductivity determining flow rates, porosity influencing storage, and the difference between drained upper limit and lower limit defining plant available water.
- **Multi-layered soil representation:** The model should capture the complexities of soil horizons by incorporating multiple layers that reflect key hydraulic soil properties and comprehensively represent the soil water balance. The model should not be limited to a fixed number of soil horizons but should realistically capture the actual horizonation.
- **Handling spatial heterogeneity:** The model should be capable of dealing with spatial variations in soil and land cover inputs and demonstrate sensitivity to changes in these inputs, allowing for realistic representation of spatial heterogeneity.
- **Simulating hydrological processes for different landscape elements:** The model should be able to simulate hydrological processes for various landscape features, including crest, midslopes, and wetlands, to capture the specific characteristics and behaviours of these elements.
- **Explicit reporting of lateral flows:** Lateral flows should be explicitly reported in the modelling outputs to account for their contribution to the overall hydrological processes.
- **Time scale:** The model should operate at a daily or smaller time scale to capture the temporal dynamics and variability of hydrological processes accurately.

By considering these minimum requirements, the selected model will be better equipped to provide reliable and comprehensive insights into the hydropedological processes associated with the developments being assesses.

10.5 INTERPRETATION OF MODELLING RESULTS

The interpretation of modelling results requires careful consideration. It is important to remember that the conceptual model is considered the basis of truth, and the objective of modelling is to provide a quantitative perspective on the concepts and determine the magnitude of the development's impact on hydropedological processes. The interpretation should align with the study's objectives, and the results can be presented as yearly or simulation period average (Table 10.1) or in smaller time-steps daily or monthly (Figure 10.1).

Table 10.1. Example of presenting modelling results as means over the simulation period.

	Before	After	% Change	% Water Balance
Rainfall	719.2	719.2		
Streamflow	234.2	202.5	-13.6	32.6
Overland flow	31.6	38.6	22.4	4.4
Lateral flow	202.7	163.8	-19.2	28.2
Percolation	72.5	59.6	-17.9	10.1
Evapotranspiration (ET)	409.5	456.8	11.5	56.9
Transpiration	377.3	225.2	-40.3	52.5
Evaporation	32.2	231.6	619.4	4.5
Potential ET	1796.6	1796.6		
Soil water				
Profile soil water	204.2	194.7	-4.7	
Topsoil water	22.3	20	-10	

Table 10.1 provides an example of the average impact of open cast mining on the water balance of a catchment. The “Before” and “After” scenarios represent different development scenarios, while “% Water Balance” indicates the relative importance of specific water components in relation to the total water balance. It is apparent that overland flow will increase by 22%, but the absolute increase is relatively small (7 mm). On the other hand, the change in evapotranspiration is small (11.5%) but accounts for 47 mm. Interpreting the modelling results should also be grounded in common sense. In the given example, the increase in overland flow occurs because the model assumes a bare surface for the open cast area.

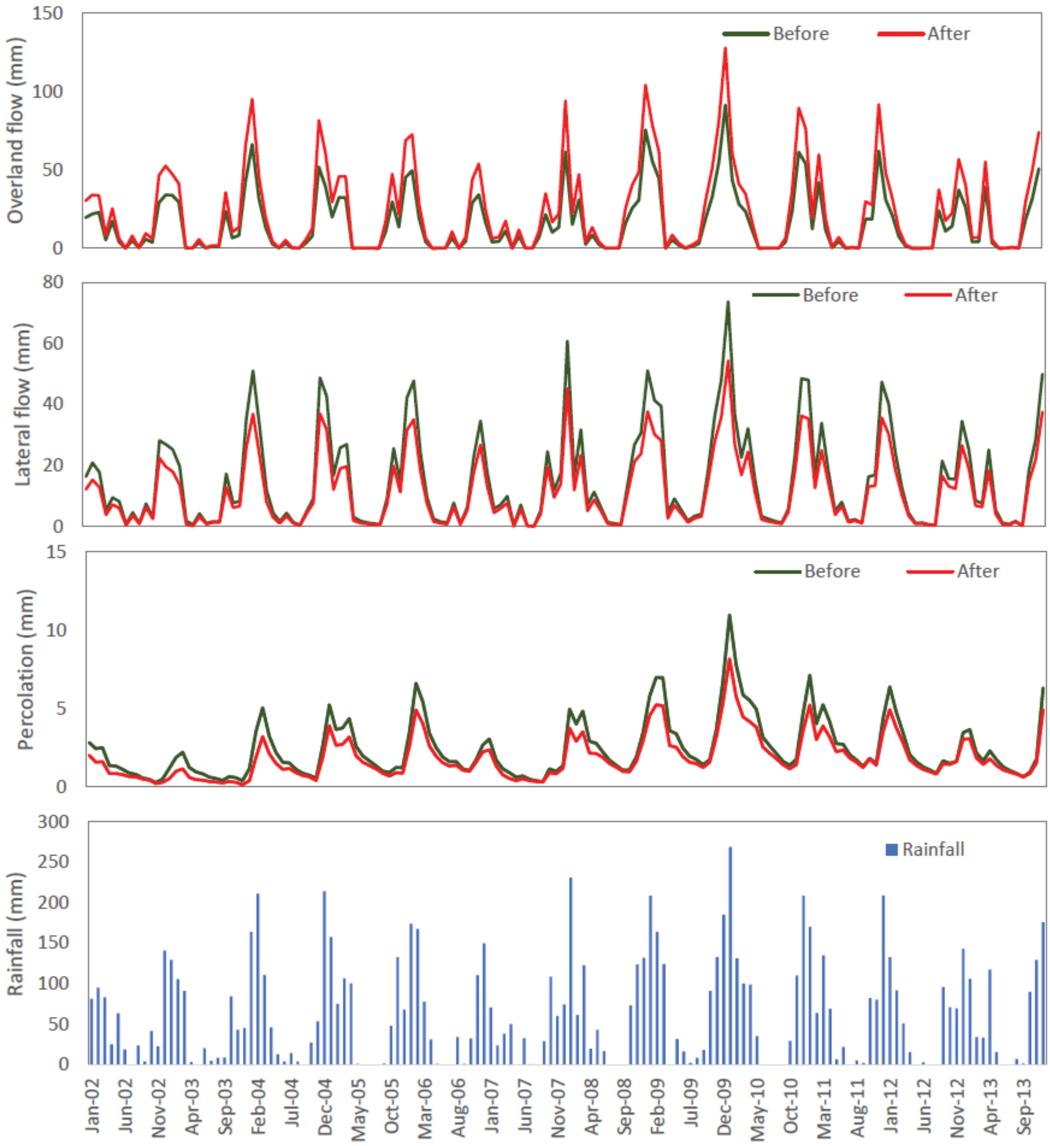


Figure 10.1. Example of a time-step representation of different water balance components obtained from the model.

When represented as a timescale, the differences and the reasons behind them become clearer. For example, in Figure 10.1, an excerpt from a study examining the impact of a residential development on hydropedological processes, it is evident that post-development, overland flow is higher compared to pre-development.

Furthermore, the magnitude of this impact is more pronounced during periods of high rainfall. The increased overland flow leads to reduced infiltration and diminished percolation to the groundwater.

10.6 KEY CONSIDERATIONS FOR HYDROPEDOLOGICAL MODELLING

It is important to reiterate that modelling provides supplementary information to the conceptual model and should not be considered as the primary output of the hydropedological assessment. The following points should always be kept in mind when setting up and reporting on modelling results:

- Ensure that the model setup accurately reflects the distribution pattern of soil and its associated parameters as defined by the conceptual model.
- Verify that the climate data used in the model is realistic. If inferred or downscaled data is employed, it should be cross-checked against measured data, especially for precipitation.
- It is expected that evapotranspiration will typically account for more than half of the water balance. If this is not the case, double-check the accuracy of the climate and vegetation data.
- Ensure an adequate simulation period, covering multiple seasons rather than focusing solely on isolated events.
- Allow for a sufficient warm-up period for the model, typically spanning at least one, but preferably two seasons.
- If the model has not been calibrated and evaluated against measured data, approach the simulations with caution and recognise their limitations.

In summary, when interpreting modelling results, it is crucial to consider the underlying conceptual model, present the results in a suitable format, and apply common sense to understand the implications of the findings in real-world scenarios.

CHAPTER 11: EXAMPLES OF HYDROPEDOLOGY IN PRACTICE

11.1 INTRODUCTION

This chapter provides practical examples of results obtained from hydropedological surveys conducted in various regions of South Africa. Due to confidentiality constraints, we refrain from providing exhaustive details about the specific sites and case studies. Instead, our focus lies on elucidating the soil morphology, soil distribution patterns, and the potential impact of development. The primary objective of this chapter is to underscore how hydropedological assessments and the resulting conceptual models of hillslope hydrology can effectively support and inform management decisions.

Three illustrative examples are employed: 1) open-cast mining, 2) residential development, and 3) a pollution study. These studies were integral components of consultancy projects, and we extend our gratitude to Digital Soils Africa for generously providing these examples. Notably, examples 1 and 3 are also featured in Van Tol et al., 2018, and we have utilised the conceptual model drawings from this publication.

11.2 EXAMPLE 1 – OPEN CAST MINING

In the first example, a coal mine in the Eastern Highveld of South Africa embarked on expanding their activities through a hillslope seep. The DWS wanted to know what the impact of mining through the hillslope seep will be on the water regime of a large valley bottom wetland of considerable local importance. A transect hydropedological survey was conducted and the pedosequence is presented in Figure 11.1.

11.2.1 Soil distribution and hydropedological response

Freely drained Hutton soils dominate the crest position and the absence of hydromorphic properties suggest that the underlying material is permeable and vertical drainage through and out of the profile is dominant (Figure 11.1-1 and Figure 11.1-A). These Hutton soils are *Recharge (deep)* soils. Downslope, grey low chroma colours and red and yellow mottles at the soil/bedrock interface of the Avalon soils indicates periodic saturation and a decrease in the permeability of the bedrock (Figure 11.1-1, B and i). These are *Interflow (soil/bedrock)* soils with lateral flow at the soil/bedrock interface dominating at this position. The lateral upslope contribution and shallower soil depth at profile C results in grey matrix colours close to the surface (Figure 11.1-3 and C) and the formation of Westleigh soils. They can hydropedologically be classified as *Interflow (shallow)* soils. As the storage capacity of this profile is exceeded water returns to the surface, visible as a hillslope seep with hydrophytic vegetation. Rusty root channels in a grey matrix are also present (Figure 11.1-ii), which can serve as an indication of long periods of saturation (Vepraskas, 2001).

Below the seepage zone, the soils also exhibit rusty root channels in a grey matrix (Figure 11.1-D and ii), however, hydromorphic indicators decrease with depth, with only red and yellow mottles in a yellow matrix present at the soil/bedrock interface (Figure 11.1-D and iii). The soils are also considerably deeper (>2 500 mm compared to 1 200 mm of profile C). The interpretation is that overland flow from the seepage face causes saturation in the topsoils (Figure 11.1-4), but only limited lateral contributions of water is received from upslope. Supporting evidence is the oximorphic nature of the Hutton soil in Figure 11.1-E. In the toeslope (Avalon in Figure 11.1-F) and valley bottom (Katspruit in Figure 11.1-G) grey matrix colours and yellow mottles are present (Figure 11.1-iv), indicating saturated conditions. Dark surface horizons in profile G signify the accumulation of organic material, which is typically an indication of anaerobic conditions in semi-arid areas (Vepraskas & Linbo, 2012). This is supported by a waterlogged profile, two weeks after opening (Figure 11.1-v). Since the soils in the valley bottom wetland is close to saturation, even small rain events might exceed the storage capacity of the soils and result in the generation of overland flow due to saturation excess.

In this hillslope, the soils of the lower slopes are fed by water from fractured rock flowpaths or groundwater and not through lateral draining vadose zone water originating from the crest and upper midslope positions.

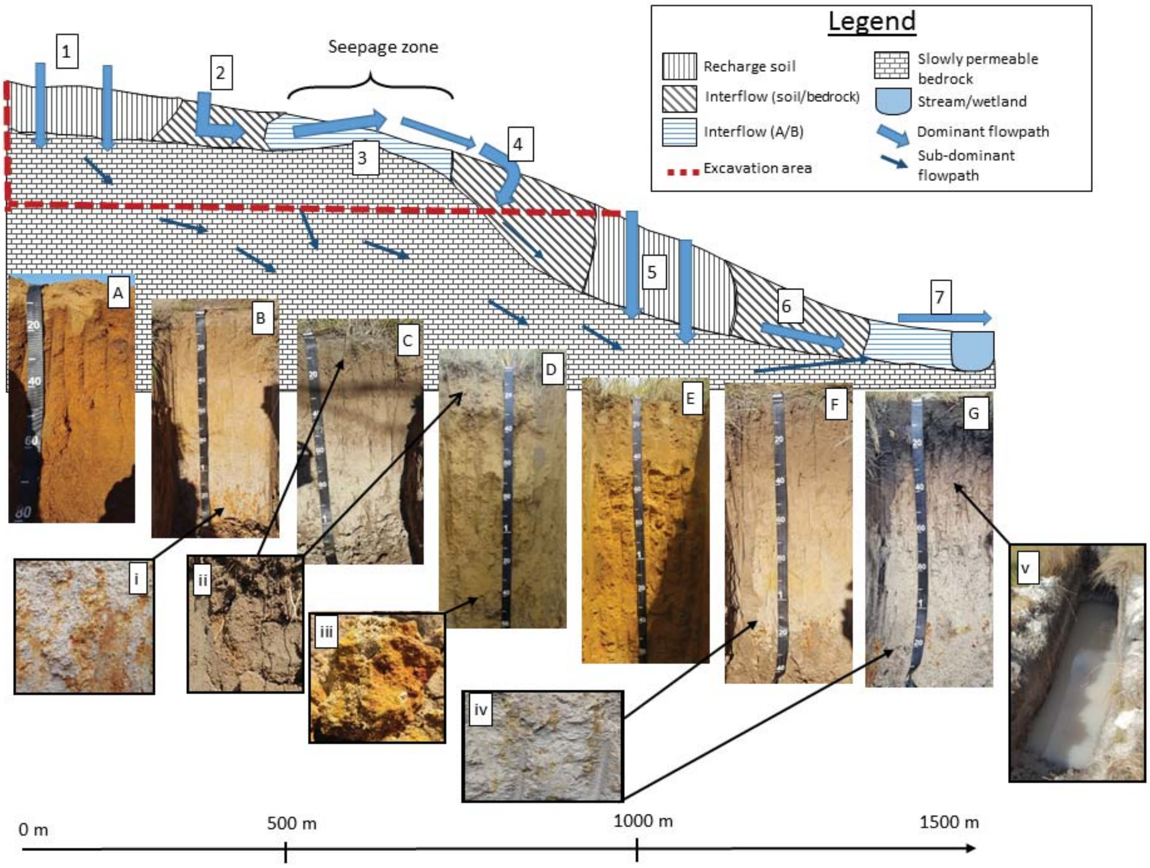


Figure 11.1. Pedosequence of representative soil profiles and their hydrolopedological behaviour of a hillslope in the Eastern Highveld of South Africa.

11.2.2 Implications for management

In this case, the hydropedological investigation indicates that mining through the seepage zone will not drastically impact the downslope wetland. For other sites with different dominant flowpaths, alternative measures such as buffer zones and artificial recharge areas will be necessary to preserve the wetlands. The identification of dominant flowpaths can be achieved through hydropedological assessments.

Aside from the evident loss of soil resources, the development will likely intersect flow paths and disrupt the hillslope seep. The impact on hydrological processes below the seep will largely depend on the depth of excavation. If the lower depth of excavation is above hydromorphic soils in the valley bottom, limited changes are likely to occur during 'normal' years. Open cast mines expose fractures in the bedrock, potentially supporting the generation of bedrock interflow.

The adverse impact of the development could be partially mitigated through the artificial maintenance of re-infiltration below the excavation (see Figure 11.1-4). This can be achieved by directing irrigation water into the open-cast area directly below the seepage zone. Extreme care should be taken to avoid erosion, and regular monitoring of water quality is essential to prevent further environmental degradation.

However, if the lower depth of excavation is deeper than the water level in the hydromorphic soils in the valley bottom (e.g. profiles F and G), the hydrology of the entire landscape will undergo significant changes. Instead of serving as a source of water for the valley bottom wetland, groundwater/fractured rock flowpaths will be reversed. This will ultimately lead to the drainage of the valley bottom wetland, drastically impacting the biodiversity of off-site streams.

In conclusion, based on the hydropedological interpretation of the soils and their spatial distribution, it is evident that the expansion of the open-cast mine will destroy the hillslope seep. However, it seems that the destruction of the seep zone will only locally impact hydrology, with limited changes to downslope landscape units or off-site streams if the depth of excavation is above the level of hydromorphic valley bottom soils. If the lower depth of excavation is deeper than the elevation of hydromorphic soils, the hydrological behaviour of the entire landscape will change, with reversed flowpaths due to groundwater level drawdown negatively impacting the wetland and streams.

11.3 EXAMPLE 2 – RESIDENTIAL DEVELOPMENT

A hydropedological assessment was undertaken to evaluate the potential impact of a planned urban development on a valley bottom wetland and prominent river in the Western Cape Province.

11.3.1 Hydropedological soil types

11.3.1.1 Responsive (saturated)

The hydropedological soil types identified as *Responsive (saturated)* included Katspruit soils featuring well-developed gley horizons within the valley bottom (Figure 11.2). During the on-site inspection, a water table was noted at approximately 1 600 mm. The source of saturation appeared to be seepage from the river rather than upslope contributions from hillslope water. This assertion is supported by the notable development of gleyed properties observed between SB1 and SB12. Notably, SB1, situated at the same elevation as the river, exhibited evidence of intense reduction, manifesting as prominent grey colours (Figure 11.2). These two profiles are in close proximity, but the distinct elevation of SB1 in relation to the river suggests that river water seeps into the profile. Responsive wet profiles, such as these, typically result in overland flow due to saturation excess.

Figure 11.2. *Responsive (wet)* soils represented by SB1 and SB12.

11.3.1.2 Recharge (deep) soils

The Addo/Augrabies soil association exhibits a sandy texture with lime accumulations extending from the neocarbonate horizon to the bedrock. While the neocarbonate horizon appears bleached when dry, it is likely a result of the light colour of the sandstone parent material rather than redoximorphic processes. Saturation evidence at the soil/bedrock interface was absent, except for a weakly developed plinthite horizon observed at >2 500 mm in SB2, possibly attributable to seepage from the river during extreme flood events.

The escalation of lime content in the deeper sections of the profile indicates that vertical flow through the profile is the prevailing process. The isotropic texture restricts lateral flow within the profile. Consequently, this serves as an illustration of a *Recharge (deep)* soil, where vertical water flow takes precedence (Figure 11.3).

In the northern part of the site (SB25), a single Fernwood soil form was identified. Albic horizons, typically associated with periodic saturation and lateral flow, are not mandatory for the formation of Fernwood soils, particularly those derived from light-coloured parent material (Van Tol et al., 2013a). In this context, the Fernwood soil is also categorised as a *Recharge (deep)* soil.

