DEVELOPING WETLAND DISTRIBUTION AND TRANSFER FUNCTIONS FROM LAND TYPE DATA AS A BASIS FOR THE CRITICAL EVALUATION OF WETLAND DELINEATION GUIDELINES BY INCLUSION OF SOIL WATER FLOW DYNAMICS IN CATCHMENT AREAS

VOLUME 2:

Preliminary Guidelines to Apply Hydropedology in Support of Wetland Assessment and Reserve Determination

Report to the
Water Research Commission

compiled by

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This report forms part of a series of three reports. The other reports are:
- *Improving the management of wetlands by including hydropedology and land type data at catchment level* (WRC Report No. 2461/1/18), and
- *Framework for the regional wetland soil contextualization* (WRC Report No. 2461/3/18).

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EXECUTIVE SUMMARY

In wetland catchments, hydropedological soil surveys, through the application of soil morphology as an established indicator of flowpaths and storage mechanisms of hillslope water, can support the identification of the most important hydrological hillslopes sustaining the wetland hydroperiod, and estimate the timing and duration of this delivered water.

Wetlands are key elements of the catchment landscape. They occur at positions in the landscape where climate, geology, topography and biology create suitable hydrologic conditions, i.e. a postive water balance. They are unique, distinctly different units, frequently managed as isolated from terrestrial ecosystems (Euliss *et al.*, 2008), and with their hydrological link to the terrestrial component of the wetland catchment often poorly understood. Yet, wetlands are dependent on rainfall infiltrating the upslope soil, being partitioned by the subsoil and fractured rock, before flowing down slope to return to the soil surface and wetland, sometimes via a river system. A wetland may thus be considered a signature of the hydrological dynamics of its surrounding catchment.

Wetlands are encapsulated within the concept of a hillslope, which extends from the catchment crest to the wetland centre. Where multiple different hillslopes can be distinguished within the catchment, the wetland hydrological characteristics may be the sum of these hillslopes. Certain hillslopes may contribute more water, and/or for longer. These may be hydropedologically rated (according to water delivery timing and quantity, through interpretation of soil horizons and application of wetland soil indicators, sometimes to depths of several metres) to identify the most critical areas in the catchment likely to provide the dominant hydrological contribution(s) to the wetland. This has implications for assessment of land uses within the catchment, which may differ in their impact on the wetland depending on their location and effect on the wetland water source(s).

This information can be derived from a soil map or Land Type information, but only where the scale of hydrological controls (hillslopes, geological structure and lithology, etc.) is in harmony with the scale of the Land Type information (sometimes it is too coarse making it impossible to interpret information about controls at a scale relevant to wetlands), and where the hydropedology aspects (typically information about deeper soil horizons) were recorded successfully in the soil forms.

Recommended steps for using a soil map or Land Type information for broad predictions of hillslope-wetland interactions include: 1) identifying the broad climate and geology region within which the wetland occurs; 2) mapping the wetland boundary and wetland catchment boundary; 3) dividing the wetland catchment into hillslopes and each hillslope into terrain morphological units based on as detailed terrain mapping or contour information as possible; 4) disaggregating the Land Type information (use the soils listed for each terrain morphological unit and assign to the terrain morphological units within each hillslope); 5) identifying flowpaths and developing a conceptual hydrological response model for each hillslope with expert interpretation of different soil/hillslope characteristics; 6) taking into consideration any additional controls on the wetland outlet which may influence the wetland water regime; and 7) estimating the proportional contribution of each hillslope to the wetland functional unit as a whole.

The guidelines make use of a hydrological response classification (i.e. recharge, shallow interflow, deep interflow and response) of South African soil forms, together with information on the soil forms in the wetland's catchment to determine the relative extent of different hydrological response types in the catchment and within specific hillslopes contained within the catchment. The classification provides a practical means of translating existing soil unit information into hydrological response unit information and can be implemented by anyone with soil interpretation skills as applied in wetland delineation. A consequence of the application of these guidelines is a much expanded project area, beyond the wetland boundary to representative areas of the wetland catchment hillslopes, and the need to excavate multiple representative soil pits or auger to depth using auger extensions.

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GLOSSARY

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: area that drains to a tributary junction.

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.

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.

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

Response: flow rate, volume, and timing of hillslope water or wetland hydropattern, 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 gradient down slope and returning to the soil surface at a lower point the landscape.

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

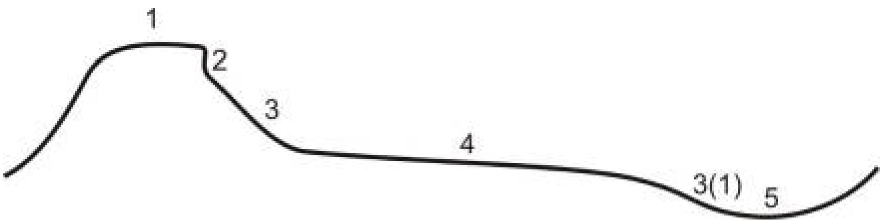
Saturated: all voids filled with water. This is seldom reached in natural conditions. Related to exclusion of air to the point where soil has anaerobic conditions.

Saturated zone: groundwater.

Seasonal saturation or inundation *(of wetland)****:*** wetland area characterised by saturation within 50 cm of the soil surface for 3 to 9 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 3 months of the year (DWAF, 2005).

Terrain morphological unit (TMU): TMU 1 represents crest, 2 scarp, 3 midslope, 3(1) secondary midslope, 4 footslope and 5 valley floor **(**Land Type Survey Staff, 2004).



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

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

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1. INTRODUCTION

These guidelines explore the spatial and temporal contribution of hillslope water to wetlands, and the application of this information to support wetland assessments. There are two parts to the guidelines:

Part 1 ***(Sections 2-6)*** *Interpreting the hydrological response (extent, volume and timing) of the wetland, e.g. after a rainfall event or more broad seasonal hydroperiod response, through identification of spatial and temporal distribution of flowpaths in the hillslope.*

Part 1 supports the identification and spatial selection of key wetland water resource areas, i.e. those hillslope areas most critical in sustaining wetland hydrology. Sections 2-5 provide background supporting information while Section 6 consolidates this supporting information into guidelines of the steps to follow on a desktop and in the field.

Part 2 ***(Section 7)*** *Predicting how land use impacts on the hillslope water source and flowpaths may affect the wetland.*

Part 2 aims to guide decisions on appropriate land use in these locations. For example, paving of crest recharge areas in the catchment may have a much more serious consequence than paving a midslope interflow area, if it is found that the crest recharge area provides the most critical, long-term water source to the wetland. Part 2 would need to be applied together with Part 1, i.e. the critical water source areas would need to first be characterised for the individual catchment.

The guidelines can be approached from three levels of study. A rapid assessment is predominantly a desktop study. It can be undertaken by a general practitioner with limited hydropedological (***hydropedology*** = study of soil-water interactions) expertise, but with GIS skills and access to the literature. A mid-level assessment requires wetland delineation field skills which are applied to identify and qualify the response of flowpaths, and characterise the links between hillslope and wetland. It requires more time and/or a larger team than a typical wetland delineation, as the area of assessment extends up slope beyond the wetland boundary to the hillslope crest(s) and the method requires that soils are investigated to refusal, which may be several metres deep in the catchment slopes. The third level is a specialist level, requiring specific hydropedological expertise to quantify the response (flow rates, volume and time). At this level, strategic field work can also be extrapolated to very large areas (hundreds of hectares) with digital soil mapping expertise.

1.1. Hillslopes as key water sources for wetlands

The application of hydropedology makes it possible to identify water resources and flowpaths within the hillslopes of the wetland catchment from crest to wetland. This is not to imply that a wetland is always found on a valley floor. Rather, it implies that even a midslope wetland has its own wetland catchment, which includes a slope and crest area. A full hillslope, for the purpose of these guidelines, is understood to include both terrestrial and wetland components, and to extend vertically downwards from the soil surface to the groundwater surface.

The contribution of hillslope water to wetlands is often underestimated. Recent studies support the fact that hillslope water may at times be the dominant supply to wetlands. Hillslope water resources are frequently overlooked, as they comprise the hidden half of the hydrological cycle, are difficult to measure, and are spatially variable and temporally extremely dynamic.

1.2. Controls on terrestrial and wetland hydrology of the hillslope

The Department of Water and Sanitation (DWS) directs us to identify and manage key wetland ecosystem drivers, namely water quantity or flow regime, water quality and geomorphology, to ensure that wetlands are used within sustainable limits, where appropriate. These guidelines are focussed on the controls on one driver in particular, water quantity.