Figure 11.3. Recharge (deep) soils represented by the Addo/Augrabies soil forms.

11.3.1.3 Recharge (shallow) soils

The Coega soils found on the mid-slope and crest positions are characterised by calcareous rock and rocks exhibiting lime accumulations around the rock fragments (Figure 11.4). Notably, in certain areas, the rock outcrops on the surface form a continuous impermeable plate expanding over several meters (see SB7 in Figure 11.4). These zones function as *Responsive (shallow)* soils due to infiltration excess. In cases where a topsoil horizon has developed on these impermeable rocks, the soil can experience temporal or seasonal saturation due to inadequate external drainage, as evidenced by the frequent presence of *Eligia* species in these areas (SB9 in Figure 11.4).

Overland flow paths are confined to the impermeable rock areas, although fractured rock generally extends downslope from the solid outcrops (Figure 11.5). Infiltration of overland flowing water prevails in these regions. Morphologically, there is no evidence of prolonged periods of saturation, such as grey hydromorphic colours (note that the soils naturally have a bleached colour). The dominant flowpath involves vertical movement into the fractured rock, with limited lateral contributions from upslope. The absence of erosion gullies, even on steep slopes, lends support to the theory that overland flow is not predominant across this landscape.

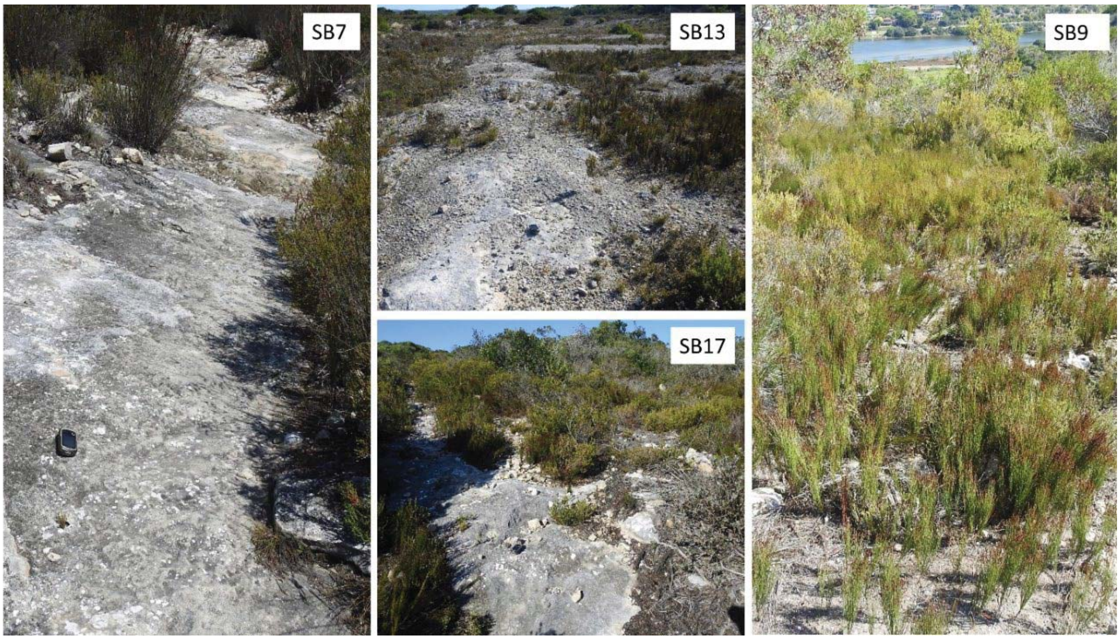


Figure 11.4. Solid carbonate and rock outcrops on the site, often frequented by *Elegia* species which occur on temporary to seasonally saturated areas.

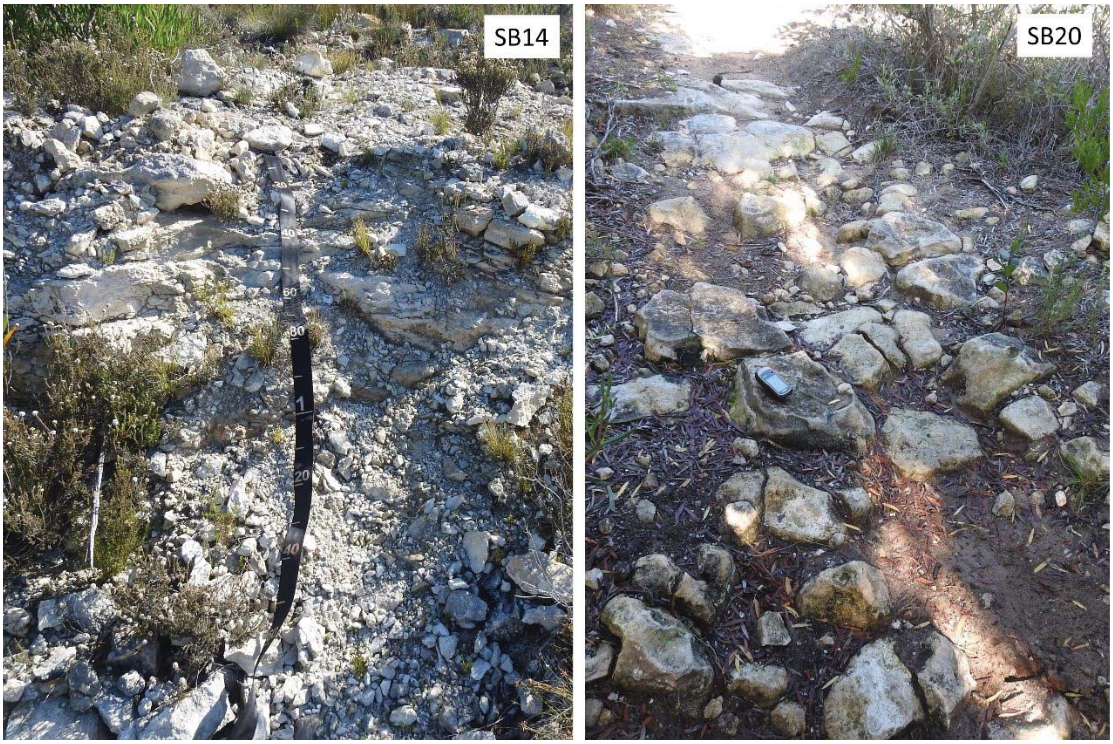


Figure 11.5. Example of fractured rock on the crest positions.

11.3.2 Hydropedological response

The site is located in an area with relatively low rainfall (<400 mm) and high potential evaporation (> 1 700 mm). This implies that most of the water will evaporate, hence the dominance of lime in the landscape. The remainder of the water will likely behave as discussed below.

Overland flow on rock outcrops is dominant on the crest and upper midslope positions. This water will however reinfiltrate into the fractured rock (Figure 11.6-1). In the footslopes, vertical drainage is dominant in the shallow and deep recharge soils (Figure 11.6-2). Vertical infiltration into the bedrock (Figure 11.6-3) and bedrock flow is possible. Overland flow on the footslopes (Figure 11.6-4), during peak rain events due to saturation excess is also likely. There is probably feedback between the river and the Katspruit soils in the valley bottom (Figure 11.6-5). The hydrological connectivity from the higher lying areas to the valley bottom is, however, not prominent as a significant gradient of increased wetness was not observed. The potential connectivity of the site to the river is limited to recharge via bedrock flowpaths (Figure 11.6-6); this is also a sub-dominant pathway.

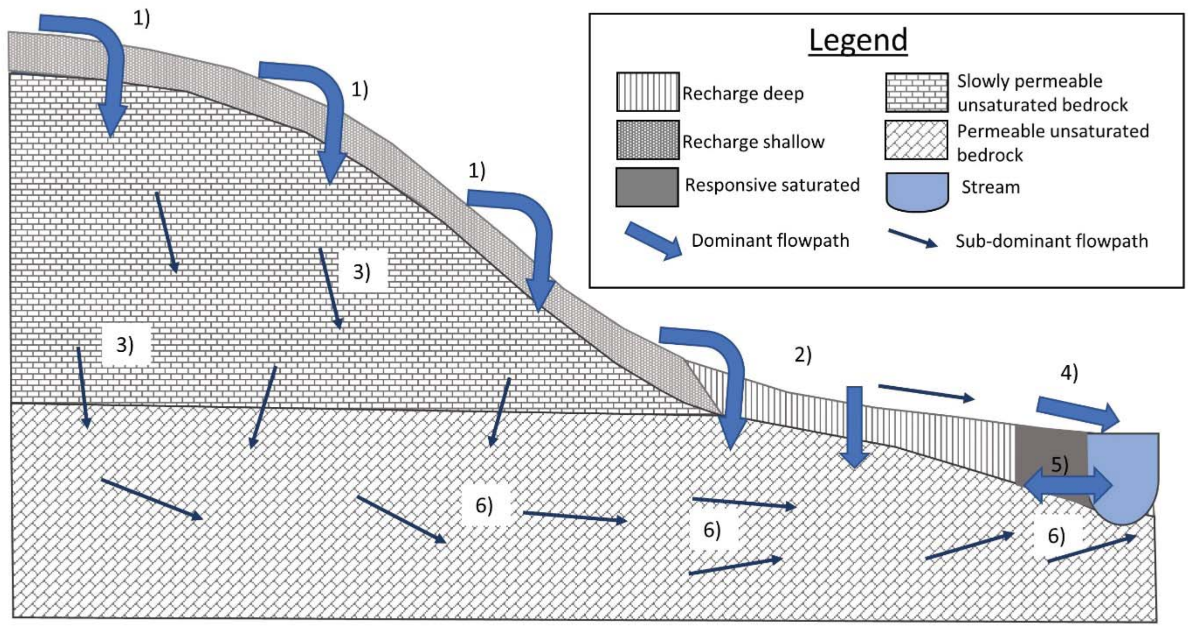


Figure 11.6. Simplified conceptual hydropedological response of the site (arrow number referred to in the text).

11.3.3 Recommendations and conclusions

The proposed development involves constructing residential properties and road infrastructure on the crest positions of the site. This will lead to surface sealing and subsequent overland flow. Notably, overland flow is already occurring on substantial portions of the crest and upper midslope positions. However, if the development permits infiltration into the fractured rock between surface-sealed areas, it is anticipated to have little impact on the hydropedological behaviour of the site.

11.4 EXAMPLE 3 – POINT SOURCE POLLUTION

In the Highveld of South Africa, a hydropedological assessment unveiled the traceability of contaminants (excessive Cl, Cu, Fe, and Zn) from a localised spill, mapped according to water flowpaths determined through interpretations of soil morphology and supported by selected hydraulic and chemical property measurements (see Figure 11.7). In the spill zone, Leptosols and Ferralsols, without any saturation indications (grey, low chroma colours, and redoximorphic mottles), suggested that vertical flow predominantly governed the flowpath in this region (Figure 11.7-A). Hydropedologically these are classified as *Recharge (deep)* soils. Auger observations and borehole logs, however, disclosed that the fractured rock solidified approximately 4 m below the surface, indicating likely lateral discharge on the fractured/solid rock interface (Figure 11.7-B). This was substantiated by the heightened presence of redoximorphic properties in downslope Plinthosols.

The gleyic horizons in the valley bottom signalled prolonged water saturation, likely sustained by a constant supply of water (and contaminants) from the fractured rock. This specific gleyic horizon, with a clay content of 53% and a Ks less than 0.5 mm.h-1, acted as a 'clay plug,' compelling lateral-flowing water upward (Figure 11.7-C). During the rainy season, the contaminant-rich water in the plinthic horizon resurfaces (Figure 11.7-D), triggering overland flow (Figure 11.7-E) and a decline in surface water quality. The hypothesis suggested that the gleyic horizon would adsorb some lateral-draining contaminants, making the transition between fractured rock and the gleyic horizon a 'hot-spot' for remediation efforts (Figure 11.7-F). Soil chemical analysis revealed elevated levels of Cu, Fe, and Zn in the gleyic and plinthic horizons. The hydropedological interpretation of soil morphology, coupled with soil hydraulic and chemical measurements, facilitated the identification of areas where phytoremediation and monitoring efforts should be concentrated and thereby assisted to protect downslope wetland and stream habitats.

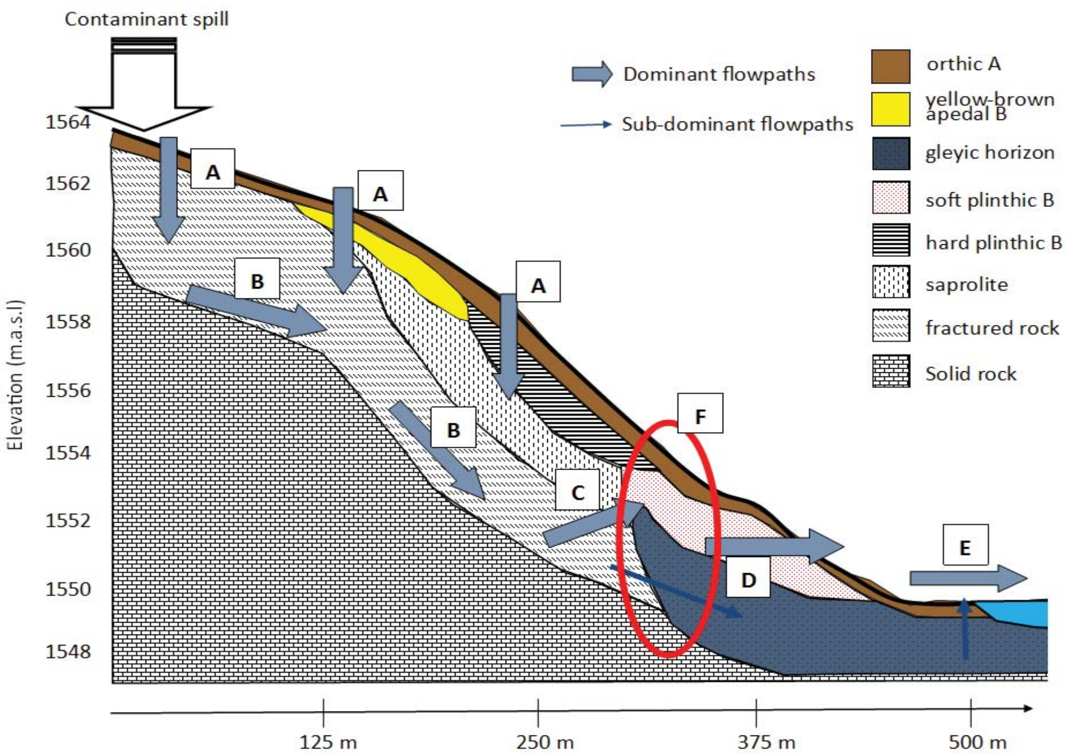


Figure 11.7. Conceptual hydrological flowpaths derived from a transect soil survey to determine the migration routes of pollutants.

CHAPTER 12: HYDROPEDOLOGY IN PRACTICE – QUESTIONS AND LESSONS

12.1 INTRODUCTION

Since the publication of the guidelines and minimum requirements for hydropedological assessments (Van Tol et al., 2021a), several consultants and officials have raised questions regarding the practicality of the guidelines. In this section, we address these practical questions that have emerged from discussions with consultants and draw upon the experience of the research team. We will typically focus on the minimum requirements and potential 'shortcuts' to effectively conduct the assessments while still ensuring the production of assessment reports of acceptable quality. Questions include:

- Can land type data alone be used for hydropedological assessments?
- Is it necessary to describe the soils down to the soil/bedrock interface or can the observation depth be limited to 1.5 m?
- Can existing PedoTransfer Functions (PTFs) be used instead of measured hydraulic property measurements to populate models?
- Is the 100 m spatial density of observations too excessive?

The focus of this section is to address these questions through scenario analyses of three case catchments namely the Weatherley catchment, Cosmo City and mining in Mpumalanga Highveld. The case studies are from different geographical areas and depict different potential land use changes. In the Weatherley catchment, grassland was converted to afforestation. In the Cosmo City case study, we look at the impact of urbanisation on water resources. The mining in Mpumalanga Highveld study, dates from a recent hydropedological assessment of the impact of open-cast coal mining on flowpaths were used (here we do not disclose the name of the mine although permission to use the data has been obtained).

Note: The case studies sites, model input parameters and modelling approach are described in detail in Van Tol et al., 2023. Here we only describe the different scenarios briefly, followed by the results and the implications for other hydropedological assessments.

12.2 WEATHERLEY RESEARCH CATCHMENT

12.2.1 Baseline model

For this case study, the hydropedological model presented in Van Tol et al. (2021b) was used as a baseline model. The hydrological model SWAT+ was used for the modelling with QSWAT+ (v.1.2.2) and the

SWAT+Editor (v.1.2.3) to set up the Weatherley catchment. The simulation period was from 1 January 1997 until 31 October 2006. A two-year warm-up period was allowed for the models to settle.

The catchment area was determined from a 30 m Digital Elevation Model (DEM) and subdivided into six sub-basins, with 63 Landscape Units (LSUs) and 286 Hydrological Response Units (HRUs) based on the soils and land use. The current land use was obtained from the South African National Land Cover Database (2013-2014). The land cover "wetland" was adjusted to the area covered by the Katspruit soils. Decision tables (Arnold et al., 2018), were used to convert the grassland to plantations during the model runs.

In the baseline model run, routing between HRUs to reflect the hydropedological understanding of flowpaths in the catchment was employed (Figure 12.1). This routing was adapted from and described in Van Tol et al. (2021b). The total flow (i.e. surface runoff and lateral flow) from *Recharge* soils was routed to the nearest, downslope *Responsive (wet)* soil (i.e. wetland). Lateral flow and 70% of the surface runoff from all the *Interflow* soils were routed to the adjacent downslope HRU, whilst the remainder of the surface runoff was routed to the nearest channel. For *Responsive (shallow)* soils, the total flow was routed to the adjacent downslope HRU. The total flow of the *Responsive (wet)* soils was allowed to flow into the nearest channel.