Hillslope water resource contributions to wetlands vary in both quantity and timing. The duration of time that the water resource is held in the terrestrial hillslope may be one of the most important drivers of wetland hydroperiod. The time between rain falling on the hillslope crest and the same water reaching the wetland may be a period that can be measured in days or may be as slow as years (Figure 1). This implies a set of controls in the water supply zone (terrestrial controls), in the transition zone to the wetland (terrestrial controls), and in the receiving and discharge zone (wetland controls). Controls are discussed throughout this document, but particularly in Section 2.

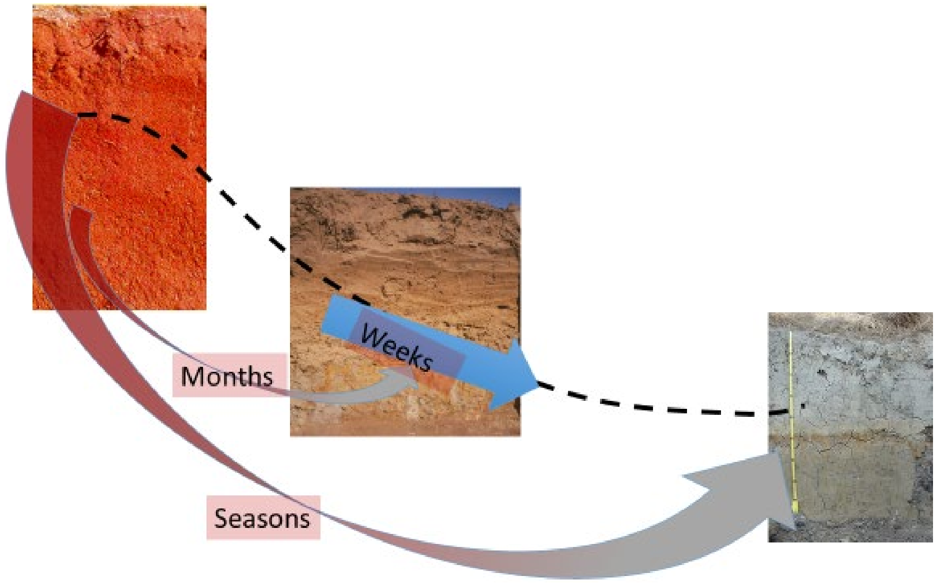


Figure 1. *Generalised residence time of water in hillslopes.*

1.3. Hillslope, terrestrial and wetland, conceptual hydrological response model

Sub-surface controls on hydrology define the hydrological response of the hillslope. The characteristics of the controls, in combination with the flowpaths (flow rate, flow volume, flow route and depth), together predict the water supply to the wetland.

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 six classes (Le Roux *et al*., 2015; Van Tol *et al*., 2013). These are presented in Section 4 and include recharge, shallow interflow, deep interflow and responsive. 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 2, 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.

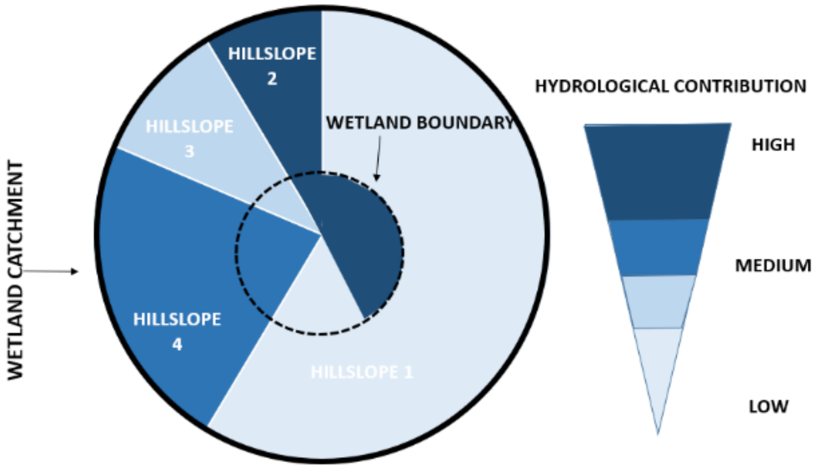


Figure 2. *A generalised wetland catchment, divided into rated hillslopes, and depicting both the wetland (within the wetland boundary) and terrestrial components of the hillslopes.*

A representation of the flow of water in soils and hillslopes is referred to as a conceptual hydrological response model. Such models are discussed further in Section 5. A graphical conceptual hydrological response model for a hillslope, and the cumulative effect for the catchment, can be as simple as Figures 1, 2, or 3, or quantified such as presented in Figure 4 of Section 5. Each hydrological response may also be presented as a hydrograph (representing a period of time between rainfall events) and includes time duration of response and amplitude (Figure 3). A practitioner should be able to develop a simple conceptual hydrological response model, supported by the guidelines in the following pages.

Figure 3 is based on an example taken from the WRC publication "Hydrology of South African Soils and Hillslopes" (HOSASH) (Le Roux *et al*., 2015) of one of the most common hillslope classes supporting wetlands in South Africa, Class 1. In Class 1, all of the main hydrological responses, namely recharge, interflow and responsive soils, are present. Two variants are shown in Figure 3; deep interflow can play a significant role or shallow interflow can dominate. After a rainfall event, the first response is peak flow, as shown in the hydrograph. This first peak of water to the wetland occurs very soon after the rainfall event, as a result of saturation excess overland flow and near-surface quick flow in the hillslope. The larger peak results from interflow water contributing from deeper soil layers. The long "tail" of the graph depicts water that followed a longer flowpath in the hillslope before eventually reaching the wetland. It subsides gradually, until the next rainfall event starts the cycle once again. Together, this contributes to a wetland water regime which would be seasonal in nature, with a water table fluctuating in response to the way the terrestrial controls manipulate the rainfall.

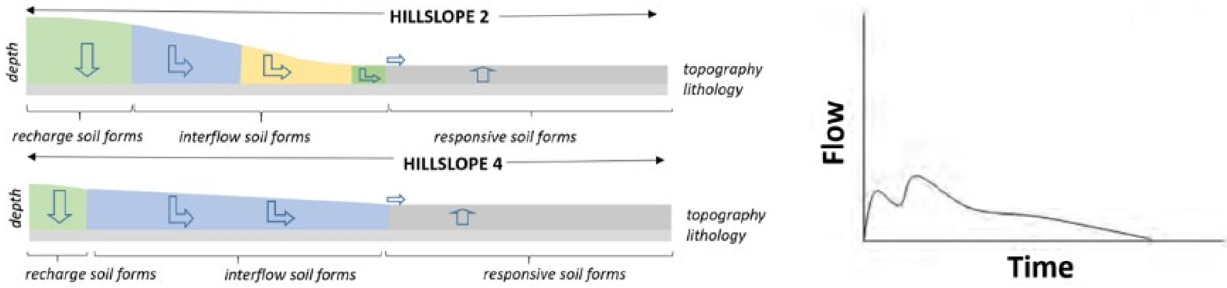


Figure 3. *Variations in hillslope flowpaths of a recharge/interflow/responsive (Class 1) hillslope (adapted from Van Tol et al., 2013).*

1.4. Contribution to wetland assessments and ecological reserve determination

The water which sustains a wetland originates from outside the boundary of the wetland ecosystem. Protection or careful management of the resource areas which capture (recharge) and transport (interflow) water within the hillslope is critical, as they often comprise much of the water that is ultimately delivered to the wetland. The water supply route to the wetland starts with infiltration and drainage of the rainwater. In the process, the soil and fractured rock are filled with drainable water. This process is called ***recharge*** as over time it is slowly emptied. The increased drainage resistance in the flowpath controls lateral flow called ***interflow***. These water resources are often not adequately protected. Legislation and protection is typically rather focussed on the wetland area itself, or expanded to a limited buffer zone surrounding the wetland. However, significant change in the ***present ecological state*** (condition) of the wetlands can very often be linked to human impact outside of the wetland on the associated hillslopes within the wetland catchment.

The effect of human impact on the wetland hydrology can be predicted within the conceptual hydrological response model, which encompasses both the wetland and the terrestrial component of the hillslope(s) of the wetland catchment hillslope(s).

The conceptual hydrological response model can also contribute to wetland reserve determination, as the contribution of the hillslopes to the wetland can be rated, and to complement the assessment of wetland buffers.