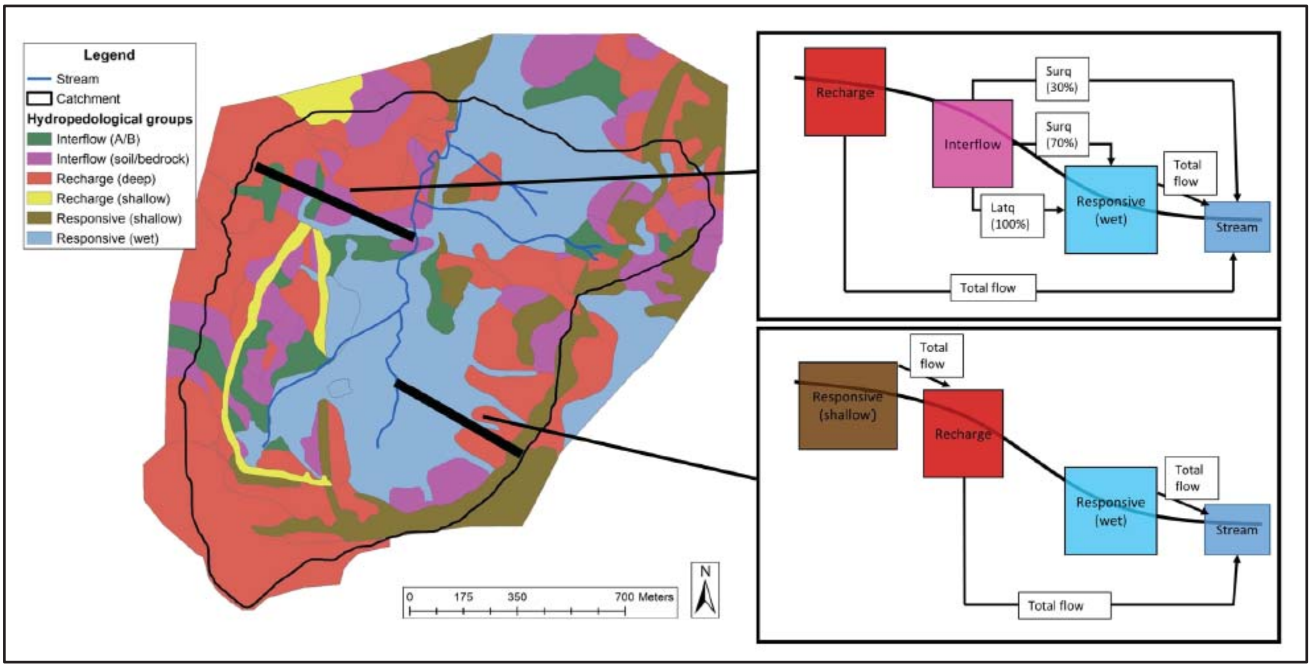


Figure 12.1. Distribution of hydropedological soil groups in the Weatherley catchment with typical routing in two hillslopes (Van Tol et al., 2021b). Latq = Lateral flow; Surq = Surface runoff.

12.2.2 Modelling scenarios

In the Weatherly research catchment we looked at four different scenarios:

> **Standard scenario:** This scenario used the same model inputs as the baseline run, except that the hydrologic routing between different HRUs were not employed.

1. **PTF scenario:** Soil inputs relying only on PTFs to parameterise soils. In this scenario, the assumption was that detailed measurements of soil hydraulic properties were not made, and that the surveyor relied on soil inputs obtained from PTFs only. Textural classes for the different horizons of Saxton and Rawls (2006) were used as inputs to the models. The parameters which were changed through this approach are the Bulk Density, the Available Water Capacity (AWC) and the saturated hydraulic conductivity.
2. **Land Type scenario:** Here we assumed that the surveyor did not visit the site but only used the land type database for the hydropedological assessment and as inputs to the model. Soil hydraulic inputs at land type level are currently the best available soil information for hydrological modelling which covers the whole of South Africa. Weatherley falls within Ac492, and this land type inventory was used to derive soil inputs.
3. **Shallow scenario:** Soil inputs where observation depth was limited to 1.5 m.

12.2.3 Results from Weatherley

Monthly total streamflow for the different model runs were compared to the measured flow at the catchments' outlet. For statistical comparisons of streamflow, we made use of widely used statistical indices namely coefficient of determination (R^2), the Root Mean Square Error (RMSE), Percent Bias (PBIAS), Nash-Sutcliffe efficiency (NSE) and the Kling-Gupta Efficiency (KGE).

The hydropedological approach markedly outperformed the other scenarios in the Weatherley catchment (Table 12.1). The *standard* and *PTF* simulations yielded acceptable NSE values according to the norms of Moriasi et al. (2007), but the PBIAS values were too low, i.e. streamflow was overestimated. Overestimation occurred in all the model runs (Figure 12.2), likely due to an underestimation of transpiration (Table 12.2). The *shallow* and *Land Type* scenarios yielded the highest R^2 values, but the PBIAS, NSE and KGE values were not acceptable. The worst model performance was obtained when only the Land Type soil information was used.

Table 12.1. Statistical indices of the accuracy of monthly streamflow simulations in Weatherley.

Scenario	R^2	RMSE	PBIAS	NSE	KGE
Hydropedology (baseline)	0.86	12.43	-21.56	0.82	0.71
Standard	0.84	18.11	-37.03	0.61	0.38
Shallow	0.87	21.13	-41.08	0.48	0.21
PTF	0.85	17.96	-38.57	0.62	0.35
Land Type	0.88	26.13	-46.23	0.20	-0.02

In terms of water balance components (Table 12.2), the *standard* scenario was most similar to the baseline. The absence of hydropedological routing did cause a considerable increase in percolation (96%) and overland flow (28%) when compared to the baseline. The same trends were observed when *PTF* derived soil information was used, but then the increases were more pronounced, 102 and 42% for overland flow and percolation, respectively. When limiting the depth of observation (*shallow* scenario), the transpiration is decreased and percolation drastically increased. Interestingly, the simulated overland flow also increased when using this soil data. With the *land type* data, most of the water balance components were grossly overpredicted when compared to the baseline data.

Soil water contents were underestimated for the *shallow* and *land type* scenarios. This is not necessarily a process error but is due to the limited soil depth assigned to the soils with these model setups. With the *standard* scenario, profile water contents were overestimated, and topsoil water contents were underestimated. The *PTF* scenario overestimated profile water contents whereas the topsoil water content simulations were comparable to the baseline.

Table 12.2. Average annual water balance components (mm) of the Weatherley catchment. % Difference refers to the change from the baseline.

Model runs	**Hydropedology (baseline)**	**Standard**		**Shallow**		**PTF**		**Land Type**	
Component			% Difference		% Difference		% Difference		% Difference
Rainfall	1012.3	1012.3		1012.3		1012.3		1012.3	
Streamflow	368.1	377.4	2.5	431.1	17.1	393.5	6.9	466.0	26.6
Overland flow	29.5	37.7	27.8	21.4	-27.2	59.3	101.5	58.1	97.3
Lateral flow	338.7	339.7	0.3	409.7	21.0	334.1	-1.3	407.8	20.4
Percolation	7.7	15.0	95.8	34.1	344.2	10.9	41.6	16.5	115.2
ET	631.4	614.8	-2.6	555.3	-12.0	615.9	-2.4	636.1	0.8
Transpiration	559.0	575.2	2.9	480.3	-14.1	527.6	-5.6	562.6	0.7
Evaporation	72.4	39.6	-45.2	75.0	3.5	88.3	22.0	73.5	1.5
ET0	1261.5	1261.5		1261.5		1261.5		1261.5	
Soil water contents									
Profile	255.6	298.2	16.7	80.6	-68.4	287.8	12.6	40.6	-84.1
Topsoil	22.1	17.2	-22.3	20.9	-5.7	22.7	2.6	13.3	-40.1

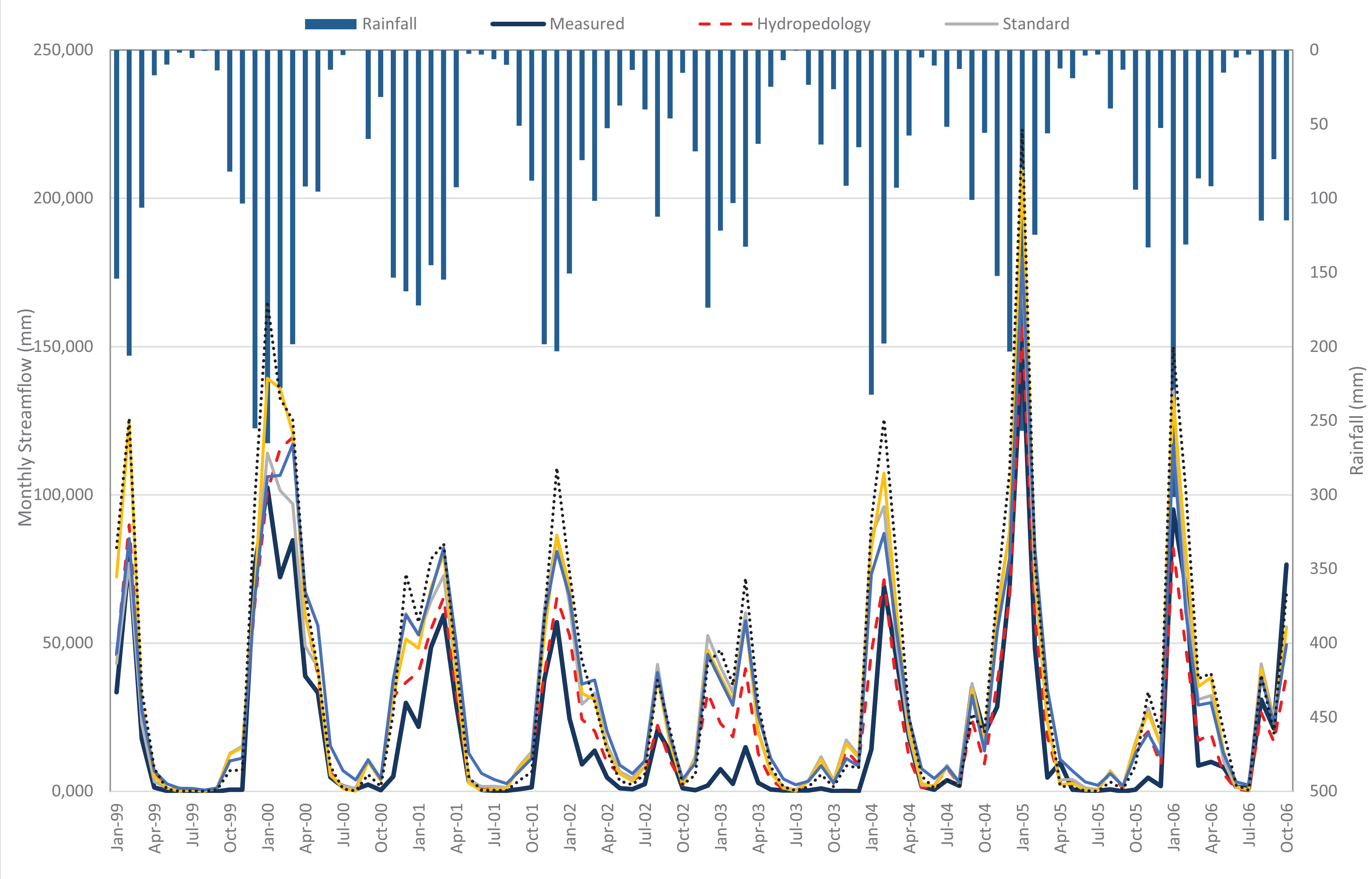


Figure 12.2. Monthly measured and simulated streamflow for the Weatherley catchment using different soil inputs.

From the Weatherley simulations, it is clear that the model is sensitive to soil inputs and that more detail yielded better simulations. Other studies confirmed the sensitivity of the SWAT model for soil inputs (Romanowicz et al., 2005; Geza and McCray, 2008). Ignoring hydropedological routing did sacrifice modelling accuracy but the changes in the water balance were relatively small. It also appears that using PTFs might yield acceptable simulation accuracy in terms of streamflow, but the internal catchment processes are not being reflected correctly. Limiting the soil observation depth to 1.5 m, caused a drastic overestimation in streamflow. In a recent study, Van Tol and Van Zijl (2022) also found that a shallow observation depth led to an overestimation in streamflow in three catchments in the KwaZulu-Natal midlands. The water balance components are also poorly reflected, especially in terms of the percolation and soil water content. The worst approach would be to use only the land type database to represent hydropedological processes. The underperformance of the land type dataset was also simulated in the Goukou catchment (Smit and Van Tol, 2022) and the Jukskei catchment (Van Tol et al., 2020a). The degree of error was, however, considerably smaller in these studies compared to the Weatherley results, presumably because the Goukou and Jukskei catchments were orders of magnitude larger than the Weatherley catchment.

12.3 COSMO CITY

12.3.1 Baseline model

In Cosmo City, the impact of urbanisation on hydrological processes was modelled. All the soil input scenarios were subjected to two different land cover inputs. The first was a *predevelopment* scenario where all the urbanised areas in the 2013/14 land cover were changed to natural grassland. In the *post-development* runs the current land cover as in the development layout was used. Simulation differences or errors are often more pronounced when scenarios of change are simulated (Van Tol et al., 2021b).

The Cosmo City catchment area was determined from a 30 m DEM and subdivided into three sub-basins. Land-cover was re-grouped into SWAT land uses with pre-defined parameters for each use. Soil information was obtained from the hydropedological survey of Van Zijl et al. (2020), which also presented appropriate hydraulic parameters.

12.3.2 Modelling scenarios

In Cosmo City we looked at three different scenarios:

1. **Standard scenario:** In this scenario, the routing between upslope and downslope LSUs were not employed. The model was run without routing between HRUs. Landscape connectivity was therefore limited. All the other inputs were the same as the *baseline.*
2. **Land Type scenario:** We assumed that the surveyor did not visit the site but only used the land type database for the hydropedological assessment and as inputs to the model. The Cosmo City catchment

lies predominantly in land type Bb1 with a small area in the north forming part of Bb2. The soil inputs for the two land types were very similar and the land type inventory was used to derive soil inputs.

3. **Simplification scenario:** In this scenario, we evaluated whether it is necessary to include the immense spatial detail in the soils as often presented in Digital Soil Maps. We simplified the soil inputs by using terrain units (TU) as boundaries for soil forms. The Tus were created by Van der Berg (2021) and differentiate between the crest, midslope footslope and valley bottoms.

These three scenarios were compared to the baseline model runs. In all the scenarios the models were run for both pre- and post-development land cover. In the absence of measured data, we only compared model outputs against the baseline without doing statistical analyses. The underlying assumption was that the model run with the most detail (i.e. the baseline) was most correct.

12.3.3 Results from Cosmo City

In Cosmo City, ignoring the hydropedological routing resulted in a considerable underestimation of overland flow, lateral flow, percolation and soil water contents (Table 12.3). By simplifying the soil inputs (*simple* scenario), the same trends as in the *standard* scenario were observed although not as pronounced.

Table 12.3. Average annual water balance components (mm) of the Cosmo City catchment prior to development. % Difference refers to the change from the baseline.

Model runs	Hydropedology (baseline)	Standard		Simple		Land Type	
Component			% Difference		% Difference		% Difference
Rainfall	616.0	616.0		616.0		616.0	
Streamflow	199.2	155.6	-21.9	162.8	-18.3	190.9	-4.2
Overland flow	31.2	22.1	-29.1	23.8	-23.8	3.3	-89.6
Lateral flow	168.0	133.5	-20.6	139.0	-17.2	187.7	11.7
Percolation	33.7	19.9	-41.0	19.4	-42.6	19.6	-41.7
ET	427.7	428.2	0.1	421.6	-1.4	398.9	-6.7
Transpiration	415.3	404.4	-2.6	409.2	-1.5	372.3	-10.3
Evaporation	12.4	23.8	91.9	12.4	-0.3	26.6	114.2
ET0	1779.0	1779.1		1779.1		1779.0	
Soil water contents							
Profile	81.6	71.6	-12.2	71.9	-11.8	32.4	-60.3
Topsoil	18.9	14.6	-22.6	18.3	-3.1	9.3	-50.5

The *land type* scenario yielded comparable streamflow predictions (-4.2% change), but the way that the water arrives at the stream is completely different from the baseline scenario. Overland flow was decreased by 90% and lateral flow increased by 12%. Soil water contents were grossly underestimated when using the land type dataset.

After converting the grassland to urban areas (Table 12.4), the differences between the *baseline, standard* and *simple* scenarios were relatively small. The only notable differences were the underestimation of percolation with the *standard* approach and the overestimation of topsoil water contents with the *simple* soil dataset. Both of these were, however, small fractions of the total water balance. The similarity between scenarios using the different datasets is likely due to the large areas which were urbanised. Overland flow is generated on these areas and hydropedological processes such as lateral flow and availing water for transpiration become less important. Scenarios using land type soil inputs still did not perform well, despite the relative uniformity in the land cover.

Table 12.4. Average annual water balance components (mm) of the Cosmo City catchment after urbanisation. % Difference refers to the change from the baseline.

Model runs	**Hydropedology (baseline)**	**Standard**		**Simple**		**Land Type**	
Component			% Difference		% Difference		% Difference
Rainfall	616.0	616.0		616.0		616.0	
Streamflow	262.4	253.7	-3.3	252.2	-3.9	271.3	3.4
Overland flow	184.8	178.9	-3.2	178.1	-3.6	168.3	-8.9
Lateral flow	77.6	74.8	-3.6	74.1	-4.5	103.0	32.7
Percolation	14.1	11.1	-21.4	14.1	0.0	12.2	-13.1
ET	345.7	343.9	-0.5	341.8	-1.1	328.2	-5.1
Transpiration	211.9	210.6	-0.6	214.6	1.3	195.4	-7.8
Evaporation	133.8	133.3	-0.4	127.2	-4.9	132.8	-0.7
ET0	1779.0	1779.0		1779.0		1779.1	
Soil water contents							
Profile	48.6	44.6	-8.3	47.2	-3.0	22.1	-54.5
Topsoil	11.3	11.2	-0.7	14.3	26.5	8.2	-27.2

Visual interpretation of monthly streamflow (Figure 12.3) supports what was observed in the summary of the water balance. Very little difference could be observed between the *hydropedological, standard* and *simple* scenarios. The only notable difference is that the scenarios using hydropedological routing provided water to the streams at the end of rainy seasons, whereas this ceased in the other model runs. The *land type* scenario tends to overestimate streamflow during wet periods and underestimate during dry spells. Similar results were reported by Smit and Van Tol (2022).

The difference in the *before* and *after* simulations using different soil input data is presented in Figure 12.4. Assuming that the baseline scenario is most correct, there is considerable deviation during wet periods when the land type data is used. The *simple* scenario yielded the most realistic streamflow predictions when compared to the baseline. During dry winter months, the hydropedological routing scenario resulted in decreased simulated streamflow. Before urbanisation, water could drain through the landscape and reach the stream several months after rains ceased. This is beautifully reflected in the *hydropedology* simulations but not as pertinent when using the other scenarios.

From the Cosmo City case study, we learned that the hydropedological routing is important to reflect flowpaths with long residence times which keep streams flowing and wetlands wet, long after rainfall ceased. It was also clear that the mechanism whereby streamflow is generated differs when using different datasets. As in Weatherley, the land type dataset is not recommended as the simulations deviated considerably from the baseline. A simplification of the soil information (*simple* scenario) did yield acceptable simulations. The dividends in streamflow prediction accuracy diminish with an increase in the catchment size. If the simplification is combined with hydropedological routing, it would most likely result in simulations which are comparable with the baseline, especially for larger hydropedological assessments.

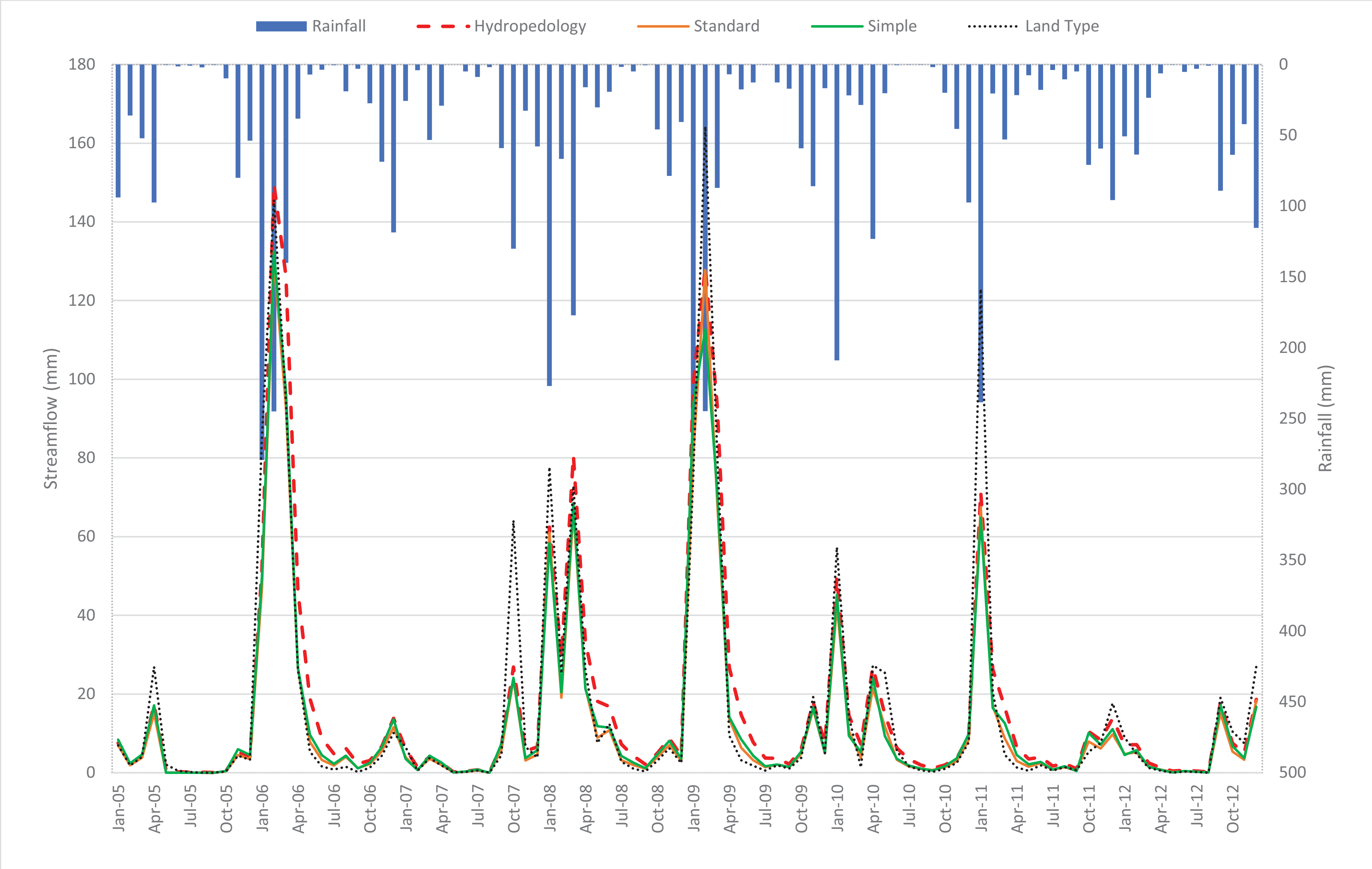


Figure 12.3. Monthly simulated streamflow for the Cosmo City catchment using different soil inputs.

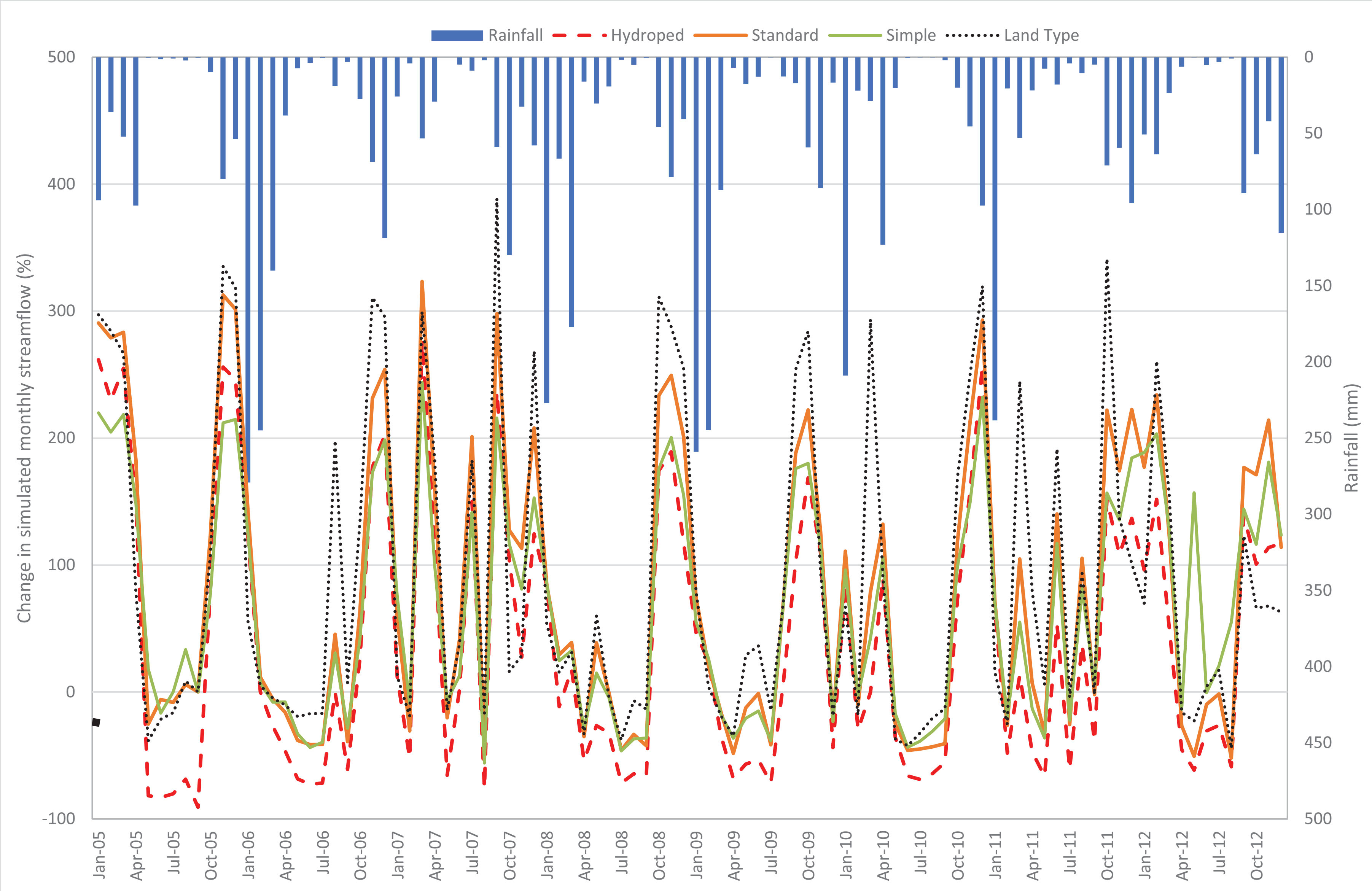


Figure 12.4. Difference (%) between *before* and *after* streamflow simulations using various soil inputs for the Cosmo City catchment.

12.4 MINING IN MPUMALANGA HIGHVELD

12.4.1 Baseline model

The catchment area (640 ha) was determined from a 30 m DEM and subdivided into 43 LSUs. The current land use was obtained from the South African National Land Cover Database (2013-2014) with predefined parameters for each of the uses. This current land use was used in the *before* scenario and the development layout, i.e. open-cast pits, were included as *mining (bare)* in the land use raster for the *after* simulation. There were 234 HRUs in the before simulation and 225 in the after simulation.

Digital Soils Africa conducted a hydropedological soil survey. The hydropedological groups of the survey were used as soil input data. The soil distribution patterns observed during the hydropedological survey were extrapolated to cover the area surrounding the proposed development. The close correlation between topographical attributes and soils, made it possible to use the terrain unit for mapping the soils. Hydraulic parameters were derived from *in-situ* and laboratory measurements of the dominant horizons.

A 13-year simulation period was selected (1998-2010). Climatic data for this period was obtained from the Climate Forecast System Reanalysis (CFSR, 1979-2014) project done by the National Centre for Environmental Prediction (NCEP) (Saha et al., 2010). WeatherGen in SWAT+ Editor used daily precipitation, temperature (minimum and maximum), wind speed, solar radiation and relative humidity from selected stations to generate daily climatic variables for the simulations. The model was allowed two years to settle.

12.4.2 Modelling scenarios

In the mining in the Mpumalanga Highveld case study, we looked at two soil input scenarios in addition to the baseline:

1. **Land Type scenario:** The assumption was that only land type data was available as soil inputs. The planned mining falls within land type Ba57, but data from Bb39 was also used to parameterise the model.
2. **PTF scenario:** The assumption was that measurements of soil hydraulic properties were not made, and that the surveyor relied on soil inputs obtained from PTFs only. Textural classes for the different horizons were used as inputs to the models of Saxton and Rawls (2006). The parameters which were changed through this approach are the Bulk Density, the Available Water Capacity (AWC) and the saturated hydraulic conductivity.

These scenarios were compared to the baseline model runs. In all the scenarios, the models were run for both pre- and post-development land cover. In the absence of measured data, we only compared model outputs against the baseline without doing statistical analyses. The underlying assumption was that the model run using the observed soil data (i.e. the *baseline*), was most correct.

12.4.3 Results from mining in the Mpumalanga Highveld

In the Mpumalanga Highveld site, streamflow in the baseline scenario before development is mainly generated through lateral flow (Table 12.5). Although the total volume of streamflow generated using the *PTF* scenario is comparable, overland flow is more pronounced. Using the *land type scenario* resulted in a simulated streamflow increase of 7%. The streamflow generation mechanism differed drastically, however, and most of the flow was from overland flow in the *land type scenario* (an increase of >900% when compared to the baseline). Simulated percolation increased when using the *PTF* scenario and there was a considerable decrease in simulated soil water contents. The *land type scenario* resulted in 50% underestimation of percolation and 15% underestimation of profile water contents, but a 16% overestimation of topsoil water contents.

Table 12.5. Average annual water balance components (mm) of the Mpumalanga Highveld site before mining. % Difference refers to the change from the baseline.

Model runs	**Hydropedology (baseline)**	**PTF**		**Land Type**	
Component			% Difference		% Difference
Rainfall	719.2	719.2		719.2	
Streamflow	209.0	200.7	-3.9	223.5	6.9
Overland flow	17.6	30.8	75.1	177.7	910.9
Lateral flow	191.4	170.0	-11.2	45.7	-76.1
Percolation	64.2	81.4	26.8	32.3	-49.7
ET	442.6	438.3	-1.0	464.4	4.9
Transpiration	358.2	369.0	3.0	339.7	-5.2
Evaporation	84.4	69.3	-17.9	124.7	47.7
ET0	1796.8	1796.8		1796.8	
Soil water contents					
Profile	183.3	147.5	-19.6	154.8	-15.5
Topsoil	32.4	12.1	-62.6	37.7	16.3

The differences in simulated streamflow between the *baseline, PTF* and *land type* scenarios were smaller in the post-development model runs (Table 12.6). Similar trends in over and underestimation of water balance components continued. For example, using the *land type scenario* resulted in 674% overestimation of overland flow and an underestimation of 47% in terms of percolation. When using the *PTF scenario*, overland flow was overestimated by 73% and percolation by 36% whilst topsoil water contents was underestimated by more than 62%.

Table 12.6. Average annual water balance components (mm) of the Mpumalanga Highveld site after mining. % Difference refers to the change from the baseline.

Model runs	Hydropedology (baseline)	PTF		Land Type	
Component			% Difference		% Difference
Rainfall	719.2	719.2		719.2	
Streamflow	193.8	191.9	-1.0	198.4	2.4
Overland flow	20.4	35.2	73.0	157.7	674.0
Lateral flow	173.4	156.7	-9.7	40.7	-76.5
Percolation	57.3	77.6	35.5	30.5	-46.8
ET	465.9	451.2	-3.2	491.8	5.6
Transpiration	299.5	310.3	3.6	280.2	-6.5
Evaporation	166.4	140.9	-15.3	211.6	27.2
PET	1796.7	1796.7		1796.7	
Soil water contents					
Profile	178.6	145.3	-18.6	147.6	-17.3
Topsoil	30.8	11.7	-62.2	33.7	9.2

Visual interpretation of simulated monthly streamflow indicates that the *land type scenario* overestimated streamflow during the wet spells and underestimated the flow during dry periods (Figure 12.5). This is due to the prominence of overland flow when the land type scenario is used. Using the *PTF scenario* resulted in an underestimation of peak flows during wet periods but was very comparable to the *baseline* scenario. It is again clear that the hydropedological routing resulted in prolonged flows after rainfall stopped.

The *land type scenario* resulted in the largest decline in streamflow generation following the open cast mining (Figure 12.6). This is probably because overland flow, the dominant flow mechanism in this scenario, accumulates in the mining area and is evaporated and does not contribute to streamflow. The high simulated evaporation (Table 12.6) supports this statement. The scenario using PTFs predicted the smallest difference between pre- and post-mining. In summary, decreases in streamflow of 7.9, 4.3 and 10.5% were predicted when the *baseline, PTF* and *land type scenarios* were used, respectively.

The mining in the Mpumalanga Highveld case study showed that different soil datasets and modelling approaches can result in comparable streamflow simulations. The mechanisms whereby the streamflow is generated can, however, differ substantially. From a management perspective, *how* water flows through the catchment might be more important than the quantity that flows over the weir at the catchment outlet. The simulations show that the *land type scenario* performed poorly when compared to the *baseline scenario*. This case study further showed that using the correct measured hydraulic parameters is important, especially in terms of soil moisture content simulations.

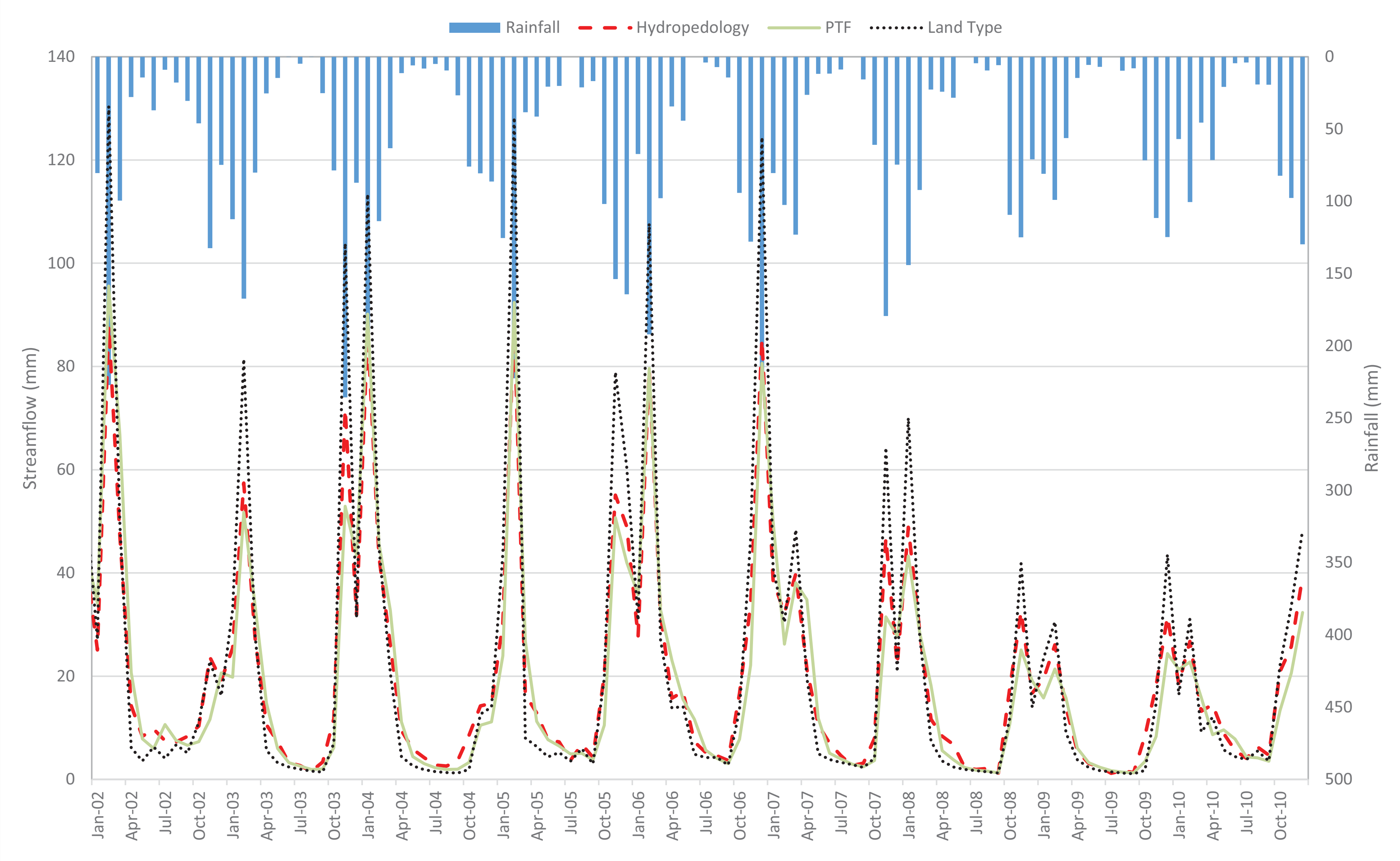


Figure 12.5. Monthly simulated streamflow for the Mpumalanga Highveld catchment using different soil inputs.