PART 1

2. TERRESTRIAL AND WETLAND CONTROLS

Flowpaths can rarely be seen or measured. However, soil-water interaction in hillslopes can be related to signatures which serve as indicators of recharge and interflow and, inferred from this, of the presence or absence of controls of the flowpaths. Indicators of areas of recharge are typically red or “bright” coloured soils, indicating oxidised conditions. From this can be inferred the absence of flow controls, in other words, limited or no resistance to infiltration. In such instances, water which has escaped evapotranspiration (ET) recharges vertically downwards, and can reach and recharge the groundwater aquifer.

Although the hillslope is often called the “unsaturated” (vadose) zone, pockets of water are frequently present. Within the hillslope, three key controls on the accumulation of these water “pockets” include: i) the zone where soil interfaces with rock, ii) the zone where topsoil interfaces with a B horizon, or iii) the interface of two soil horizons with distinctly different permeability. These controls force water to move laterally, especially in combination with the prevailing gradient. Interflow may accumulate on impermeable saprolite or at the valley bottom. Following sufficient accumulation of saturation, water tables rise, flow laterally, and return through the saprolite, rising through the deep subsoil then shallow subsoil to the surface to form wetlands. This is the converse of the commonly held idea of water entering and accumulating from the surface of the wetland. In some hillslopes, multiple flowpaths may be active, both shallow and deep, conveying water at different rates (slow or fast). Overall, deeper flow within the vadose zone is slower and contributes most to the wetland water budget, while shallower flow is faster and much may be lost to ET.

2.1. Climate

Climate makes a contribution to wetland hydroperiod in several ways. For example, in mountainous areas with high and effective rainfall (i.e. the majority of it infiltrates the soil), and an extensive storage system within the mountain lithology, the constant water contribution may support peat accumulation in wetlands. Rocky areas and shallow soils have high ET excess and respond more effectively to rain. At a regional scale, therefore, wetness is expected to increase with effective rainfall. Locally, however, the hydroperiod is controlled by hillslope and wetland controls.

Increased rainfall, decrease in temperature, a high base saturation and periodic saturation, individually or in combination, slightly increase the accumulation of organic carbon. Organic C in wetlands is associated with a combination of high rainfall, a large effective recharge area and controlled return flow. The impact of climate should be assessed, taking effective recharge into account.

2.2. Soil horizons

Soil controls water flow through texture and bulk density visible in the morphology, and soils are also the product of processes of soil formation driven by hydrology. As most South African soils are mature or old, the soil horizons, signatures of these processes, are well expressed. Through the process of classification, South African soils are defined by their horizons. South African soil survey documentation has over decades declared horizons as the core of natural soils (MacVicar *et al.*, 1965; Van der Eyk *et al.*, 1969). They are extremely important in hydropedology. Hydrologically, the topsoil controls the recharge and overland flow relationship, while interflow is controlled within the deep and shallow soil horizons.

Soils and their horizons relate to the interflow hydrology of the hillslope. This implies that downward flow after rain, interflow following that, and the wetting of wetland soils upwards through accumulation of saturation, must all be incorporated into the interpretation of soils. The deeper soil horizons are dependent on pedon and hillslope hydropedology, and therefore reflect the signatures of the combined process. The relationship between soil and hydrology is interactive, as soils also participate in the hydrological control in polypedons and hillslopes. It is, therefore, useful to classify soils using the natural elements.

2.3. Lithology

Rock can be broadly grouped into permeable and non-permeable. In addition to controls within soil horizons, flowpaths below the soil zone follow rock fractures (permeable) and sedimentary bedding planes (impermeable). Rocks play an important recharge role where they are fractured, such as when underlying Mispah (on solid rock) and Glenrosa (on weathering rock) soils. Conversely, sedimentary layering of bedding planes impedes drainage and leads to lateral flow or interflow in the above-lying soils. Dominant bedding planes control flow that may accumulate sufficiently to return to the soil surface in mid-slope positions, at times resulting in a repeating sequence of soils (catena) and flow distribution pattern.

2.4. Topography

The distribution of soils in the landscape and hillslope is systematic, and repeating patterns can be established. The deeper soil horizons are dependent on pedon and hillslope hydropedology, and therefore reflect the signatures of the combined process. In soil terminology, the distribution of soils across or down slope is a ***catena***. Patterns of soil distribution related to terrain morphology have been recognised since 1935, and applied in reconnaissance-scale surveys, including the Land Type Survey (Land Type Survey Staff, 2004). The catenal relationship implies that the impact of hillslope water increases down slope due to interflow, ultimately accumulating in the wetland where it returns to the surface. This is not only true of the profile curvature (down slope) but also of the planform curvature (lateral). A change in colour of the topsoil and subsoil is typical of the plinthic catena of South Africa.

This relationship between topographical setting and soil type from crest to valley bottom is used to predict the distribution of soils and can cut down on fieldwork and cost. Digital Soil Mapping uses this relationship with success. The sequential (catenal) distribution can repeat itself, in relation to recharge, interflow, responsive processes.

2.5. Additional wetland controls

It is widely recognised that wetland hydrology and functions vary according to hydrogeomorphic wetland types. The hydrogeomorphic (HGM) wetland classification system was developed in the USA by Brinson (1993), and defines wetlands based on their landscape position, dominant water source, and direction(s) of water movement (or hydrodynamics). The "*Classification system for wetlands and other aquatic ecosystems in South Africa"* (Ollis *et al.,* 2013) follows the HGM approach to wetland classification, and describes five main wetland types in South Africa.

Schumm (1979) and Knighton (1998) identified a number controls over river form and behaviour, and these have also been confirmed and expanded upon with regard to their contribution to shaping wetland formation and evolution in southern Africa (Table 1).

Table 1. *Documented controls on wetland formation in southern Africa (adapted from Job, 2014)*

Process	Example	Source
Planing of easily weathered and eroded lithologies (such as Karoo Supergroup sedimentary rocks) upstream of a resistant lithology (such as a dolerite dyke)	Klip River floodplain, eastern Free State. Stillerust vlei, KwaZulu-Natal Drakensberg foothills	Tooth *et al.* (2004), Tooth and McCarthy (2007), Grenfell *et al.* (2008)
Faulted basins	Okavango Delta, Botswana.	McCarthy *et al.* (1997)
Sagging due to deep weathering and volume loss of volcanic rocks	Dartmoor vlei, KwaZulu-Natal Midlands, Kings Flats pan, Grahamstown, Eastern Cape	Edwards (2009), Alistoun (2013)
Tributary impoundment by a trunk	Hlatikulu vlei blocking Northington wetland Umfolozi floodplain blocking Futululu wetland Mkuze floodplain blocking Mdlanzi wetland	Grenfell *et al.* (2008), Grenfell *et al.* (2010), Ellery *et al.* (2012)
Trunk impoundment by a tributary	Wakkerstroom vlei, northern KwaZulu-Natal	Joubert and Ellery (2013)
Biological / "ecosystem engineers"	Goukou River palmiet peatland, Riversdale, Western Cape	Job (2014), Sieben (2012)

2.6. Conclusion

At a regional scale, wetness is expected to increase with effective rainfall. Locally, however, the wetland hydroperiod is controlled by terrestrial and wetland controls. The size of the wetland catchment, depth impermeability of the restricting lithology, as well as hillslope gradient, can all affect the ultimate wetland hydroperiod. In general, hillslope water dominates in smaller wetlands in high order catchments (i.e. zero order catchments with no streams or headwaters as well as first order catchments where streams initiate).

The current classification system of six hydrological hillslopes (Section 4) only takes the terrestrial controls into consideration. To infer wetland hydroperiod, an additional climate factor and wetland controls need to be taken into account.

3. HYDROLOGICAL SOIL CLASSES

3.1. Redox, reduced and oxidised morphology indicators

Water flows within spatially distributed flowpaths in the vadose zone. The rate of flow is controlled through interaction with the soil (the biologically active upper part of the vadose zone), as well as the biologically inactive fractured rock (Le Roux *et al.*, 2015). Flow rate and biological activity have an impact on the redox state and evaporation rate of the water. Variation in these factors will control oxidation, reduction, alternating oxidation-reduction processes, and the morphological indicators of these processes.

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 as unit (three-dimensional), the variation in indicators needs to be considered. Note that a thorough knowledge of pedogenesis from arid, semi-arid to humid climates, and the relationship of the resulting soil properties with water flux, cannot be comprehensively captured within these brief guidelines, the majority of which are applicable to semi-arid and wetter climates of South Africa. In arid areas, evaporation dominates, and leaves signatures of precipitates (Van Tol *et al.*, 2013; Tinnefeld, 2016).

Wetlands occur at the point of the terrestrial hillslope where hydrologic conditions create a positive water balance, and where there is prolonged saturation within the top 500 mm of the soil. The range of seasonal (intermittent) to permanent reduction close to the soil surface is expressed as a wetland ecosystem. This same soil morphology expressed deeper beneath the soil surface is applied in hydropedology to interpret sub-surface flowpaths and storage, and to assess the basic flowpaths and rates of water flow in the vadose zone. The dominant hydrological processes of flow at different rates leave signatures within the hillslope such as typical E or G horizons. Along the hydrological hillslope, soil conditions may vary from permanently oxidised, through varying degrees of reduction, to permanently reduced.

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). The rate of oxygen supply and the rate of biological activity contributes to expand the sphere of reduction conditions of near saturation extending the area of reduction beyond the saturated zone. Saturation in fractured rock generally does not influence the redox condition of water due to the lack of an energy resource to the microbes (McCarty and Bremner, 1992). In the deep subsoil, the process is slow due to a limited resource of energy. However, as the organic matter in the soil increases towards the soil surface, reduction is initiated sooner. Where soil saturation reaches the surface as inundation, conditions for reduction are expected to be optimal for that soil. Saturation with water slows down the supply of oxygen to the soil. This impact on reduction is expected to increase down the profile. Combined with the decrease in organic matter content down the profile, the reduction profile may vary. Stagnant saturation or inundation of soil, together with microbial activity, results in depletion of oxygen, exploiting other compounds (e.g. nitrate and other reducible compounds) and elements such as manganese (Mn) and iron (Fe) as suppliers of electrons in the redox reaction and commonly used as visible indicators of the redox process.

Anaerobic conditions therefore result when

a) there is organic matter present,
b) micro-organisms are actively oxidising organic material,
c) the soil is saturated, and
d) dissolved oxygen is removed from the pores (Vepraskas*,* 1995).

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).

Reduction dominates the chemistry of wetland soils, and alternating reduction and oxidation results in distinctive soil characteristics that persist in the soil, leaving signatures of the dominant chemical condition, making them particularly useful as indicators of hydrological processes in soils in the vadose zone. In arid zones, the duration of saturation (especially in soil where ET is high) is short, and organic C content low, limiting reduction. Precipitates of calcium and magnesium are used as signatures of the rates of flow (Van Tol *et al*., 2013; Tinnefeld, 2016).

The degree of saturation sufficient for redox reactions to take place was investigated by Van Huyssteen *et al*. (2005) and supported by several subsequent studies across South Africa (Jennings, 2007; Kuenene *et al*., 2013; Mapeshoane, 2013). The results indicate a range in the degree of saturation varying between 70 and 80%. This implies that reduction morphology can occur above the water table in the capillary fringe but is limited to the zone immediately above the water table. Discussions of the hydrologic thresholds for wetlands have generally emphasised the duration of flooding or saturation needed for reduction to be reached. Vepraskas (1995) states that wetland hydrology involves four related elements, namely: saturation in relation to water table depth; duration of saturation and its relation to growing season; frequency of saturation or flooding; and critical depth of saturation.

These factors are related to the hydrological conditions controlling oxygen exchange and the time required for oxygen to be depleted by microbe activity. Improved understanding of the availability of easily oxidizable organic matter and its relationship with soil depth is an on-going research need. Soils that are infrequently saturated may require an extended period of saturation for anaerobic conditions, and in certain wetlands and wetland types, saturation itself, rather than anoxia, is responsible for the presence of hydrophytes (Tiner, 1999).

Redox morphology

Redoximorphic features have been used for more than three decades to identify soil wetness conditions (Fiedler and Sommer, 2004). In the wetland environment, the presence and abundance of the reduced chemical compounds are thus an indication of intensity and duration of saturation.

The following has been adapted from Swanepoel *et al*. (2008).

The relationship of colour and wetness is largely explained by the oxidation and reduction of Fe and Mn in this redox sequence (Sumner, 2000; Faulkner and Richardson, 1989). In a well-aerated soil, Fe will be present in the oxidised form. The ferric iron [Fe(III)] gives typical reddish to yellow colours to the soil (McBride, 1994). Under saturated conditions, ferric iron could be reduced to ferrous iron [Fe(II)], 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 landscapes via soil solution along redox gradients (Fiedler and Sommer, 2004). After removal of Fe, the soil now has greyer colours and low chromas, and these colour patterns are commonly used to predict the depth of seasonal saturation (Hayes and Vepraskas, 2000).

Bleaching is a recent indicator of reduction and occurs for some time (weeks) after the rain storm (post-event). Bleaching, when combined with a sandy texture, usually around Fe/Mn concretions, is a basic indicator of redox and some leaching.

Distribution of mottling, related to biopores and ped faces and cores, is an indication of periodic saturation (Bouma, 1983). Random distribution of mottling is usually also vesicular, with bleached sandy matrix material. The indications are that there is a degree of interflow in these soils, compared to soils with related distribution patterns.

Oxidised morphology

Red colours indicate that oxidised conditions prevail during and after rain events. The first signs of reduction include black Mn accumulations (the amount depends on the Mn contents of the parent material). The association with reduction is visible in the increase in black mottles down the profile and down slope. High content of smectite clay is related to parent material and darkening to the high clay content.

Age of redox features

The accumulation and hardening of Fe/Mn as concretions and horizons is often referred to as irreversible and relict. The systematics in soil formation and hillslope processes serve as foundation of deciding between relict and active features. No relict hard plinthite reported in literature could be confirmed in a study on plinthite formation (Le Roux *et al.*, 2005). They are in relationship with soil conditions and either the current climate or a climate related to the current climate distribution of South Africa.

Morphological indicators of hydrology in arid climates

In arid climates, the hillslope hydrology is as erratic as the rainfall, and reduction or redox expression in soil morphology is less common. Soil morphology indicates that soils in arid zones rarely saturate long enough for reduction and development of reduction or redox morphology. Morphological indicators are therefore discussed separately and briefly below. They are focussed on the observation of precipitates, such as lime, which form extremely slowly and are often perceived as relict, but are good indicators of flowpaths. The solubility of calcareous, gypsum and salt compounds will 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 (personal observation).

Regional **calcareous deposits** are common in arid zones. In arid zones, calcareous deposits occur in the hillslope where calcium-rich parent materials occur, typically at the crest. In pedons where vertical flow paths dominate, the calcium carbonate leaches downwards. Where interflow is dominant and recharge low, the carbonate contents increase down slope. Calcareous deposits coincide with redox morphology in the arid/semi-arid transition zone (personal observation). They are a good indicator of flowpaths, and can be tracked from where they dissolve during weathering, to where they precipitate, where the water dries out.

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. Table of hydrological soil classes

Van Huyssteen *et al.* (2005), Le Roux (1996) and Le Roux *et al.* (2015) have illustrated the value of soil classification in predicting the soil water regime. Drawing on the evidence of soil morphology, soil chemistry and terrain evaluation properties, soil types may be grouped according to their hydrological response (Van Tol *et al*., 2011, 2013) (Table 2).

Table 2. *Hydropedological soil classes (a hydrological response classification of South African soil forms, adapted from Van Tol et al., 2013)*

Recharge		Interflow		Responsive	
Deep	**Shallow**	**A, E and/or B horizon**	**In deep subsoil, saprolite or fractured rock**	**Shallow or slow infiltration**	**Saturated**
Augrabies, Bonheim	Garies	Cartref	Addo, Askam	Arcadia	Champagne
Brandvlei, Clovelly	Glenrosa	Coega	Avalon, Bainsvlei	Melanic/ solid rock	Katspruit
Concordia, Constantia	Knersvlakte	Dresden	Bloemdal Dresden	Orthic A/ solid rock	Rensburg
Dundee, Etosha	Mayo	Estcourt	Fernwood		Willowbrook
Gamoep, Griffin	Milkwood*	Klapmuts	Glencoe		
Groenkop, Houwhoek	Mispah*	Kroonstad	Immerpan		
Hutton, Inanda	Witbank	Longlands	Lamotte		
Inhoek, Jonkersberg		Nomanci (on solid rock)	Montagu		
Kimberley, Kinkelbos			Pinedene		
Kranskop*, Lusiki		Oudtshoorn	Plooysburg		
Magwa, Molopo		Wasbank	Prieska		
Namib, Oakleaf		Westleigh	Sepane		
Pinegrove, Shortlands			Steendal		
Swartland			Tukulu		
Sweetwater			Vilafontes		
Trawal, Tsitsikama			Westleigh		
Valsrivier			Witfontein		

**Hard rock is fractured and has a high conductivity. Solid rock is impermeable and does not store or release water.*

Table 2 must be applied in conjunction with Tables 3, 4 and 5 in the following sections. These tables discuss the individual soil horizons and their interpretation in more detail.