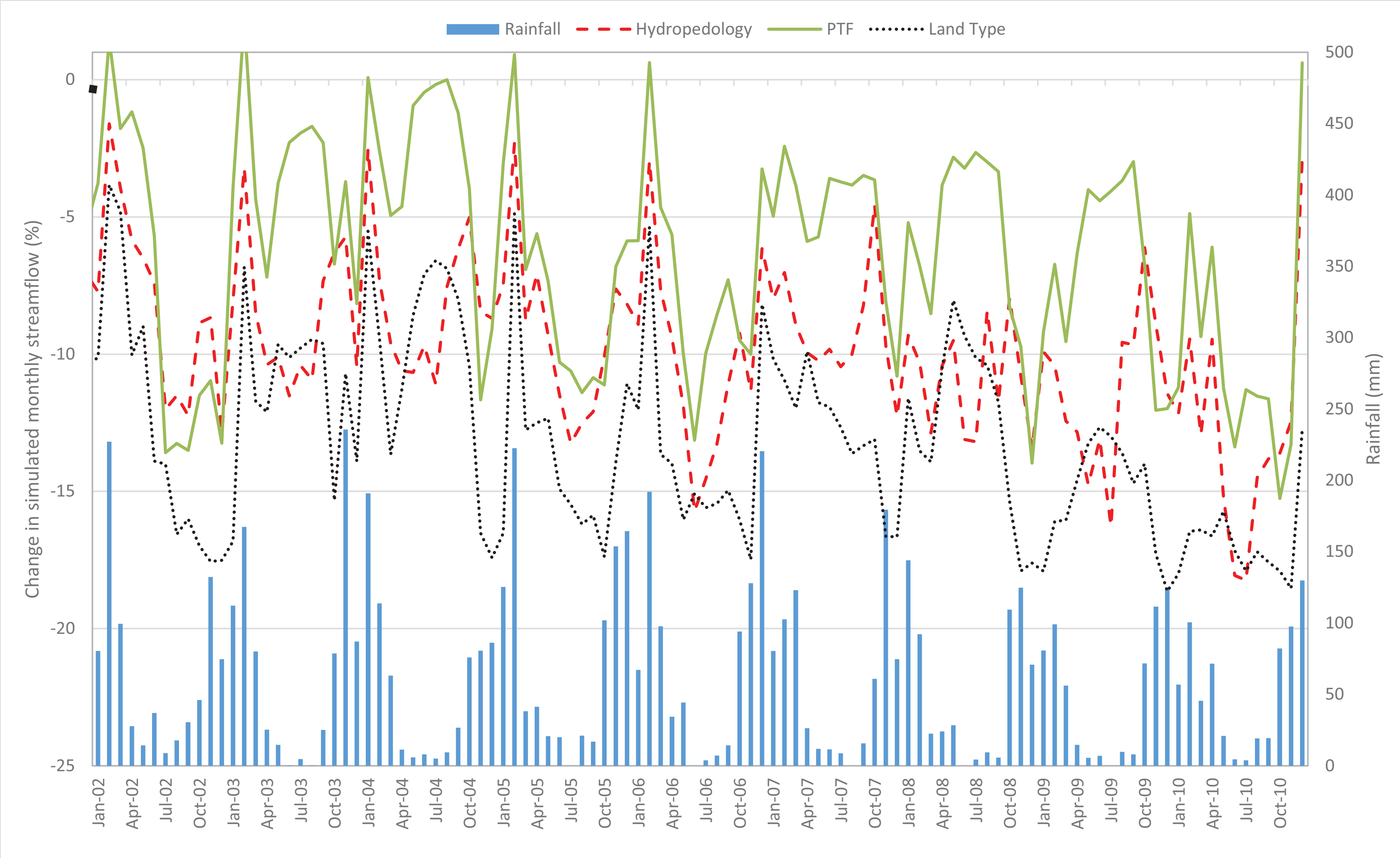


Figure 12.6. Difference (%) between *before* and *after* streamflow simulations using various soil inputs for the Mpumalanga Highveld catchment.

12.5 GENERAL CONCLUSIONS FROM CASE STUDIES

In this chapter we addressed four pertinent questions related to the hydropedological assessments:

1. Can land type data alone be used for hydropedological assessments?
2. Is it necessary to describe the soils down to the soil/bedrock interface or can the observation depth be limited to 1.5 m?
3. Can existing PedoTransfer Functions (PTFs) be used instead of measured hydraulic property measurements to populate models?
4. Is the 100 m spatial density of observations recommended in existing guidelines excessive?

Through scenario analysis and modelling of three case studies we are confident that these questions were addressed adequately:

1. Land type data alone cannot be used in hydropedological assessments. In all three case studies, using land type information alone yielded unrealistic water balance simulations when statistically compared with measured flow as well as comparisons with baseline simulations. Land type information is useful for identification of representative hillslopes and should assist with identification of appropriate delineation techniques for wetland assessments (Job and Le Roux, 2018). But the land type database in its current form is not suitable as model inputs for hydropedological assessments.
2. It is necessary to describe the entire soil profile up to the bedrock. The soil/bedrock interface is critical in generating lateral flows and if this transition is not described and characterised properly it might lead to misunderstanding of the dominant flow generation mechanisms. The model was also sensitive to soil depth as this determines the storage capacity of the catchment/hillslope, amount and rate of recharge as well as the amount of water available for transpiration.
3. Using PTFs for model parameterisation yielded acceptable simulations despite not using locally derived functions. Considerable deviations in the streamflow generation mechanisms and soil water content simulations were, however, observed. PTFs are generally only accurate in the areas where they were developed. In another WRC project, a specific objective is to develop regional PTFs for a range of hydraulic properties for model parameterisation. Until these are available, our recommendation would be to measure the relevant properties directly.
4. The 100 m observation depth is excessive, and the focus should rather be to make observations on different terrain units. Capturing the soil distribution patterns should be the main focus and, in a relatively small area, is mostly related to the topography. Vegetation differences can also serve as an indication of different water regimes and should therefore be considered when observation densities are determined.

CHAPTER 13: RECOMMENDATIONS FOR THE WAY FORWARD

During the development process, the project team presented drafts of the guidelines at various forums, including workshops and conferences, engaging stakeholders such as government officials from the DWS and the DFFE, as well as environmental impact practitioners and consultants. These guidelines received exceptional support, yet stakeholders have expressed three requests:

1. **Additional training:** The effectiveness of the guidelines developed in this project relies on the ability of decision makers to enforce them and consultants to apply them. While training courses are available for consultants and will be bolstered by the materials from this project, government officials often face challenges in accessing these resources. Future work should aim to provide in-house training to government officials from the DWS and DFFE in selected provinces to address this gap.
2. **Spatial layer:** Another challenge is the lack of a spatial layer indicating areas in South Africa where hydropedological surveys are necessary. This project provided a decision tree for determining the need and level of assessment, but the creation of a spatial layer that could be incorporated into the screening tool is still outstanding. This gap was identified as a pressing issue in stakeholder meetings. At the foundation of the spatial layer would be a map of hydropedological hillslope types. This could facilitate the processes to create regional wetland delineation guidelines.
3. **Additional applications:** Expand the guidelines to encompass advice for civil engineers (especially in road construction) and address water quality issues stemming from farming, infrastructure development, and waste management. Future work should strive to extend the guidelines to cover hydropedological assessments for pollution, engineering, modelling and other agricultural projects. Although the principles will be the same, discipline specific guidelines will increase the usability thereof.

REFERENCES

Alistoun, J., 2013. The origin of endorheic pans on the African Erosion Surface north of Grahamstown, South Africa. Unpublished MSc Thesis, Rhodes University, Grahamstown.

Adelana S, Xu Y, and Vrbka P., 2010. A conceptual model for the development and management of the Cape Flats aquifer, South Africa. Water SA 36: 461-471.

Amore, D.V.D., Stewart, S.R. & Huddleston, J.H., 2004. Saturation, Reduction, and the Formation of Iron-Manganese Concretions in the Jackson-Frazier Wetland, Oregon. *Soil Science Society of America Journal,* 68, 1012-1022.

Arnold, J.G., Bieger, K., White, M.J., Srinivasan, R., Dunbar, J.A. & Allen, P.M., 2018. Use of Decision Tables to Simulate Management in SWAT+. *Water*, 10, 713.

Asano, Y., Uchida, T. & Ohte, N., 2002. Residence times and flow paths of water in steep 127esources127i. *Journal of Hydrology,* 261, 5-7.

Atkinson, T.C., 1979. Techniques for measuring subsurface flow on hillslopes. In Kirkby, M. J. (Ed.), Hillslope Hydrology. Wiley, New York, 73-120.

Bachmair, S., Weiler, M. & Troch, P.A., 2012. Intercomparing hillslope hydrological dynamics: Spatio-temporal variability and vegetation cover effects. *Water Resources Research*, 48, doi:10.1029/2011WR011196

Bieger, K., Arnold, J.G., Rathjens, H., White, M.J., Bosch, D.D. & Allen, P.M., 2017. Introduction to SWAT+, a Completely Restructured Version of the Soil and Water Assessment Tool. *Journal of the American Water Resources Association,* 53, 115-130.

Bouma, J., 1983. Hydrology and soil genesis of soils with aquic moisture regimes. In L.P. Wilding, N.E. Smeck & G.F. Hall (eds.). Pedogenesis and Soil Taxonomy. I. Concepts and interactions. Elsevier, Amsterdam.

Bouwer, D., Le Roux, P.A.L., Van Tol, J.J. & Van Huyssteen, C.W., 2015. Using ancient and recent soil properties to design a conceptual hydrological response model. *Geoderma,* 241, 1-11.

Brady, R.C., Weil, N.C., 2016. The Nature and Properties of Soils. Pearson Education.

Bootsma, A., Elshehawi, S., Grootjans, A., Grundling, P-L., Khosa, S., Butler, M., Brown, L. and Schot, P., 2019. Anthropogenic disturbances of natural ecohydrological processes in the Matlabas mountain mire, South Africa. *S Afr J Sci*, 115, 5-6. Doi: 10.17159/ sajs.2019/5571

Brinkman, R., 1970. Ferrolysis, a hydromorphic soil forming process. *Geoderma*, 3, 199-206.

Brinson, M.M., 1993. A hydrogeomorphic classification for wetlands. Wetland Research Programme Technical Report WRP-DE-4. US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. Washington, DC.

Browne, M., Lorentz, S., Murugan, S. & Bredin, I. 2020. Watercourse Buffers in the Sugarcane Landscape: A Buffer Delineation Approach, Hydrological Simulation and Investigation of Costs and Benefits. Water Research Commission, Pretoria.

Buttle, J.M. & McDonald, D.J., 2002. Coupled vertical and lateral preferential flow on a forested slope. *Water Resources Research,* 38, 1-16. Doi:10.1029/2001WR000773

Colvin, C., Le Maitre, D., Saayman, I. & Hughes, S. 2007. Aquifer dependent ecosystems in key hydrogeological type settings in South Africa. WRC Report No. TT 301/07. Water Research Commission, Pretoria.

Cowden, C., 2011. Wetland Community of Practice: KZN. Mission Statement, Principles, Minimum Standards, Best Practice & Capacity Building.

Driessen, P. & Deckers, J., 2001. Lecture notes on the major soils of the world. http://www.fao.org/DOCREP/003/Y1899E/y1899e09.htm. (Retrieved 26/05/2008).

Du, E., Rhett Jackson, C., Klaus, J., McDonnell, J.J., Griffiths, N.A., Williamson, M.F., Greco, J.L. & Bitew, M., 2016. Interflow dynamics on a low relief forested hillslope: Lots of fill, little spill. *Journal of Hydrology*, 534, 648-658. Doi:10.1016/j.jhydrol.2016.01.039

Department of Water Affairs and Forestry (DWAF), 2005. A practical field procedure for identification and delineation of wetland and riparian areas. Department of Water Affairs and Forestry, Pretoria.

Edwards, R., 2009. The origin and evolution of Dartmoor Vlei in the KwaZulu-Natal Midlands, South Africa. MSc Thesis, University of KZN.

Ellery, W.N., Kotze, D.C., McCarthy, T.S., Tooth, S., Grenfell, M., Beckedahl, H., Quinn, N. & Ramsay, L., 2009. The origin and evolution of wetlands. Water Research Commission, Pretoria.

Ellis, F., 1988. *Die gronde van die Karoo (The soils of the Karoo).* PhD thesis, Stellenbosch University, Stellenbosch.

Fanning, D.S. and Fanning, M.C.B., 1989. Soil morphology, genesis and classification. John Wiley and Sons Inc.

FAO, 2006. *Guidelines for soil description.* Rome. Doi:10.2165/00115677-199701040-00003

Fey, M., 2010. Soils of South Africa. Their distribution, properties, classification, genesis, use and environmental Significance. Cambridge, New York.

Fiedler, S. & Sommer, M., 2004. Water and redox conditions in wetland soils—their influence on pedogenic oxides and morphology. *Soil Science Society of America Journal* 68(1) DOI: 10.2136/sssaj2004.0326

Freer, J.E., Beven, K.J., McDonnell, J.J. & Peters, N.E., 2002. The role of bedrock topography on subsurface stormflow. *Water Resources Research,* 38, 1-16. Doi:10.1029/2001WR000872

Geza, M., & McCray, J.E., 2008. Effects of soil data resolution on SWAT model stream flow and water quality predictions. *Journal of Environmental Management.* 88, 393-406.

Graham, C.B., McDonnell, J.J. & Woods, R., 2010. Hillslope thresholds response to rainfall: (1) a field based forensic approach. *Journal of Hydrology,* 393, 65-76.

Grenfell, S., Grenfell, M., Ellery, F., Job, N. and Walters, D., 2019. A genetic geomorphic classification system for southern African palustrine wetlands: global implications for the management of wetlands in drylands. *Frontiers in Environmental Science*. 7:174. Doi: 10.3389/fenvs.2019.00174

Grundling, P., Grootjans, A.P., Price, J.S. & Ellery, W.N., 2013. Development and persistence of an African mire: How the oldest South African fen has survived in a marginal climate. *CATENA*, 110, 176-183. Doi : 10.1016/j.catena.2013.06.004.

Harrison, R.L., Van Tol, J.J. & Toucher, M., 2022. Using hydropedological characteristics to improve modelling accuracy in Afromontane catchments. *Journal of Hydrology: Regional Studies.* https://doi.org/10.1016/j.ejrh.2021.100986

Hayes, W.A. & Vepraskas, M.J., 2000. Morphological changes in soils produced when hydrology is altered by ditching. *Soil Science Society of America Journal* 64(5), 1893-1904.

Helme, N. and Desmet, P.G., 2006. A description of the endemic flora and vegetation of the Kamiesberg Uplands, Namaqualand, South Africa. Report for CEPF/SKEP.

Hughes, D.A. & Sami, K., 1993. The Bedford Catchments. An introduction to their physical and hydrological characteristics. Report No.235/2/93. Water Research Commission, Pretoria.

Jackson, C.R. 2005. A conceptual model for characterizing hillslope hydrologic behavior between the bookends of 100% vertical percolation and 100% interflow. Poster. IAHS SLICE workshop, September 25-28, H.J. Andrews Experimental Forest, OR.

Jenness, J., Brost B. & Beier, P. 2013. Land Facet Corridor Designer: Extension for ArcGIS. Jenness Enterprises. Available at: http://www.jennessent.com/arcgis/land_facets.htm

Jennings, K., 2007. Effect of varying degrees of water saturation on redox conditions in a yellow brown apedal B soil horizon. Unpublished MSc thesis. University of Free State, Bloemfontein.

Jennings, K., Le Roux P.A.L., Van Huyssteen C. W., Hensley M. & Zere, T.B., 2008. Redox behavior in a soil of the Kroonstad form in the Weatherley catchment, Eastern Cape Province. *South African Journal of Plant Soil,* 25 (4) 204-213.

Job, N., 2008. Report on the application of the Department of Water Affairs and Forestry wetland delineation method to wetlands of the Western Cape. Report No. K8-718. Water Research Commission, Pretoria.

Job, N.M., 2014. Geomorphic origin and dynamics of deep, peat-filled, valley bottom wetlands dominated by palmiet (*Prionium serratum)* – a case study based on the Goukou Wetland, Western Cape. Unpublished MSc thesis. Rhodes University, Grahamstown.

Job, N., Mbona, N., Dayaram, A. & Kotze, D., 2018. *Guidelines for mapping wetlands in South Africa*. SANBI Biodiversity Series 28.

Job, N.M., Le Roux, P.A.L., Turner, D.P., Van der Waals, J.H., Grundling, A.T., Van der Walt, M., de Nysschen, G.P.M. & Paterson, D.G., 2018. Improving the management of wetlands by including hydropedology and land type data at catchment level. *WRC Report No. 2461/1/18,* Water Research Commission, Pretoria, South Africa.

Kelbe B.E., Grundling A.T., Price J.S., 2016. Modelling water-table depth in a primary aquifer to identify potential wetland hydrogeomorphic settings on the northern Maputaland Coastal Plain, KwaZulu-Natal, South Africa. Hydrogeol J. DOI 10.1007/s10040-015-1350-2.

Kim, H.Y., Sidle, R.C. & Moore, R.D., 2005. Shallow lateral flow from a forested hillslope: Influence of antecedent wetness. *Geoderma* 60, 293-306

Kraft, P., Vaché, K.B., Frede, H.-G. Breuer, L., 2011. A hydrological programming language extension for integrated catchment models, *Environmental Modelling Software,* doi: 10.1016/j.envsoft.2010.12.009

Kotze, D.C., Klug, J.R., Hughes, J.C., Breen, C.M., 1996. Improved criteria for classifying hydric soils in South Africa. *South African Journal of Plant and Soil,* 13(3): 67-73, DOI: 10.1080/02571862.1996.10634378.

Kuenene, B.T., Van Huyssteen, C.W., Le Roux, P.A.L. & Hensley, M., 2011. Facilitating interpretation of the Cathedral Peak VI catchment hydrograph using soil drainage curves. *South African Journal of Geology,* 114, 525-234.

Kuenene, B.T., Van Huyssteen, C.W. & le Roux, P.A.L., 2013. Selected soil properties as indicators of soil water regime in the Cathedral Peak VI catchment of KwaZulu-Natal, South Africa. *South African Journal of Plant and Soil* 30(1): 1-6.

Kutílek, M., 1966. Soil Science in Water Management. SNTL, State Publisher of Technical Literature, Prague. 275 pp. (In Czech: Vodohospodarska Pedologie).

Kutílek, M., 2004. Soil hydraulic properties as related to soil structure. *Soil Tillage Research,* 79, 175-184. Doi:10.1016/j.still.2004.07.006.

Kutílek, M. & Nielson, D.R., 2007. The interdisciplinarity of hydropedology. *Geoderma,* 138, 252-260.

Land Type Survey Staff, 1972-2006. *Land types of South Africa:* Digital map (1:250 000 scale) and soil inventory datasets. ARC-Institute for Soil, Climate and Water, Pretoria.

Le Roux, P.A.L., 1996. *Nature and occurrence of redoximorphic soils in South Africa.* Ph.D. in Soil Science. University of the Free State, Bloemfontein.

Le Roux, P.A.L., Du Preez, C.C. & Buhmann, C., 2005. Indications of ferrolysis and structure degration in an Estcourt soil and possible relations with plinthite formation. *S. Afr. J. Plant Soil* 22, 199-205.

Le Roux, P.A.L., Ellis, F., Merryweather, F., Schoeman, J.L., Snyman, K., Van Deventer P.W. & Verster, E. 1999.Guidelines for the mapping and interpretation of the soils of South Africa. Unpublished report. University of the Free State, Bloemfontein.

Le Roux, P.A.L., Van Tol, J.J., Kunene, B.T., Hensley, M., Lorentz, S.A., Van Huyssteen, C.W., Hughes, D.A., Evison, E., Van Rensburg, L.D. & Kapangaziwiri, E., 2011. Hydropedological interpretation of the soils of selected catchments with the aim of improving efficiency of hydrological models: WRC Project K5/1748. Water Research Commission, Pretoria.

Le Roux, P.A.L., Hensley, M., Lorentz, S., Van Tol, J.J., Van Zijl, G.M., Kuenene, B.T., Bouwer, D., Freese, C.S., Tinnefeld, M. & Jacobs, C.C., 2015. HOSASH: Hydrology of South African Soils and Hillslopes. WRC Report No. 2021/1/15. Water Research Commission, Pretoria.

Lin, H.S., 2003. Hydropedology: bridging disciplines, scales, and data. *Vadose Zone Journal,* 2, 1-11.

Lin, H.S., Kogelman, W., Walker, C. & Bruns, M.A., 2006. Soil moisture patterns in a forested catchment: A hydropedological perspective. *Geoderma* 131, 345-368.

Lin, H.S., Brooks, E.S., McDaniel, P. & Boll, J.A.N., 2008. Hydropedology and Surface / Subsurface Runoff Processes, in: Anderson, M.G. (Ed.), *Encyclopedia of Hydrological Sciences*. John Wiley & Sons, pp. 1-25.

Lin, H.S., 2010. Linking principles of soil formation and flow regimes. *Journal of Hydrology,* 393, 3-19. Doi:10.1016/j.jhydrol.2010.02.013

Lorentz, S.A., Bursey, K., Idowu, O., Pretorius, C. & Ngeleka, K., 2007. Definition and upscaling of key hydrological processes for application in models. Report No. K5/1320. Water Research Commission, Pretoria.

Luxmoore, R.J., 1981. Micro-, meso-, and 130esources130ity of soil. *Soil Science Society of America Journal,* 45, 671-672.

MacFarlane, D.M. & Bredin, I.P., 2017. Buffer Zone Guidelines for Rivers, Wetlands and Estuaries Buffer Zone Guidelines for Rivers, Wetlands and Estuaries. WRC Report No TT, 715/17. Water Research Commission, Pretoria.

MacFarlane, D.M., Ollis, D.J. & Kotze, D.C., 2020. WET-Health Version 2.0: A technique for rapidly assessing wetland health. WRC Report No. TT 820/20. Water Research Commission, Pretoria.

Mapeshoane, B., 2013. Soil hydrology and hydric soil indicators of the Bokong wetlands in Lesotho. Unpublished MSc thesis. University of Free State, Bloemfontein.

McBride, R.G., 1994. Relationships between soil properties and yield variability and the potential for establishing management zones for site-specific management in North Carolina. PhD Thesis, North Carolina State University, Raleigh NC.

McCarthy, T., Barry, M., Bloem, A., Ellery, W.N., Heister, H., Merry, C.L., Ruther, H. and Sternberg, H., 1997. The gradient of the Okavango fan, Botswana, and its sedimentological and tectonic implications. *Journal of Africa Earth Sciences* 24(1): 65-78

McDaniel, P., Regan, M.P., Brooks, E.S., Boll, J.A.N., Barndt, S., Falen, A., Young, S.K. & Hammel, J.E., 2008. Linking fragipans, perched water tables, and catchment-scale hydrological processes. *Catena,* 73, 166-173. Doi:10.1016/j.catena.2007.05.011

McGlynn, B.L., McDonnel, J.J. & Brammer, D.D., 2002. A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand. *Journal of Hydrology,* 257, 1-26.

McGuire, K.J., McDonnell, J.J., Weiler, M., Kendall, C., McGlynn, B.L., Welker, J.M. & Seibert, J., 2005. The role of topography on catchment-scale water residence time. *Water Resources Research,* 41, doi:10.1029/2004WR003657.

McGuire, K.J. & McDonnell, J.J., 2010. Hydrological connectivity of hillslopes and streams: Characteristic time scales and nonlinearities. *Water 131esources Research,* 46, doi:10.1029/2010WR009341

Meyer, R., 2014. Hydrogeology of Groundwater Region 10: the Karst Belt. TT 553/13. Water Research Commission. Pretoria.

Milne, G., 1935. Some suggested units of classification and mapping particularly for East African soils. *Soil Research*, 4, 183-198.

Moriasi, D., Arnold, J., Van Liew, M., Bingner, R., Harmel, R. & Veith, T., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE*, 50(3), 885-900. Doi: 10.13031/2013.23153.

Mosley, M.P., 1979. Streamflow generation in a forested watershed, New Zealand. *Journal of Hydrology,* 15, 795-806.

Munsell Color (Firm), 2010. Munsell soil color charts: with genuine Munsell color chips. Grand Rapids, MI Munsell Color*,*

Netterberg, F., 1978. Dating and correlation of calcretes and other pedocretes. *Trans. Geol. Soc. S. Afr.,* 81, 379-391.

Nieber, J.L., Bauters, T.W.J. Steenhuis, T.S. & Parlange, J.Y., 2000 Numerical simulation of experimental gravity-driven unstable flow in water repellent sand. *Journal of Hydrology,* 231, 295-307.

NRC, 2005. Review of the GAPP Science and Implementation Plan. Committee to Review the GAPP Science and Implementation Plan, National Research Council. Washington, DC

O'Geen, A.T., 2013. Soil Water Dynamics. *Nature Education Knowledge,* 4(5):9.

Ollis, D.J., Snaddon, C.D., Job, N.M. & Mbona, N., 2013. Classification system for wetlands and other aquatic ecosystems in South Africa. User Manual: Inland Systems. SANBI Biodiversity Series 22.

Ollis, D.J., Day, J.A., Malan, H.L., Ewart-Smith, J.L. & Job, N.M., 2014. Development of a decision-support framework for wetland assessment in South Africa and a decision-support protocol for the rapid assessment of wetland ecological condition. WRC Report No. TT 609/14. Water Research Commission, Pretoria.

Omar, M.Y., Le Roux, P.A.L. & Van Tol, J.J., 2014. Interactions between stream channel incision, soil water levels and soil morphology in a wetland in the Hogsback area, South Africa. *South African Journal of Plant and Soil,* 31, 187-194.

Pachepsky, Y.A. & Rawls, W.J., 2004. Development of pedotransfer functions in soil hydrology. Elsevier, Amsterdam.

Park, S.J., McSweeney, K. & Lowery, B., 2001. Identification of the spatial distribution of soils using a process-based terrain characterization. *Geoderma,* 103, 249-272. Doi:10.1016/S0016-7061(01)00042-8.

Park, S.J. & Van De Giesen, N., 2004. Soil-landscape delineation to define spatial sampling domains for hillslope hydrology. *Journal of Hydrology,* 295, 28-46.

Philip, J. R., 1992. Falling head ponded infiltration, *Water Resources Research*, 28, 2147-2148.

Pretorius, M.L., Van Huyssteen, C.W., Brown, L.R., Grundling, A.T. & Downs, C.T., 2020. A characterisation of wetland soil types on the Maputaland Coastal Plain, South African Journal of Plant and Soil, 37:5, 389-403, doi: 10.1080/02571862.2020.1814433

Retter, M., Kienzler, P. & Germann, P. F., 2006. Vectors of subsurface stormflow in a layered hillslope during runoff initiation. *Hydrology and Earth Systems Science,* 10, 309-320.

Riddell, E.S., Nel, J., Van Tol, J., Fundisi, D., Jumbi, F., Van Niekerk, A., & Lorentz, S., 2020. Groundwater-surface water interactions in an ephemeral savanna catchment, Kruger National Park. Koedoe, 62, 2. https://doi.org/10.4102/koedoe.v62i2.1583

Rodgers, P., Soulsby, C., Waldron, S. & Tetzlaff, D., 2005. Using stable isotope tracers to assess hydrological flow paths, residence times and landscape influences in a nested mesoscale catchment. *Hydrology and Earth Systems Science,* 9, 139-155. doi:10.5194/hess-9-139-2005

Romanowicz, A.A., Vanclooster, M., Rounsevel, M. & La Junesse, I., 2005. Sensitivity of the SWAT model to the soil and land use data parametrisation: A case study in the Thyle catchment, Belgium. *Ecological Modelling,* 187, 27-39.

Russel, W., 2009. *WET-Rehab Methods: National Guidelines and methods for wetland rehabilitation* Section 1.6. Water Research Commission.

Saha, S., Moorthi, S., Pan, H.L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D. & co-authors, 2015. The NCEP Climate Forecast System Reanalysis. *Bull Am Meteorol Soc*. 91 1015-1057.

Savenije, H.H.G. & Van der Zaag, P., 2008. Integrated water resource management: Concepts and issues. *Physics and Chemistry of the Earth,* 33, 290-297.

South African Wetland Society (SAWS)., 2014. Wetland delineation working group position paper on wetland delineation. Cape Town.

Saxton, K.E. & Rawls, W.J., 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Science of America Journal*, 70, 1569-1578.

Schoenenberger, P.J. & Wysocki, D.A., 2005. Hydrology of soils and deep regolith: a nexus between soil geography, ecosystems and land management. *Geoderma*, 126, 117-128. doi:10.1016/j.geoderma.2004.11.010

Schulze, R.E., 1985. Hydrological characteristics and properties of soils in Southern Africa 1: Runoff response. *Water SA* 11, 121-128.

Schwertmann, U., 1985. The effect of pedogenetic environments on iron oxide minerals. *Advances in Soil Science,* 1, 171-200.

Shankar, N. & Achyuthan, H., 2007. Genesis of calcic and petrocalcic horizons from Coimbatore, Tamil Nadu: Micromorphology and geochemical studies. *Quaternary International* 175, pp. (140-154).

Schrader, A., and Winde, F., 2015. Unearthing a hidden treasure: 60 years of karst research in the Far West Rand, South Africa. *S. Afr. j. sci.* 111:5-6. doi.org/10.17159/sajs.2015/20140144.

Sieben, E.J.J., 2012. Plant functional composition and ecosystem properties: the case of peatlands in South Africa. *Plant Ecology* 213(5): 809-820.

Šimunek, J., Van Genuchten, M.T. & Šejna, M., 2006. The HYDRUS Software Package for Simulating Two- and Three-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media; Technical Manual, Version 1.0; PC Progress: Prague, Czech Republic, 2006.

Sivapalan, M. 2003a. Prediction in ungauged basins: a grand challenge for theoretical hydrology. *Hydrological Processes,* 17, 3163-3170.

Sivapalan, M., 2003b. Process complexity at hillslope scale, process simplicity at the watershed scale: is there a connection? *Hydrol. Process.* 17, 1037-1041.

Smit, I.E. & Van Tol, J.J., 2022. Impacts of Soil Information on Process-Based Hydrological Modelling in the Upper Goukou Catchment, *South Africa Water 2022,* 14, 407. https://doi.org/10.3390/w14030407

Smit, I.E., Van Zijl, G.M., Riddell, E.S. & Van Tol, J.J., 2023. Examining the value of hydrological soil data on hydrological modelling at different scales in the Sabie catchment, South Africa. *Vadose Zone Journal.* doi: 10.1002/vzj2.20280

Smith, K. & Van Huyssteen, C.W., 2011. The effect of degree and duration of water saturation on selected redox indicators: pe, Fe^{2+} and Mn^{2+}. *South African Journal of Plant and Soil.* 28, 118-125.

Soil Classification Working Group (SCWG), 1991. Soil Classification: A taxonomic system for South Africa. *Department of Agricultural Development*, Pretoria.

Soil Classification Working Group, 2018. Soil Classification: A Natural and Anthropogenic System for South Africa. ARC-Institute for Soil, Climate and Water, Pretoria.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, Twelfth Ed. ed. U.S. Department of Agriculture.

Soulsby, C., Tetzlaff, D., Rodgers, P., Dunn, S.M. & Waldron, S., 2006. Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: An initial evaluation. *Journal of Hydrology,* 325, 197-221. doi:10.1016/j.jhydrol.2005.10.024.

Soulsby, C. & Tetzlaff, D., 2008. Towards simple approaches for mean residence time estimation in ungauged basins using tracers and soil distributions. *Journal of Hydrology,* 363, 60-74. doi:10.1016/j.jhydrol.2008.10.001.

Soulsby, C., Tetzlaff, D. & Hrachowitz, M., 2009. Tracers and transit times: windows for viewing catchment storage? *Hydrological Processes,* 23, 3503-3507. doi:10.1002/hyp.

Speed, M., Tetzlaff, D., Soulsby, C., Hrachowitz, M. & Waldron, S., 2010. Isotopic and geochemical tracers reveal similarities in transit times in contrasting mesoscale catchments. *Hydrological Processes,* 24, 1211-1224. doi:10.1002/hyp.7593

Spence, C. & Woo, M.K., 2003. Hydrology of subarctic Canadian shield: Soil-filled valleys. *Journal of Hydrology,* 279, 151-166. doi:10.1016/S0022-1694(03)00175-6

Tanner, JL., Smith, C., Ellery, W,N., and Schlegel, P., 2019. Palmiet wetland sustainability: A hydrological and geomorphological perspective on system functioning. Institute for Water Research, Rhodes University. Report No. 2548/1/18. Water Research Commission, Pretoria.

The Non-affiliated Soil Analysis Work Committee, 1990. Handbook of Standard Soil Testing Methods for Advisory Purposes. Pretoria: Soil Science Society of South Africa.

Ticehurst, J.L., Cresswell, H.P., McKenzie, N.J. & Glover, M.R., 2007. Interpreting soil and topographic properties to conceptualise hillslope hydrology. *Geoderma*, 137, 279-292. doi:10.1016/j.geoderma.2006.06.016

Tiner, R.W., 1999. Wetland Indicators: A guide to wetland identification, delineation, classification, and mapping. Lewis Publishers, CRC Press Inc., 2000 Corporate Boulevard NW, Boca Raton, FL 33431; (561) 994-0555.

Tooth, S., Brandt, D., Hancox, P.J. & McCarthy, T.S., 2004. Geological controls on alluvial river behaviour: a comparative study of three rivers on the South African Highveld. *Journal of African Earth Sciences* 38: 79-97.

Tooth, S. & McCarthy, T.S., 2007. Wetlands in drylands: Key geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. *Progress in Physical Geography* 31: 3-41.

Tromp-Van Meerveld, I. & McDonnell, J. J., 2006a Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope. *Water Resour. Res.* 42, W02410, doi.10.1029/2004WR003778.

Tromp-Van Meerveld, I. & McDonnell, J.J., 2006b. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research,* 42, doi:10.1029/2004WR003800.

Tromp-Van Meerveld, I., Peters, N.E. & McDonnell, J.J., 2007. Effect of bedrock permeability on subsurface stormflow and the water balance of a trenched hillslope at the Panola Mountain Research Watershed , Georgia , USA 769, 750-769. doi:10.1002/hyp.

Tromp-Van Meerveld, I. & Weiler, M., 2008. Hillslope dynamics modelled with increasing complexity. *Journal of Hydrology,* 361, 24-0.

Uchida, T., Asano, Y., Ohte, N. & Mizuyama, T., 2003. Analysis of flowpath dynamics in a steep unchanneled hollow in the Tanakami Mountains of Japan. *Hydrological Processes,* 17, 417-430. doi:10.1002/hyp.1133

Uhlenbrook, S., Wenninger, J. & Lorentz, S., 2005. What happens after the catchment caught storm? Hydrological processes at the small, semi-arid Weatherley catchment, South-Africa. *Adv. Geosci.* 2, 237-241.

United Nations, 2017. The Sustainable Development Goals Report. New York.

U.S. Army Corps of Engineers (USACOE)., 1987. Corps of Engineers Wetland Delineation Manual by Environmental Laboratory. Available from: U.S. Army Waterways Expt. Station, ER-W, Vicksburg.

U.S. Army Corps of Engineers (USACOE), 2006. Interim regional supplement to the Corps of Engineers Wetland Delineation Manual: Arid West Region. J.S. Wakeley, R.W. Lichvar, and C.V. Noble. (eds). ERDC/EL TR-06-16. U.S. Army Corps of Engineers, U.S. Army Engineer Research and Development Centre, Vicksburg.

USDA Natural Resources Conservation Service (USDA-NRCS)., 2010. Field Indicators of Hydric Soils in the United States. G.W. Hurt (ed). Wetland Science Institute and Soils Division. United States Department of Agriculture, Natural Resources Conservation Service, Wetland Science Institute, Louisiana.

Van der Waals, J.H., Paterson, D.G., Grundling, A., Turner, D.P., Van Huyssteen C.W. & Rossouw, P.S. (undated). Review of Soil Form and Wetness Indicators for Wetland Delineation in South Africa. Submitted to *WaterSA*

Van Breedeman, N. & Brinkman, R., 1976. Chemical equilibria and soil formation. In G. H. Bolt & M. G. M. Bruggenwert (eds.). Soil chemistry. A. Basic elements. Elsevier, Amsterdam.

Van Huyssteen, C.W., Hensley, M., Le Roux, P.A., Zere, T.B. & Du Preez, C.C., 2005. The relationship between soil water regime and soil profile morphology in the Weatherley catchment, an afforestation area in the Eastern Cape. Water Research Commission, Pretoria.

Van Huyssteen, C.W., 2008. A review of advances in hydropedology for application in South Africa. *South African Journal of Plant and Soil*, 25, 245-254.

Van Tol, J., Le Roux, P.A.L. & Hensley, M., 2010a. Soil as indicator of hillslope hydrological behaviour in the Weatherley Catchment , Eastern Cape , South Africa. *Water SA,* 36, 513-520.

Van Tol, J., Le Roux, P.A.L. & Hensley, M., 2010b. Soil indicators of hillslope hydrology in Bedford catchment. *South African Journal of Plant and Soil,* 27, 242-251.

Van Tol, J., Le Roux, P.A.L & Hensley, M., 2012. Pedotransfer functions to determine water conducting macroporosity in South African soils. *Water Science and Technology,* 65, 550-7. doi:10.2166/wst.2012.885

Van Tol, J., Hensley, M. & Le Roux, P.A.L., 2013a. Pedological criteria for estimating the importance of subsurface lateral flow in E horizons in South African soils. *Water SA,* 39, 47-56.

Van Tol, J., Le Roux, P.A., Lorentz, S. & Hensley, M., 2013b. Hydropedological Classification of South African Hillslopes. *Vadose Zone Journal*, 12. doi:10.2136/vzj2013.01.0007

Van Tol, J.J., Van Zijl, G.M., Riddell, E.S. & Fundisi, D., 2015. Application of hydropedological insights in hydrological modelling of the Stevenson Hamilton Research Supersite, Kruger National Park, South Africa. *Water SA* 41, 525-533.

Van Tol, J.J., Le Roux, P.A.L. & Lorentz, S.A., 2017. The science of hydropedology – linking soil morphology with hydrological processes. *Water Wheel*, June/July 2017.

Van Tol, J.J. & Lorentz, S.A., 2018. Hydropedological interpretation of soil distribution patterns to characterise groundwater/surface-water interactions. *Vadose Zone Journal.* Doi: 10.2136/vzj2017.05.0097

Van Tol, J.J., Lorentz, S.A., Van Zijl, G.M. & Le Roux, P.A.L., 2018. The contribution of hydropedological assessments to the availability and sustainable water, for all (SDG#6). *In* Lal, R., Horn, R. & Kosaki, T. (eds). Soil and Sustainable Development Goals. Catena-Schweizerbart, Stuttgart. 102-117.

Van Tol, J.J. & Le Roux, P.A.L., 2019. Hydropedological grouping of South African soil forms. *South African Journal of Plant and Soil.* Doi: 10.1080/02571862.2018.1537012.

Van Tol, J.J., 2020. Hydropedology in South Africa: advances, applications and research opportunities. *South African Journal of Plant and Soil.* Doi: 10.1080/02571862.2019.1640300

Van Tol, J.J., Van Zijl, G.M. & Julich, S., 2020a. Importance of detail soil information for hydrological modelling in an urbanised environment. *Hydrology*, 7, 34. Doi: 10.3390/hydrology7020034

Van Tol, J.J., Julich, S., Bouwer, D. & Riddell, E.S., 2020b. Hydrological response in a savanna hillslope under different rainfall regimes, *Koedoe* 62(2), a1602. Doi: 10.4102/koedoe.v62i2.1602

Van Tol, J.J., Bouwer, D. & Le Roux, P.A.L., 2021a. DWS guidelines for hydropedological surveys and minimum requirements. *Department of Water and Sanitation*.