3.3. Recharge hydrological soil class

Process. Recharge refers to filling with water. Hydrologically, recharge soils take in water at rates similar or faster than the overlying horizon and rainfall intensity. To recharge a soil, evapotranspiration has to be exceeded (described as “ET excess”). Dry soils are recharged with ET excess water when it rains. When their water-holding capacity is exceeded, the water then recharges vertically to the underlying saprolite. Horizons of any hydrological soil class can underlie recharge soil horizons and influence the pedon and hillslope response. In this way, hydropedological recharge water does not necessarily reach the groundwater, but typically feeds the wetland via deep interflow.

Recharge properties to consider include the **area of hillslope** covered, compared to interflow and responsive area, and **volume of the recharge store**, including the saprolite and fractured rock zone. Fractured (not solid) rock exposures are rated high for their contribution to recharge. The fracture system differs between different lithologies. The draining water is water not held by adhesion in rocks. The fractured rock zone is often by far the largest storage volume.

Indicators. Recharge soil horizons are recognised by their lack of redox or reduction morphology.

Impacts. Large areas of recharge increase the potential amount of water a wetland can receive from its catchment. Any reduction of infiltration into recharge soils, often combined with increased overland flow, reduces the impact of rainfall on wetland hydroperiod. Examples of this reduction include surface sealing from structures (mainly roofs) and roads. Transpiration, especially by deep-rooted shrubs and trees, increases the volume that has to be recharged before the water reaches the fractured rock and reduces the contribution of these soils to wetlands. A change from grassland to afforestation is expected to impact on the wetness of the hydroperiod. Increased extraction of water, e.g. through increased transpiration, reduces interflow and the contribution to the wetness of the wetland. When considering area of terrestrial hillslope and storage volume, the vegetation factor needs to be considered. The infiltration rate of soils under natural veld compared with disturbed (ploughed or mixed) may be underestimated a hundred-fold and needs to be quantified. It also depends on tree and shrub cover. The main factor assessing the impact of vegetation on terrestrial flow is the leaf area index and root depth. Trees have a much larger leaf area compared to grass, and a much deeper root distribution.

Table 3. *Hydrological interpretation of diagnostic horizons and other soil properties affecting recharge of lower horizons and materials*

Soil feature	Description	Hydrological interpretation
Soil depth	Soils are deeper because the horizons are thicker and/or more horizons are present	Thicker soils are associated with wetter climates. 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.
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 A/R interflow.
Red apedal B 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 B horizon	Subsoil in recharge soils. On saprolite or fractured rock	Indicates faster drainage than rainfall infiltration. Calcareous families indicate less 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.
Yellow-brown apedal B horizon	Subsoil in recharge soil. On saprolite or fractured rock. Lower in landscape	The hydrology is the same as for the red apedal B 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 B horizon	Subsoil in recharge soil when on saprolite, fractured rock or solid rock	The hydrology varies along with varying saturated hydraulic conductivity.
Lithocutanic horizon	Usually crest positions	Recharge to fractured rock.

Melanic A horizon Orthic A horizon Humic A horizon	Overlying permeable or impermeable horizons	The hydrological response of these horizons is controlled by the subsoil horizons. Recharge of underlying oxidised horizons. Locally, shallow interflow on solid rock at steep slopes. Flow recharge through fractured rock.
Vertic A horizon	Overlying permeable or impermeable horizons	Infiltration rates are high in natural veld and no-till fields. In cultivated land it may be responsive in the rainy season. On impermeable horizons it indicates poor drainage of on level positions and return flow in slopes.
E horizon	Podzol soil forms	Recharge lower horizon. Interflow may be present deeper down the profile.
	Overlying red and yellow-brown apedal B horizons	There are no data or indications that the underlying horizons are less permeable. Bleaching is related to biological activity rather than underlying impermeability.
	Neocutanic B horizon	The rate of saturated hydraulic conductivity is uncertain and may enhance interflow. Most probably bleaching due to biological activity.
Podzol B	Second or third horizon in profile	Recharge of underlying material.
Placic pan	In podzol horizon	The “pan” is not continuous and does not influence the hydrology of the podzol.
Stratified alluvium	Floodplains	Stratification controls water movement.

3.4. Interflow hydrological soil class

Process. Interflow occurs in soil horizons which overlie less permeable horizons. The horizon which restricts drainage may occur at any depth. These horizons depend on recharge return flows from the upslope land and, where permeable, also receive water from overlying horizons. It is, therefore, important to analyse the morphology of the profiles higher up in the hillslope and down slope of an observation. The interflow area varies in slope gradient and in fracture system, and the water content of interflow horizons and soils varies from periodically to permanently saturated. The rate of flow is mainly controlled by slope (Van Tol *et al*., 2013). In interflow soils, the duration of saturation increases vertically down the soil profile and also down slope (Van Huyssteen *et al.,* 2005), as soils saturate from the bottom upwards, with increased duration of saturation down slope. Increased wetness of the deep subsoil in midslope and lower slopes is evidence of interflow in fractured rock to the soil saprolite and deep subsoil in a down slope direction.

Interflow flowpaths are present where hills have more fractures, closer to the soil surface. These return flows are related to interflow in the fractured rock zone and differ in lithology. For example, in Clarens Sandstone, the water follows vertical cracks and flows laterally in dominant bedding planes to exit the sandstone body. Exit points are visible as lichen strips in the Lichens Pass, near Golden Gate, Free State Province. The same process occurs underground. After recharge of the soil, water flows down cracks and then follows a path of cracks leading to the soil lower down. Where the water exceeds the flow and volume of pores, it returns to the surface via the saprolite, deep subsoil, subsoil, topsoil and out on to the surface. Generally, the flow rate increases upwards so that the return flow typically stabilises in one horizon. The simplest model is the sandstones with a wedge-shaped interflow water body. Soil interflow is usually within the ET zone and interpreted to contribute to wetland hydroperiod only if it is below the root zone. This is also the case with fractured rock interflow.

Interflow flowpaths are divided into shallow (< 500 mm) and deep (> 500 mm) flowpaths. The type of interflow is related to the horizons and soil forms (Table 4). Where shallow and deep interflow paths meet, it is usually in the wetland.

Deep interflow is dependent on recharge taking a deep to very deep flowpath (Figure 1). It is related to increasing drainage restriction of the fractured rock. The restriction is not necessarily close to the observed horizon. It may be a zone of slower flow and different chemical character. Deep interflow can therefore be return flow from the fractured rock to the soil. Deep interflow is active weeks to months after rainfall (post-event) and is seasonally driven. Deep interflow through the fractured rock system is usually controlled by a dominant bedding plain at depth as is found in some Karoo sediments or a sand body in the midslope as found in Table Mountain Sandstone, storing large amounts of water. The response to the wetland is post-seasonal and may take years to reach the wetland (Le Roux *et al.,* 2010).

Shallow interflow (Figure 1) is dependent on recharge higher up in the hillslope and a shallow impermeable deep interflow layer. The impermeable layer is not necessarily shallow, but water can build up on a layer only to leave its signatures closer to the soil surface. In this case it is post-event and seasonally driven. Shallow interflow is typically return flow from deep interflow. In cases such as the Cartref soil form, indications are that it forms on a shallow layer of impermeability and, therefore, saturates during rain storms and immediately afterwards, i.e. an event-driven response.

Indicators. Shallow and deep interflow soils are identified by reduction and redox occurring in second and third horizons at least. These soils typically have an interflow component and a return flow component. They have a seasonal response, however, the deep subsoil may be a continuously saturated flowpath. Indicators of flowpaths in the transition from terrestrial to wetland are quite complex. The most common transition is an increase in wetness in the deep subsoil, evidenced by redox features (e.g. mottles) gradually replaced by reduction features (e.g. gleyed soils) as conditions become wetter for longer.