Van Tol, J.J., Bieger, K. & Arnold, G., 2021b. A Hydropedological approach to simulate streamflow and soil water contents with SWAT+. *Hydrological Processes.* DOI:10.1002/hyp.14242.

Van Tol, J.J. & Van Zijl, G.M., 2022. South Africa needs a hydrological soil map: a case study from the upper uMgeni catchments. *Water SA,* 48(4) 335-347. https://doi.org/10.17159/wsa/2022.v48.i4.3977.

Van Tol, J.J., Job, N., Bouwer, D. & Murugan, S., 2023. Advancing the management of wetland resources in South Africa: Integrating hydropedology into wetlands management and development authorization at catchment and site scales. Deliverable 3 – Case Study Report. Project K5/00552. Water Research Commission, Pretoria.

Van Zijl, G.M., Le Roux, P.A.L. & Turner, D.P., 2013. Disaggregation of land types using terrain analysis, expert knowledge and GIS methods. *South African Journal of Plant and Soil* 30(3), 123-129.

Van Zijl, G.M., Van Tol, J.J., Bouwer, D., Lorentz, S.A. & Le Roux, P.A.L. 2020. Combining Historical Remote Sensing, Digital Soil Mapping and Hydrological Modelling to Produce Solutions for Infrastructure Damage in Cosmo City, South Africa. *Remote Sensing,* 12, 433. doi:10.3390/rs12030433.

Vasilas, L.M. & Vasilas, B.L., 2013. Hydric soil identification techniques. In: J.T. Anderson and C.A. Davis (eds), Wetland Techniques. Springer.

Vepraskas, M.J. & Bouma, J., 1976. Model studies on mottle formation simulating field conditions. *Geoderma* 15,217-230.

Vepraskas, M.J., 1995. Redoximorphic features for identifying Aquic conditions. NC Agr. Res. Service, NC State University, Raleigh, NC. Technical Bulletin 301. Available from: Department of Agricultural Communications, Box 7603, North Carolina State University, Raleigh, NC 27695-7603; (919) 515-3173.

Vepraskas, M.J. & Lindbo, D.L., 2012. Redoximorphic features as related to soil hydrology and hydric soils. Chapter 5. In: Hydropedology (H. Lin ed). Elsevier.

Webster, R. 2000. Is soil variation random? *Geoderma* 97, 149-163.

Weiler, M. & McDonnell, J., 2004. Virtual experiments: a new approach for improving process conceptualization in hillslope hydrology. *Journal of Hydrology,* 285, 3-18.

Whipkey, R.Z., 1965. Subsurface stormflow from forested slopes. *Int. Assoc. Sci. Hydrology. Bull.* 10, 74-85.

Whipkey, R.Z. & Kirkby, M. J., 1979. Flow within the soil. In Kirkby M. J (Ed.), Hillslope Hydrology. Wiley, New York, 121-143.

Woods, R. & Rowe, L., 1996. The changing spatial variability of subsurface flow across a hillslope. *Journal of Hydrology,* 31, 49-84.

APPENDICES: LISTING NOTICES

These listing notices[19] are for activities not falling within regulated zones. Listed activities will not automatically trigger the need for authorisation from DWS but will require authorisation from DFFE. Level 1 refers to activities where investigation should start with a *Basic* hydropedological assessment. Level 2 are those activities which require a *Full* hydropedological assessment from the onset.

A: BASIC ENVIRONMENTAL IMPACT ASSESSMENT

Activity	Activity description	Hydropedological assessment	Level
1	The development of facilities or infrastructure for the generation of electricity from a renewable resource where- (i) the electricity output is more than 10 megawatts but less than 20 megawatts; or (ii) the output is 10 megawatts or less but the total extent of the facility covers an area in excess of 1 hectare; excluding where such development of facilities or infrastructure is for photovoltaic installations and occurs within an urban area.	No, unless direct impact on important water course (water quantity)	-
2	The development and related operation of facilities or infrastructure for the generation of electricity from a non-renewable resource where- (i) the electricity output is more than 10 megawatts but less than 20 megawatts; or (ii) the output is 10 megawatts or less but the total extent of the facility covers an area in excess of 1 hectare.	No, unless direct impact on important water course (water quantity)	
3	The development and related operation of facilities or infrastructure for the slaughter of animals with a product throughput of- (i) poultry exceeding 50 poultry per day; (ii) reptiles, game and red meat exceeding 6 units per day; or (iii) fish, crustaceans and amphibians with a wet weight product throughput of 20 000 kg per annum.	No, unless direct impact on important water course (water quality)	
4	The development and related operation of facilities or infrastructure for the concentration of animals for the purpose of commercial production in densities that exceed- (i) 20 square metres per large stock unit and more than 500 units per facility; (ii) 8 square meters per small stock unit and; a. more than 1 000 units per facility excluding pigs where (b) applies; or b. more than 250 pigs per facility excluding piglets that are not yet weaned; (iii) 30 square metres per crocodile at any level of production, excluding crocodiles younger than 6 months; (iv) 3 square metre per rabbit and more than 500 rabbits per facility; or (v) 250 square metres per ostrich or emu and more than 50 ostriches or emus per facility.	No, unless direct impact on important water course (water quality)	
5	The development and related operation of facilities or infrastructure for the concentration of- (i) more than 1 000 poultry per facility situated within an urban area, excluding chicks younger than 20 days; (ii) more than 5 000 poultry per facility situated outside an urban area, excluding chicks younger than 20 days; (iii) more than 5000 chicks younger than 20 days per facility situated within an urban area; or (iv) more than 25000 chicks younger than 20 days per facility situated outside an urban area.	No, unless direct impact on important water course (water quality)	
6	The development and related operation of facilities, infrastructure or structures for aquaculture of- (i) finfish, crustaceans, reptiles or amphibians, where such facility, infrastructure or structures will have a production output exceeding 20 000 kg per annum (wet weight); and	No, unless direct impact on important water course (water quality)	

[19] Based on Listing Notices of 2019, should these listing notices be amended or repealed, Level 1 & 2 hydropedological assessment should be applied on the latest regulations

	(ii) molluscs and echinoderms, where such facility, infrastructure or structures will have a production output exceeding 30 000 kg per annum (wet weight); or (iii) aquatic plants, where such facility, infrastructure or structures will have a production output exceeding 60 000 kg per annum (wet weight); excluding where the development of such facilities, infrastructure or structures is for purposes of sea-based cage culture in which case activity 7 in this Notice applies.		
7	The development and related operation of facilities, infrastructure or structures for aquaculture of sea-based cage culture of finfish, crustaceans, reptiles, amphibians, molluscs, echinoderms and aquatic plants, where the facility, infrastructure or structures will have a production output exceeding 50 000 kg per annum (wet weight).	No	
8	The development and related operation of hatcheries or agri-industrial facilities outside industrial complexes where the development footprint covers an area of 2 000 square metres or more.	No	
9	The development of infrastructure exceeding 1000 metres in length for the bulk transportation of water or storm water- (i) with an internal diameter of 0,36 metres or more; or (ii) with a peak throughput of 120 litres per second or more; excluding where- (a) such infrastructure is for bulk transportation of water or storm water or storm water drainage inside a road reserve; or (b) where such development will occur within an urban area.	No, unless direct impact on important water course (water quantity)	
10	The development and related operation of infrastructure exceeding 1000 metres in length for the bulk transportation of sewage, effluent, process water, waste water, return water, industrial discharge or slimes- (i) with an internal diameter of 0,36 metres or more; or (ii) with a peak throughput of 120 litres per second or more; excluding where- (a) such infrastructure is for bulk transportation of sewage, effluent, process water, waste water, return water, industrial discharge or slimes inside a road reserve; or (b) where such development will occur within an urban area.	Yes	1
11	The development of facilities or infrastructure for the transmission and distribution of electricity- (i) outside urban areas or industrial complexes with a capacity of more than 33 but less than 275 kilovolts; or (ii) inside urban areas or industrial complexes with a capacity of 275 kilovolts or more.	No	
12	The development of- (i) canals exceeding 100 square metres in size; (ii) channels exceeding 100 square metres in size; (iii) bridges exceeding 100 square metres in size; (iv) dams, where the dam, including infrastructure and water surface area, exceeds 100 square metres in size; (v) weirs, where the weir, including infrastructure and water surface area, exceeds 100 square metres in size; (vi) bulk storm water outlet structures exceeding 100 square metres in size; (vii) marinas exceeding 100 square metres in size; (viii) jetties exceeding 100 square metres in size; (ix) slipways exceeding 100 square metres in size; (x) buildings exceeding 100 square metres in size; (xi) boardwalks exceeding 100 square metres in size; or (xii) infrastructure or structures with a physical footprint of 100 square metres or more; where such development occurs- (a) within a watercourse; (b) in front of a development setback; or (c) if no development setback exists, within 32 metres of a watercourse, measured from the edge of a watercourse; – excluding- (aa) the development of infrastructure or structures within existing ports or harbours that will not increase the development footprint of the port or harbour; (bb) where such development activities are related to the development of a port or harbour, in which case activity 26 in Listing Notice 2 of 2014 applies; (cc) activities listed in activity 14 in Listing Notice 2 of 2014 or activity 14 in Listing Notice 3 of 2014, in which case that activity applies; (dd) where such development occurs within an urban area; or (ee) where such development occurs within existing roads or road reserves.	Yes (i, ii, iv, v)	1

13	The development of facilities or infrastructure for the off-stream storage of water, including dams and reservoirs, with a combined capacity of 50000 cubic metres or more, unless such storage falls within the ambit of activity 16 in Listing Notice 2 of 2014.	Yes (water quantity)	1
14	The development of facilities or infrastructure, for the storage, or for the storage and handling, of a dangerous good, where such storage occurs in containers with a combined capacity of 80 cubic metres or more but not exceeding 500 cubic metres.	Yes (water quality)	1
15	The development of structures in the coastal public property where the development footprint is bigger than 50 square metres, excluding – (i) the development of structures within existing ports or harbours that will not increase the development footprint of the port or harbour; (ii) the development of a port or harbour, in which case activity 26 in Listing Notice 2 of 2014 applies; (iii) the development of temporary structures within the beach zone where such structures will be removed within 6 weeks of the commencement of development and where indigenous vegetation will not be cleared; or (iv) activities listed in activity 14 in Listing Notice 2 of 2014, in which case that activity applies.	No	
16	The development and related operation of facilities for the desalination of water with a design capacity to produce more than 100 cubic metres of treated water per day.	No	
17	Development- (i) in the sea; (ii) in an estuary; (iii) within the littoral active zone; (iv) in front of a development setback; or (v) if no development setback exists, within a distance of 100 metres inland of the high-water mark of the sea or an estuary, whichever is the greater; in respect of- (a) fixed or floating jetties and slipways; (b) tidal pools; (c) embankments; (d) rock revetments or stabilising structures including stabilising walls; (e) buildings of 50 square metres or more; or (f) infrastructure with a development footprint of 50 square metres or more – but excluding- (aa) the development of infrastructure and structures within existing ports or harbours that will not increase the development footprint of the port or harbour; (bb) where such development is related to the development of a port or harbour, in which case activity 26 in Listing Notice 2 of 2014 applies; (cc) the development of temporary infrastructure or structures where such structures will be removed within 6 weeks of the commencement of development and where indigenous vegetation will not be cleared; or (dd) where such development occurs within an urban area.	No	
18	The planting of vegetation or placing of any material on dunes or exposed sand surfaces of more than 10 square metres, within the littoral active zone, for the purpose of preventing the free movement of sand, erosion or accretion, excluding where (i) the planting of vegetation or placement of material relates to restoration and maintenance of indigenous coastal vegetation undertaken in accordance with a maintenance management plan; or (ii) such planting of vegetation or placing of material will occur behind a development setback.	No	
19	The infilling or depositing of any material of more than 5 cubic metres into, or the dredging, excavation, removal or moving of soil, sand, shells, shell grit, pebbles or rock of more than 5 cubic metres from- (i) a watercourse; (ii) the seashore; or (iii) the littoral active zone, an estuary or a distance of 100 metres inland of the high-water mark of the sea or an estuary, whichever distance is the greater but excluding where such infilling, depositing , dredging, excavation, removal or moving- (a) will occur behind a development setback; (b) is for maintenance purposes undertaken in accordance with a maintenance management plan; or (c) falls within the ambit of activity 21 in this Notice, in which case that activity applies.	Yes (i)	1
20	Any activity including the operation of that activity which requires a prospecting right in terms of section 16 of the Mineral and Petroleum Resources Development Act,	Yes	1

	2002 (Act No. 28 of 2002), including associated infrastructure, structures and earthworks, directly related to prospecting of a mineral resource, including activities for which an exemption has been issued in terms of section 106 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002).		
21	Any activity including the operation of that activity which requires a mining permit in terms of section 27 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002), including associated infrastructure, structures and earthworks directly related to the extraction of a mineral resource, including activities for which an exemption has been issued in terms of section 106 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002).	Yes	1
22	The decommissioning of any activity requiring – (i) a closure certificate in terms of section 43 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002); or (ii) (ii) a prospecting right, mining right, mining permit, production right or exploration right, where the throughput of the activity has reduced by 90% or more over a period of 5 years excluding where the competent authority has in writing agreed that such reduction in throughput does not constitute closure.	No	
23	The development of cemeteries of 2500 square metres or more in size.	Yes (water quality)	1
24	The development of- (i) a road for which an environmental authorisation was obtained for the route determination in terms of activity 5 in Government Notice 387 of 2006 or activity 18 in Government Notice 545 of 2010; or (ii) a road with a reserve wider than 13,5 meters, or where no reserve exists where the road is wider than 8 metres; but excluding- (a) roads which are identified and included in activity 27 in Listing Notice 2 of 2014; or (b) roads where the entire road falls within an urban area.	No	
25	The development and related operation of facilities or infrastructure for the treatment of effluent, wastewater or sewage with a daily throughput capacity of more than 2000 cubic metres but less than 15000 cubic metres.	Yes (water quality)	1
26	Residential, retail, recreational, tourism, commercial or institutional developments of 1000 square metres or more, on land previously used for mining or heavy industrial purposes; excluding – (i) where such land has been remediated in terms of part 8 of the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008) in which case the National Environmental Management: Waste Act, 2008 applies; or (ii) where an environmental authorisation has been obtained for the decommissioning of such a mine or industry in terms of this Notice or any previous NEMA notice; or (iii) where a closure certificate has been issued in terms of section 43 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002) for such land.	Yes	1
27	The clearance of an area of 1 hectares or more, but less than 20 hectares of indigenous vegetation, except where such clearance of indigenous vegetation is required for- (i) the undertaking of a linear activity; or (ii) maintenance purposes undertaken in accordance with a maintenance management plan.	No	
28	Residential, mixed, retail, commercial, industrial or institutional developments where such land was used for agriculture or afforestation on or after 01 April 1998 and where such development: (i) will occur inside an urban area, where the total land to be developed is bigger than 5 hectares; or (ii) will occur outside an urban area, where the total land to be developed is bigger than 1 hectare; excluding where such land has already been developed for residential, mixed, retail, commercial, industrial or institutional purposes.	Yes	1
29	The release of genetically modified organisms into the environment, where assessment for such release is required by the Genetically Modified Organisms Act, 1997 (Act No. 15 of 1997) or the National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004).	No	
30	Any process or activity identified in terms of section 53(1) of the National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004).	No	
31	The decommissioning of existing facilities, structures or infrastructure for- (i) any development and related operation activity or activities listed in this Notice, Listing Notice 2 of 2014 or Listing Notice 3 of 2014;	No	

	(ii) any expansion and related operation activity or activities listed in this Notice, Listing Notice 2 of 2014 or Listing Notice 3 of 2014;		
	(iii) any development and related operation activity or activities and expansion and related operation activity or activities listed in this Notice, Listing Notice 2 of 2014 or Listing Notice 3 of 2014;		
	(iv) any phased activity or activities for development and related operation activity or expansion or related operation activities listed in this Notice or Listing Notice 3 of 2014;or		
	(v) any activity regardless the time the activity was commenced with, where such activity:		
	a. is similarly listed to an activity in (i), (ii), (iii), or (iv) above; and		
	b. is still in operation or development is still in progress;		
	excluding where-		
	(aa) activity 22 of this notice applies; or		
	(bb) the decommissioning is covered by part 8 of the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008) in which case the National Environmental Management: Waste Act, 2008 applies.		
32	The continuation of any development where the environmental authorisation has lapsed and where the continuation of the development, after the date the environmental authorisation has lapsed will meet the threshold of any activity or activities listed in this Notice, Listing Notice 2 of 2014, or Listing Notice 3 or Listing Notice 4 of 2014.	Depends on development	
33	The underground gasification of 300 kilograms or more coal per day, including any associated operation.	Yes (water quality)	1
34	The expansion or changes to existing facilities for any process or activity where such expansion or changes will result in the need for a permit or licence or an amended permit or licence in terms of national or provincial legislation governing the release of emissions or pollution, excluding-	Yes	1
	(i) where the facility, process or activity is included in the list of waste management activities published in terms of section 19 of the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008) in which case the National Environmental Management: Waste Act, 2008 applies; or		
	(ii) the expansion of or changes to existing facilities for the treatment of effluent, wastewater or sewage where the capacity will be increased by less than 15 000 cubic metres per day.		
35	The expansion of residential, retail, recreational, tourism, commercial or institutional developments on land previously used for mining or heavy industrial purposes, where the increased development footprint will exceed 1000 square meters; excluding –	No	
	(i) where such land has been remediated in terms of part 8 of the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008) in which case the National Environmental Management: Waste Act, 2008 applies; or		
	(ii) where an environmental authorisation has been obtained for the decommissioning of such a mine or industry in terms of this Notice or any previous NEMA notice; or		
	(iii) where a closure certificate has been issued in terms of section 43 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002) for such land.		
36	The expansion of facilities or structures for the generation of electricity from a renewable resource where-	No, unless direct impact on important water course (water quantity)	
	(i) the electricity output will be increased by 10 megawatts or more, excluding where such expansion takes place on the original development footprint; or		
	(ii) regardless the increased output of the facility, the development footprint will be expanded by 1 hectare or more; excluding where such expansion of facilities or structures is for photovoltaic installations and occurs within an urban area.		
37	The expansion and related operation of facilities for the generation of electricity from a non-renewable resource where-	No, unless direct impact on important water course (water quantity)	
	(i) the electricity output will be increased by 10 megawatts or more, excluding where such expansion takes place on the original development footprint; or		
	(ii) regardless the increased output of the facility, the development footprint will be expanded by 1 hectare or more.		
38	The expansion and related operation of facilities for the slaughter of animals where the daily product throughput will be increased by more than-	No, unless direct impact on important water course (water quality)	
	(i) 50 poultry;		
	(ii) 6 units of reptiles, red meat and game; or		