In mineral soils at the transition from the terrestrial to the wetland zone of the hillslope, a change in morphology indicates a split into two flowpaths. Most common is the flowpath that feeds the event and post-event saturated A and E horizons. Besides the rain, some interflow is also expected. The seasonally to permanently wet G horizon cannot be saturated for much longer than the E horizon. The G horizon must be linked to the long, slow flowpaths in the fractured rock system. In granite landscapes, the subsoil flowpaths are limited to saprolite as indicated by plinthic character under the prismacutanic B horizon of bleached Sterkspruit or Estcourt soils. During large storms, flow exceeds conductivity of the saprolite and water flows over the prismacutanic horizon to form a seep line. A Fernwood soil form at the nick point is an indication of repeated intense weathering enhanced by extremely varying conditions at the nick point. One or more deep permanently saturated flowpaths can be active in a terrestrial hillslope. In granite soils, a G horizon frequently occurs at depths exceeding 1 m and as a 4^{th} or 5^{th} horizon, indicating slow flow at depth. A flowpath may also occur beneath the saprolite. These horizons serve as active flowpaths between rainy seasons and have an impact on the duration of wetland hydroperiod.

Impacts. Shallow interflow, irrespective of soil or fractured rock, is commonly within range of land use change activities. The contribution of interflow areas to recharge is affected by surface sealing. The hydrological zone sensitive to land use change extends beyond the typical wetland buffer zone. The extent is dictated by the depth of the flowpaths which have been identified as critical contributors to wetland hydrology and whether the land use change will negatively affect them.

Table 4. *Hydrological interpretation of soil horizons associated with interflow*

Soil feature	Properties	Hydrological interpretation
Deep interflow hydrological soil class		
E horizon	Third horizon or deeper. Often on solid rock	The horizon indicates seasonal to post-seasonal interflow. In the dry semi-arid climates, it may be active only in abnormally wet years.
G 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.
G horizon, mottled	Water flow above and/or below the G horizon	Mottling in overlying horizon indicates periodic saturation but underlying bright mottling under common G horizons.
Solid rock	Solid	Feed interflow.
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.
Shallow interflow		
Orthic A horizon	Bleached and overlying less permeable horizons	Pedocutanic, prismacutanic, hardpan carbonate, solid rock. Event to post-event driven in long hillslopes.
Orthic A horizon	Chromic and on steep slopes	Near surface macropore quick flow. Event driven.
E 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	Post-event driven.
Dorbank	Shallow soil	Event driven.
Prismacutanic B 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 B horizon	Shallow, structured subsoil	The Klapmuts form behaves similarly to the Estcourt. See prismacutanic.

3.5 Responsive hydrological soil class

Soils saturated to the surface support peak flow and, although the overland flow depends on the event-driven surface runoff, the soil is wetted from hillslope interflow (Table 5). During and after rain events makes a contribution but deep interflow feeds the subsoils and even topsoils to stay wet all year round.

Table 5. *Hydrological interpretation of topsoil horizons with slow infiltration associated with peak flow*

Hydrological feature	Properties	Hydrological interpretation
Responsive hydrological soil class		
Vertic A horizon	Extreme swelling	In cultivated land, infiltration is very slow in the wet state.
Gley at the surface	Permanently wet	Duplex soils are seasonal responsive and post-seasonal, shallow interflow soils. Permanently wet soils are responsive all year round.
High organic and peat soils	Stable water table	Organic soils indicate permanent saturation.

3.6 Hydrological response to rainfall events

The rainfall response, predominantly within the interflow zone, can be characterised as follows:

Event-driven interflow implies that the process is only active during and immediately after a rain event or a series of rain events. 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 interflow occurs in topsoils only in midslope and footslope. It is more typical down slope in second and third horizons. Where flow from subsoil horizons builds up to saturate topsoils, two flowpaths may be established, a shallow flowpath that can be event- to permanently saturated, and a deep flow path that can be seasonally to permanently saturated. The soil morphology indicating these horizons is better developed in the transition to the temporary wetland.

4. HYDROLOGICAL HILLSLOPE CLASSES

The distribution of soils in the landscape and hillslope is systematic, and repeating patterns can be established. The sequence of recharge, interflow and responsive areas in hillslopes, and the response and contribution to wetlands, varies accordingly as discussed below. Six hydrological hillslopes (named Class 1 to 6), each with a broadly defined hydrological response, have been described for South Africa (Van Tol *et al.*, 2013). The classes are not presented sequentially from 1 to 6 below, but are rather introduced starting with those classes where wetland occurrence as a result of hillslope hydrology is rare, to those which most commonly support wetlands, with seasonal or permanent wetland hydroperiods.

The hydrological hillslope classes are made up of varying combinations of the three basic soil hydrological types: recharge, interflow and responsive (Van Tol *et al.,* 2011). While the recharge class falls firmly within the terrestrial section of the hillslope, and the responsive class falls firmly within the wetland section, the interflow class occurs across both terrestrial and wetland (seep wetland types) sections of the hillslope. Where interflow is deep and can be observed only when it enters the wetland, the flowpath is in the fractured rock with associated properties in the wetland. There are indications that these flowpaths wet the wetland from underneath. Where the flowpath is shallow, in the upper section of the soil, due to the higher organic carbon content, redox morphology is more common, depending on the extent and depth of indicators of redox and reduction.

Wetlands are rare:

Class 2 is a responsive hillslope, often without a wetland but sometimes with a stream along the valley floor. The flowpaths are overland and near surface. They are steep, often with solid rock outcrops and thin soils. The soil is often eroded, and a good example is the Clarens sandstone outcrops. Peak flow after rain dominates the hydrology of this hillslope. A fractured outcrop will put it in Class 3.

Class 5 is a small recharge area with a large interflow section. The lack of a wetland is an indication that water is lost by transpiration in the interflow section, i.e. the interflow is predominantly shallow.

<u>Wetlands fed by hillslope water are rare, the hillslopes recharge to groundwater. Wetlands in this landscape are, therefore, predominantly driven by groundwater:</u>
<u>Class 3</u> is a hillslope with a large recharge area. The hillslope has some interflow, possibly in the valley bottom. This model is typical of dolomite landscapes. The recharge of groundwater is high.

<u>Wetlands, if present, are not extensive and likely seasonal or temporarily wet:</u>
The opposite to Class 5, **<u>Class 6</u>** is a large recharge area with small interflow and responsive areas. However, as with Class 5, interflow areas are predominantly shallow and lose water to ET, which decreases the amount of hillslope water reaching the wetland.

<u>Wetlands are common, and range from seasonal (most common) to permanent, depending on the characteristics of the flowpath(s):</u>
<u>Class 1</u> is a recharge/interflow/responsive (wetland) hillslope. It is the most common combination used in hydrological models. The flowpath medium (fractured rock, deep subsoil, shallow subsoil or topsoil) and depth of interflow is critical in the contribution to the hydroperiod of the wetland. Slopes with low gradient, shallow flowpaths and soil interflow are associated with relatively dry wetlands. Water losses by ET in the interflow section are dominant.

<u>Wetlands are common and often permanently wet:</u>
<u>Class 4</u> is a large recharge area hillslope with a wetland in the valley bottom. It often has a small interflow section. This is typical of mountainous areas and wetlands with a wet hydroperiod.

5. QUANTIFICATION OF THE CONTRIBUTION OF HILLSLOPES

A model taking into account the terrestrial hillslope characteristics can predict the potential water supply from terrestrial hillslopes to wetlands. This can be useful in developing the reserve determination for a wetland, and in estimating the impact of land use change on either recharge or interflow, and ultimately on the water regime of the wetland.

A hydropedological response map of the wetland catchment divided into hydrological hillslopes (a conceptual hydrological response model) can be developed and translated into a format to suit a hydrological model. The parameters required by the hydrologist need to be gathered during a hydropedological field survey. The accuracy produced with digital soil mapping based on extrapolation of selected field information has been shown to be acceptable (Van Zijl *et al*., 2014). Hydropedology supports a sub-routine focussed on the intermediate horizon between the soil and groundwater, added to the ACRU-Int model (Lorentz *et al*., 2007). This has been shown to improve streamflow prediction, especially towards the end of base flow, when interflow contribution dominates (Lorentz *et al.,* 2007). Semi-quantification of wetland controls can be considered to predict changes in wetland wetness.