	(iii) 20 000 kg wet weight per annum of fish, crustaceans and amphibians.		
39	The expansion and related operation of facilities for the concentration of animals for the purpose of commercial production in densities that will exceed- (i) 20 square metres per large stock unit, where the expansion will constitute more than 500 additional units; (ii) 8 square meters per small stock unit, where the expansion will constitute more than; a. 1 000 additional units per facility or more excluding pigs where (b) applies; or b. (b) 250 additional pigs, excluding piglets that are not yet weaned; (iii) 30 square metres per crocodile at any level of production where the expansion will constitute an increase in the level of production, excluding crocodiles younger than 6 months; (iv) 3 square metre per rabbit where the expansion will constitute more than 500 additional rabbits; or (v)250 square metres per ostrich or emu where the expansion will constitute more than 50 additional ostriches or emus.	No, unless direct impact on important water course (water quality)	
40	The expansion and related operation of facilities for the concentration of poultry, excluding chicks younger than 20 days, where the capacity of the facility will be increased by- (i) more than 1 000 poultry where the facility is situated within an urban area; or (ii) more than 5 000 poultry per facility situated outside an urban area.	No, unless direct impact on important water course (water quality)	
41	The expansion and related operation of facilities, infrastructure or structures for aquaculture of- (i) finfish, crustaceans, reptiles or amphibians, where the annual production output of such facility, infrastructure or structures will be increased by 20 000 kg (wet weight) or more; (ii) molluscs and echinoderms where the annual production output of such facility, infrastructure or structures will be increased by 30 000 kg (wet weight) or more; or (iii) aquatic plants where the annual production output of such facility, infrastructure or structures will be increased by 60 000 kg (wet weight) or more; excluding where the expansion of facilities, infrastructure or structures is for purposes of sea-based cage culture in which case activity 42 in this Notice will applies.	No, unless direct impact on important water course (water quality)	
42	The expansion and related operation of facilities, infrastructure or structures for aquaculture of sea-based cage culture of finfish, crustaceans, reptiles, amphibians, molluscs, echinoderms and aquatic plants where the annual production output of such facility, infrastructure or structures will be increased by 50 000 kg (wet weight) or more.	No	
43	The expansion and related operation of hatcheries or agri-industrial facilities outside industrial complexes, where the development footprint of the hatcheries or agri-industrial facilities will be increased by 2 000 square metres or more.	No, unless direct impact on important water course (water quality)	
44	The expansion of cemeteries by 2500 square metres or more.	Yes (water quality)	1
45	The expansion of infrastructure for the bulk transportation of water or storm water where the existing infrastructure- (i) has an internal diameter of 0,36 metres or more; or (ii) has a peak throughput of 120 litres per second or more; and a. where the facility or infrastructure is expanded by more than 1000 metres in length; or b. where the throughput capacity of the facility or infrastructure will be increased by 10% or more; excluding where such expansion- (aa) relates to transportation of water or storm water within a road reserve; or (bb) will occur within an urban area.	No, unless direct impact on important water course (water quantity)	
46	The expansion and related operation of infrastructure for the bulk transportation of sewage, effluent, process water, waste water, return water, industrial discharge or slimes where the existing infrastructure- (i) has an internal diameter of 0,36 metres or more; or (ii) has a peak throughput of 120 litres per second or more; and a. where the facility or infrastructure is expanded by more than 1000 metres in length; or b. where the throughput capacity of the facility or infrastructure will be increased by 10% or more; excluding where such expansion- (aa) relates to transportation of sewage, effluent, process water, waste water, return water, industrial discharge or slimes within a road reserve; or (bb) will occur within an urban area.	Yes (water quality)	1

47	The expansion of facilities or infrastructure for the transmission and distribution of electricity where the expanded capacity will exceed 275 kilovolts and the development footprint will increase.	No	
48	The expansion of- (i) canals where the canal is expanded by 100 square metres or more in size; (ii) channels where the channel is expanded by 100 square metres or more in size; (iii) bridges where the bridge is expanded by 100 square metres or more in size; (iv) dams, where the dam, including infrastructure and water surface area, is expanded by 100 square metres or more in size; (v) weirs, where the weir, including infrastructure and water surface area, is expanded by 100 square metres or more in size; (v) bulk storm water outlet structures where the bulk storm water outlet structure is expanded by 100 square metres or more in size; or (vi) marinas where the marina is expanded by 100 square metres or more in size; where such expansion or expansion and related operation occurs- (a) within a watercourse; (b) in front of a development setback; or (c) if no development setback exists, within 32 metres of a watercourse, measured from the edge of a watercourse; excluding- (aa) the expansion of infrastructure or structures within existing ports or harbours that will not increase the development footprint of the port or harbour; (bb) where such expansion activities are related to the development of a port or harbour, in which case activity 26 in Listing Notice 2 of 2014 applies; (cc) activities listed in activity 14 in Listing Notice 2 of 2014 or activity 14 in Listing Notice 3 of 2014, in which case that activity applies; (dd) where such expansion occurs within an urban area; or (ee) where such expansion occurs within existing roads or road reserves.	Yes (i, ii, iv, v)	1
49	The expansion of – (i) jetties by more than 100 square metres; (ii) slipways by more than 100 square metres; (iii) buildings by more than 100 square metres; (iv) boardwalks by more than 100 square metres; or (v) infrastructure or structures where the physical footprint is expanded by 100 square metres or more; where such expansion or expansion and related operation occurs- (a) within a watercourse; (b) in front of a development setback; or (c) if no development setback exists, within 32 metres of a watercourse, measured from the edge of a watercourse; excluding- (aa) the expansion of infrastructure or structures within existing ports or harbours that will not increase the development footprint of the port or harbour; (bb) where such expansion activities are related to the development of a port or harbour, in which case activity 26 in Listing Notice 2 of 2014 applies; (cc) activities listed in activity 14 in Listing Notice 2 of 2014 or activity 14 in Listing Notice 3 of 2014, in which case that activity applies; (dd) where such expansion occurs within an urban area; or (ee) where such expansion occurs within existing roads or road reserves.	Yes (iii, iv, v)	1
50	The expansion of facilities or infrastructure for the off-stream storage of water, including dams and reservoirs, where the combined capacity will be increased by 50000 cubic metres or more.	Yes (water quantity)	1
51	The expansion of facilities for the storage, or storage and handling, of a dangerous good, where the capacity of such storage facility will be expanded by more than 80 cubic metres.	Yes (water quality)	1
52	The expansion of structures in the coastal public property where the development footprint will be increased by more than 50 square metres, excluding such expansions within existing ports or harbours where there will be no increase in the development footprint of the port or harbour and excluding activities listed in activity 23 in Listing Notice 3 of 2014, in which case that activity applies.	No	
53	The expansion and related operation of facilities for the desalination of water where the design capacity will be expanded to produce an additional 100 cubic metres or more of treated water per day.	No	
54	The expansion of facilities –	No	

	(i) in the sea; (ii) in an estuary; (iii) within the littoral active zone; (iv) in front of a development setback; or (v) if no development setback exists, within a distance of 100 metres inland of the highwater mark of the sea or an estuary, whichever is the greater; in respect of- (a) fixed or floating jetties and slipways; (b) tidal pools; (c) embankments; (d) rock revetments or stabilising structures including stabilising walls; (e) buildings where the building is expanded by 50 square metres or more; or (f) infrastructure where the development footprint is expanded by 50 square metres or more, but excluding- (aa) the expansion of infrastructure or structures within existing ports or harbours that will not increase the development footprint of the port or harbour; or (bb) where such expansion occurs within an urban area.		
55	Expansion- (i) in the sea; (ii) in an estuary; (iii) within the littoral active zone; (iv) in front of a development setback; or (v) if no development setback exists, within a distance of 100 metres inland of the highwater mark of the sea or an estuary, whichever is the greater; in respect of (i) facilities associated with the arrival and departure of vessels and the handling of cargo; (ii) piers; (iii) inter- and sub-tidal structures for entrapment of sand; (iv) breakwater structures; (v) coastal marinas; (vi) coastal harbours or ports; (vii) tunnels; or (viii) underwater channels; but excluding the expansion of infrastructure or structures within existing ports or harbours that will not increase the development footprint of the port or harbour.	No	
56	The widening of a road by more than 6 metres, or the lengthening of a road by more than 1 kilometre- (i) where the existing reserve is wider than 13,5 meters; or (ii) where no reserve exists, where the existing road is wider than 8 metres; excluding where widening or lengthening occur inside urban areas.	No	
57	The expansion and related operation of facilities or infrastructure for the treatment of effluent, wastewater or sewage where the capacity will be increased by 15000 cubic metres or more per day and the development footprint will increase by 1000 square meters or more.	Yes (water quality)	1
58	The increase of the amount of coal gasified underground, where any such increase exceeds 300 kg per day, including any associated operation.	Yes (water quality)	1
59	The expansion and related operation of facilities or infrastructure for the refining, extraction or processing of gas, oil or petroleum products where the installed capacity of the facility will be increased by 50 cubic metres or more per day, excluding facilities for the refining, extraction or processing of gas from landfill sites.	Yes	1
60	The expansion and related operation of facilities or infrastructure for the bulk transportation of dangerous goods- (i) in gas form, outside an industrial complex, by an increased throughput capacity of 700 tons or more per day; (ii) in liquid form, outside an industrial complex or zone, by an increased throughput capacity of 50 cubic metres or more per day; or (iii) in solid form, outside an industrial complex or zone, by an increased throughput capacity of 50 tons or more per day.	Yes (water quality)	1
61	The expansion of airports where the development footprint will be increased.	Yes	1
62	The expansion of facilities or infrastructure for marine telecommunication where there will be an increased development footprint.	No	
63	The expansion of facilities or infrastructure for the transfer of water from and to or between any combination of the following- (i) water catchments; (ii) water treatment works; or (iii) impoundments;	No	

	where the capacity will be increased by 50 000 cubic metres or more per day, but excluding water treatment works where water is treated for drinking purposes.		
64	The expansion of railway lines, stations or shunting yards where there will be an increased development footprint, excluding- (i) railway lines, shunting yards and railway stations in industrial complexes or zones; (ii) underground railway lines in mines; or (iii) additional railway lines within the railway line reserve.	No	
65	The expansion and related operation of an island, anchored platform or any other permanent structure on or along the sea bed, where the expansion will constitute an increased development footprint, excluding expansion of facilities, infrastructure or structures for aquaculture purposes.	No	
66	The expansion of a dam where- (i) the highest part of the dam wall, as measured from the outside toe of the wall to the highest part of the wall, was originally 5 metres or higher and where the height of the wall is increased by 2,5 metres or more; or (ii) where the high-water mark of the dam will be increased with 10 hectares or more.	Yes	1
67	Phased activities for all activities. (i) listed in this Notice, which commenced on or after the effective date of this Notice; or (ii) similarly listed in any of the previous NEMA notices, which commenced on or after the effective date of such previous NEMA Notices; where any phase of the activity may be below a threshold but where a combination of the phases, including expansions or extensions, will exceed a specified threshold; excluding the following activities listed in this Notice- 17(i)(a-d); 17(ii)(a-d); 17(iii)(a-d); 17(iv)(a-d); 17(v)(a-d); 20; 21; 22; 24(i); 29; 30; 31; 32; 34; 54(i)(a-d); 54(ii)(a-d); 54(iii)(a-d); 54(iv)(a-d); 54(v)(a-d); 55; 61; 62; 64 and 65.		

*Level 1 = Start with Basic Assessment, Level 2 = Start with Full Assessment

B: FULL ENVIRONMENTAL IMPACT ASSESSMENT

Activity	Activity description	Hydropedological assessment	Level
1	The development of facilities or infrastructure for the generation of electricity from a renewable resource where the electricity output is 20 megawatts or more, excluding where such development of facilities or infrastructure is for photovoltaic installations and occurs within an urban area.	No, unless direct impact on important water course (water quantity)	
2	The development and related operation of facilities or infrastructure for the generation of electricity from a non-renewable resource where the electricity output is 20 megawatts or more.	No, unless direct impact on important water course (water quantity)	
3	The development and related operation of facilities or infrastructure for nuclear reaction including energy generation, the production, enrichment, processing, reprocessing, storage or disposal of nuclear fuels, radioactive products, nuclear waste or radioactive waste.	Yes (water quality)	1
4	The development of facilities or infrastructure, for the storage, or storage and handling of a dangerous good, where such storage occurs in containers with a combined capacity of more than 500 cubic metres.	Yes (water quality)	1
5	The development and related operation of facilities or infrastructure for the refining, extraction or processing of gas, oil or petroleum products with an installed capacity of 50 cubic metres or more per day, excluding – (i) facilities for the refining, extraction or processing of gas from landfill sites; or (ii) the primary processing of a petroleum resource in which case activity 22 in this Notice applies.	Yes	1
6	The development of facilities or infrastructure for any process or activity which requires a permit or licence in terms of national or provincial legislation governing the generation or release of emissions, pollution or effluent, excluding (i) activities which are identified and included in Listing Notice 1 of 2014; (ii) activities which are included in the list of waste management activities published in terms of section 19 of the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008) in which case the National Environmental Management: Waste Act, 2008 applies; or	Yes	1

	(iii) the development of facilities or infrastructure for the treatment of effluent, wastewater or sewage where such facilities have a daily throughput capacity of 2000 cubic metres or less.		
7	The development and related operation of facilities or infrastructure for the bulk transportation of dangerous goods- (i) in gas form, outside an industrial complex, using pipelines, exceeding 1000 metres in length, with a throughput capacity of more than 700 tons per day; (ii) in liquid form, outside an industrial complex, using pipelines, exceeding 1000 metres in length, with a throughput capacity of more than 50 cubic metres per day; or (iii) in solid form, outside an industrial complex, using funiculars or conveyors with a throughput capacity of more than 50 tons day.	Yes	1
8	The development of- (i) airports, or (ii) runways or aircraft landing strips longer than 1,4 kilometres.	Yes	1
9	The development of facilities or infrastructure for the transmission and distribution of electricity with a capacity of 275 kilovolts or more, outside an urban area or industrial complex.	No	
10	The development of facilities or infrastructure for marine telecommunication.	No	
11	The development of facilities or infrastructure for the transfer of 50 000 cubic metres or more water per day, from and to or between any combination of the following – (i) water catchments; (ii) water treatment works; or (iii) impoundments; excluding treatment works where water is to be treated for drinking purposes.	Yes	1
12	The development of railway lines, stations or shunting yards excluding – (i) railway lines, shunting yards and railway stations in industrial complexes or zones; (ii) underground railway lines in a mining area; or (iii) additional railway lines within the railway line reserve.	No	
13	The physical alteration of virgin soil to agriculture, or afforestation for the purposes of commercial tree, timber or wood production of 100 hectares or more.	Yes	1
14	The development and related operation of- (i) an island; (ii) anchored platform; or (iii) any other structure or infrastructure on, below or along the sea bed; excluding – (a) development of facilities, infrastructure or structures for aquaculture purposes; or (b) the development of temporary structures or infrastructure where such structures will be removed within 6 weeks of the commencement of development and where indigenous vegetation will not be cleared.	No	
15	The clearance of an area of 20 hectares or more of indigenous vegetation, excluding where such clearance of indigenous vegetation is required for- (i) the undertaking of a linear activity; or (ii) maintenance purposes undertaken in accordance with a maintenance management plan.	No	
16	The development of a dam where the highest part of the dam wall, as measured from the outside toe of the wall to the highest part of the wall, is 5 metres or higher or where the highwater mark of the dam covers an area of 10 hectares or more.	Yes	1
17	Any activity including the operation of that activity which requires a mining right as contemplated in section 22 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002), including associated infrastructure, structures and earthworks, directly related to the extraction of a mineral resource, including activities for which an exemption has been issued in terms of section 106 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002).	Yes (Level 2 for open cast mines)	1 2
18	Any activity including the operation of that activity which requires an exploration right as contemplated in section 79 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002), including associated infrastructure, structures and earthworks.	Yes (Level 2 for open cast mines)	1 2
19	The removal and disposal of minerals contemplated in terms of section 20 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002), including associated infrastructure, structures and earthworks, directly related to prospecting of a mineral resource, including activities for which an exemption has been issued in terms of section 106 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002).	Yes	1
20	Any activity including the operation of that activity which requires a production right as contemplated in section 83 of the Mineral and Petroleum Resources	Yes	1

	Development Act, 2002 (Act No. 28 of 2002), including associated infrastructure, structures and earthworks, directly related to the primary processing of a petroleum resource.		
21	Any activity including the operation of that activity associated with the primary processing of a mineral resource including winning, reduction, extraction, classifying, concentrating, crushing, screening and washing but excluding the smelting, beneficiation, refining, calcining or gasification of the mineral resource in which case activity 6 in this Notice applies.	No	
22	Any activity including the operation of that activity associated with the primary processing of a petroleum resource including winning, extraction, classifying, concentrating, water removal, but excluding the refining of gas, oil or petroleum products in which case activity 5 in this Notice applies.	Yes	1
23	The reclamation of an island or parts of the sea.	No	
24	The extraction or removal of peat or peat soils, including the disturbance of vegetation or soils in anticipation of the extraction or removal of peat or peat soils, but excluding where such extraction or removal is for the rehabilitation of wetlands in accordance with a maintenance management plan.	Yes	2
25	The development and related operation of facilities or infrastructure for the treatment of effluent, wastewater or sewage with a daily throughput capacity of 15000 cubic metres or more.	Yes	1
26	Development- (i) in the sea; (ii) in an estuary; (iii) within the littoral active zone; (iv) in front of a development setback; or (v) if no development setback exists, within a distance of 100 metres inland of the high-water mark of the sea or an estuary, whichever is the greater; in respect of – (a) facilities associated with the arrival and departure of vessels and the handling of cargo; (b) piers; (c) inter- and sub-tidal structures for entrapment of sand; (d) breakwater structures; (e) coastal marinas; (f) coastal harbours or ports; (g) tunnels; or (g) underwater channels; but excluding the development of structures within existing ports or harbours that will not increase the development footprint of the port or harbour.	No	
27	The development of – (i) a national road as defined in section 40 of the South African National Roads Agency Limited and National Roads Act, 1998 (Act No. 7 of 1998); (ii) a road administered by a provincial authority; (iii) a road with a reserve wider than 30 metres; or (iv) a road catering for more than one lane of traffic in both directions; but excluding the development and related operation of a road for which an environmental authorisation was obtained for the route determination in terms of activity 5 in Government Notice 387 of 2006 or activity 18 in Government Notice 545 of 2010, in which case activity 24 in Listing Notice 1 of 2014 applies.	No	
28	Commencing of an activity, which requires an atmospheric emission license in terms of section 21 of the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004), excluding – (i) activities which are identified and included in Listing Notice 1 of 2014; (ii) activities which are included in the list of waste management activities published in terms of section 19 of the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008) in which case the National Environmental Management: Waste Act, 2008 applies; or (iii) the development of facilities or infrastructure for the treatment of effluent, wastewater or sewage where such facilities have a daily throughput capacity of 2000 cubic metres or less.	No	
29	The expansion and related operation of facilities for nuclear reaction including energy generation, the production, enrichment, processing, reprocessing, storage or disposal of nuclear fuels, radioactive products, nuclear waste or radioactive waste.	Yes	1

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