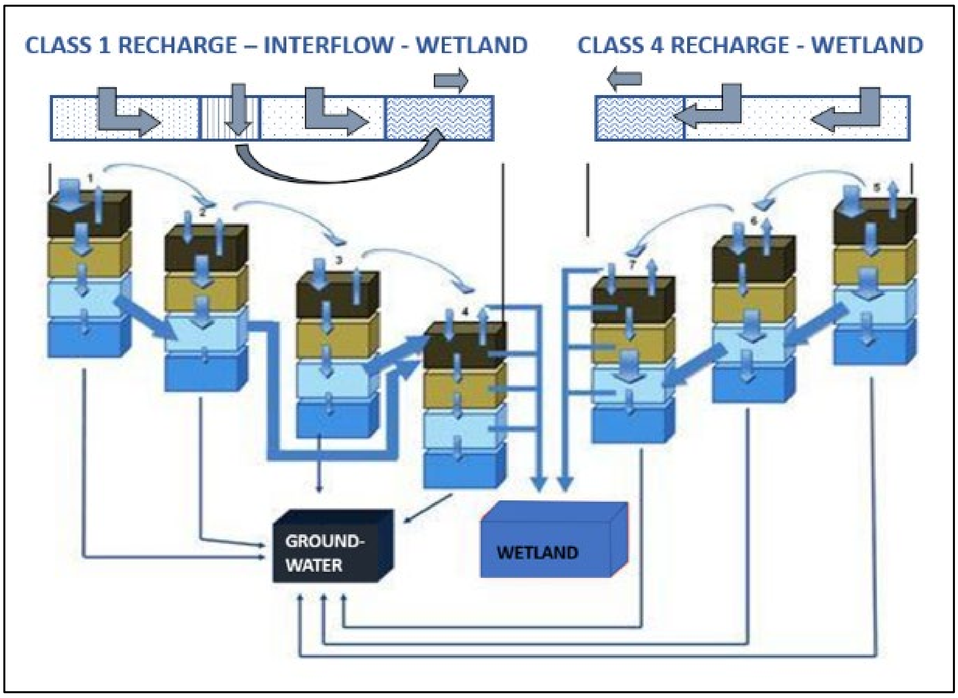


Figure 4. *Example of hillslope hydrological response Classes 1 and 4 contributing to a model (Le Roux et al., 2015).*

6. GUIDELINES PART 1: IDENTIFICATION OF HILLSLOPE WATER SOURCE AND FLOWPATHS TO WETLAND

To support the assessment of drivers of wetland hydrology, a step by step procedure to characterise the hillslopes of a wetland catchment is outlined in the following pages (Figure 5). The level of assessment should be in accordance with the anticipated intensity and scale of land use change impacts. Both the type and risk of impact is important.

DESKTOP PREPARATION

1. Delineate draft wetland boundary

- Map wetland on desktop

2. Delineate wetland catchment

- Map wetland catchment on desktop

3. Consider the role of regional aquifer and rivers

4. Assign hydrological soil class

- Use legend of existing soil map, if available **OR** Use soil forms from Land Type data

5. Divide wetland catchment into hydrological hillslope response classes

- Delineate terrain morphological units (topographic profile curvature)
- Delineate hillslopes (planform curvature)
- Disaggregate Land Type data, allocate soil map
- Classify hillslopes hydrologically

FIELD VISIT

Support with detailed plant and soil auger observations

6. Verify hydrological soil class and hydrological hillslopes

- Verify presence and extent of recharge, interflow and responsive soil groups and arrange into similar hydrological hillslopes

7. Based on Step 6, delineate wetland boundary

- Interpret wetland indicators

8. Within wetland, map wetland hydrological units

- Identify representatives of hydroperiod

9. Based on Step 6, identify terrestrial and wetland controls

- Interpret soil and hydrological properties as well as distribution pattern of soils and hydrological groups to identify controls

DESKTOP FOLLOW-UP

10. Develop and rate conceptual hydrological response model of hillslopes

- Assign a hydrological response Class 1-6 to hillslope(s)
- Predict wetland hydrological response (timing, duration, extent)
- Rate hillslopes according to their contribution to the wetland as indicated by the hydropedological class
- Where required (level of risk and impact), quantify the hillslope contribution using a model

Figure 5. *Proposed work flow.*

STEP 1: DELINEATE DRAFT WETLAND BOUNDARY (DESKTOP STUDY)

Map wetland on desktop checking across multiple imagery resources.

Support: Ideally, make use of imagery across both wet and dry seasons, from recent to historical.

Large-scale	Medium	Fine-scale
LANDSAT (30/15 m pixel) SPOT4 (20/10 m pixel)	SPOT5 (10/5 m pixel) Ortho photographs (<1 m) Google Earth	QUICKBIRD (2.4/0.6 m) Aerial photography (<1 m) Google Earth

Reference: Guidance on how to identify and map a wetland on desktop is provided in *Guidelines for mapping wetlands in South Africa*. Job, N., Mbona, N., Dayaram, A., and Kotze, D. 2018. SANBI Biodiversity Series 28.

STEP 2: DELINEATE WETLAND CATCHMENT (DESKTOP STUDY)

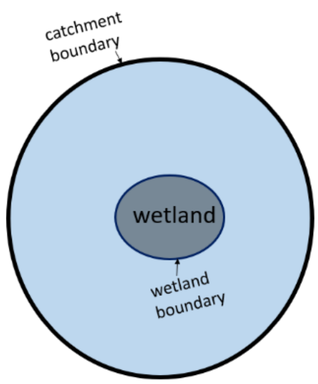
Map wetland catchment on desktop based on topographic contours. Joining all the highest points around a particular wetland, typically delineates the catchment boundary. For large study areas with multiple wetlands, wetland catchments may also be derived.

Support: GIS or topographic map

Resource	Source	Description
5 m or 20 m interval contours and 1: 10 000 spot heights	CD: NGI*	Contour lines help to identify watersheds and drainage, showing the flow of water in the landscape.
Digital elevation models	Multiple sources	Digital Elevation Models (DEM) support modelling of catchment boundaries.

*Chief Directorate: National Geospatial Information

Reference: Guidance on how to identify and map the catchment of a wetland is provided in *WET-Rehab Methods: National Guidelines and methods for wetland rehabilitation* Section 1.6. Russel, W. 2009. Water Research Commission.



STEP 3: CONSIDER THE ROLE OF REGIONAL AQUIFERS AND RIVERS ON WETLAND HYDROLOGY IF FOUND TO BE PRESENT (DESKTOP STUDY)

If the water source is potentially a stream, river or regional groundwater, the assessment must be widened beyond the steps listed in these guidelines. A few preliminary pointers are offered in the following section, but since the focus of these guidelines is on the assessment of hillslope contributions, substantive guidance on groundwater and river contributions is beyond their scope.

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 to the wetland. To field verify the suspected contribution by a stream, check the stream level relative to the prevailing wetland water level. Wetland water levels higher than stream level are likely indicative of a hillslope contribution.

Groundwater contribution to wetlands is difficult to verify without detailed investigation. In many areas, groundwater only makes a contribution in large rivers (Riddel *et al.*, 2014). When possible, incorporate information on the depth to regional groundwater from boreholes or a geotechnical report. The presence of wetland field indicators (Section 3) of a stable hydroperiod (such as gleying or peat soils) may provide supporting evidence of a groundwater contribution, although these indicators may also occur when groundwater is absent, such as when the climate is favourable, in the presence of strong downstream wetland controls, and several other factors.

References: Guidance related to identification of wetland water sources can be found in:

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

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

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

MacFarlane, D.M., Kotze, D.C., Ellery, W.N., Walters, D., Koopman, V., Goodman, P. and Goge, C. 2009. WET-Health: A technique for rapidly assessing wetland health. WRC Report No. TT 340/08. Water Research Commission, Pretoria.

STEP 4: ASSIGN HYDROLOGICAL SOIL CLASS TO WETLAND CATCHMENT SOILS (DESKTOP STUDY)

Table 2 in Section 4 provides a full list of South African soil forms, each allocated to the one of the three hydrological soil classes of Table 6. For example, Hutton falls within the recharge soil class, Bloemdal within the interflow soil class and Katspruit within the responsive soil class. If an existing hydropedological soil map is available, group the soil forms, according to how water is expected to move through them in the hillslope, into the three main hydrological soil class groups listed in Table 6.

Table 6. *Summary of hydrological soil classes*

	Soil morphology indicators	Hydrological process
Recharge	Redox or reduction morphology is absent	Water exceeding ET* flows vertically downwards, with no drainage resistance.
Interflow	Redox morphology occurs at any depth	Bleached sandy soils imply faster lateral water flows. Grey sticky clays imply slow and continuous flow. Mottling implies fluctuating wet and dry conditions. All influenced by depth of drainage resistance.
Responsive	Wetland soil morphology at shallow depth (expressed in plants and wetland ecosystem)	Saturated in the peak rainy season. Response varies.

* *ET = evapotranspiration. The amount of ET excess water depends on climate, soil and vegetation.*

Support: Section 3 and Tables 2, 3, 4 and 5.

References: Further guidance on hydrological soil classes is available in:

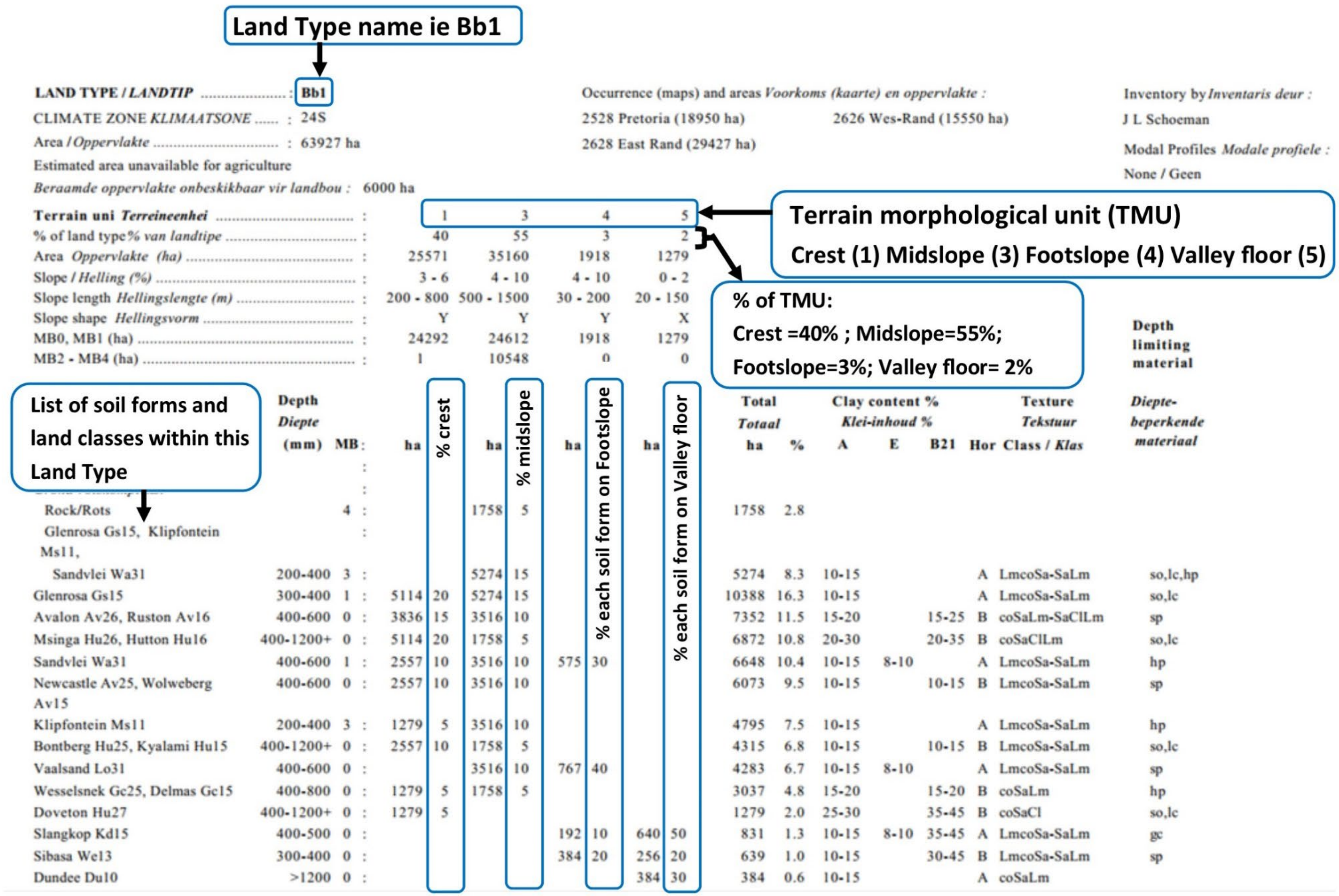
Van Tol, J.J., Le Roux, P.A.L., Lorentz, S.A. and Hensley, M. 2013. Hydropedological classification of South African hillslopes. *Vadose Zone Journal* 12(4).

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 and Jacobs, C.C. 2015. HOSASH: Hydrology of South African Soils and Hillslopes. WRC Report No. 2021/1/15. Water Research Commission, Pretoria.

If no existing hydropedological soil map is available, it is possible to approximate one through disaggregation of Land Type data (Van Zijl *et al.,* 2013), or appoint a specialist to prepare a hydropedological soil map. Disaggregation of Land Type data is explained in Step 5.

Reference: Further examples of disaggregation of Land Type data are available in:

Van Zijl, G.M., Le Roux, P.A.L. and 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.



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

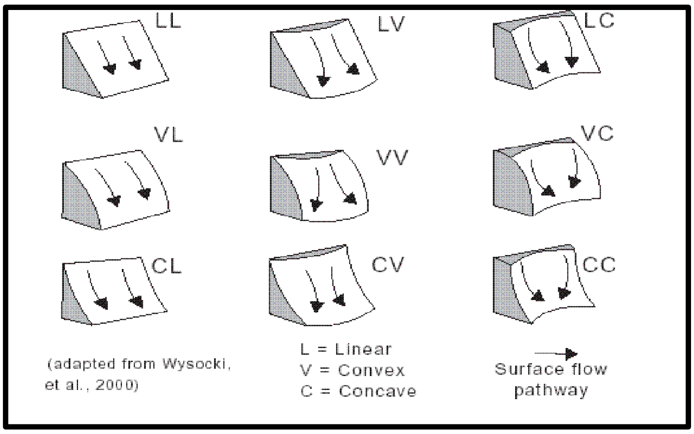
Terrain uni *Terreineenhei*	1	3	4	5
% of land type *% van landtipe*	40	55	3	2
Area *Oppervlakte (ha)*	25571	35160	1918	1279
Slope / *Helling (%)*	3 - 6	4 - 10	4 - 10	0 - 2
Slope length *Hellingslengte (m)*	200 - 800	500 - 1500	30 - 200	20 - 150
Slope shape *Hellingsvorm*	Y	Y	Y	X
MB0, MB1 (ha)	24292	24612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

	Depth *Diepte* (mm)	MB	ha	% crest	ha	% midslope	ha	% each soil form on Footslope	ha	% each soil form on Valley floor	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 6. *Elementary hydropedological disaggregation of Land Type Bb1 inventory.*

STEP 5: DIVIDE WETLAND CATCHMENT INTO HYDROLOGICAL HILLSLOPE RESPONSE CLASSES (DESKTOP STUDY)

The wetland catchment can be divided into morphologically similar hillslopes (Figure 6) through applying the shape of the terrain morphological units (TMU) (Figure 7). These typically include crest, slope (upper, mid and foot) and valley floor, but may be further sub-divided. The relationship with 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. To apply this technique, specialist soil science knowledge is required. The impact of slope and relief should be taken into account (Figure 7 and Table 7).



The distribution down slope (catena) can be used to infer the hydrological class for the wetland catchment. As planform curvature also plays a role, skilled scientists can distinguish between different soils on the ridges and in depressions on the slopes of the Land Type.

Figure 7. *Profile and planform terrain forms (Schoenenberger et al., 2002).*

Table 7. *Impact of slope shape on the interpretation of flowpaths*

Profile curvature	Characteristics of soils	Typical flowpaths
Convex	Drain water to saprolite, weathered rock. Shallow soils, few horizons.	Low drainage resistance if any. Recharge saprolite fractured rock.
Concave	Receive water from up slope through fractured rock to soil return flow. Related to deeper soils and more horizons. Redox morphology increases down slope.	Preferable flowpaths return to saprolite, deep subsoils to shallow soil flow. Increase noticeable in lower part.
Straight	Homogeneous diffuse flow, moderate number of soil horizons.	Homogeneous distribution of flow in homogeneous fracture system. Increased duration of flow down slope.

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 recharge the hillslope and may limit the interflow zone to a small fraction. Concave slopes generally have more interflow. These flowpaths may be deep.

Support sources:

Software	GIS raster layers	Non-GIS
ArcGIS/SAGA/QGIS	30 m DEM available nationally	Topographic map

References: Selected terrain analysis and digital soil mapping references include:

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

Van Zijl, G.M., Le Roux, P.A.L. and 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.

Curvature from crest to valley bottom of the typical hillslope is expressed in the terrain sketch of the Land Type inventory. These are not to scale and are generalised for the whole area, thus needing be adjusted in the field for the specific site. The impact of profile curvature on flowpaths is increased by planform curvature in the order of concave>linear>convex. This relationship improves with a wetter climate. 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. The catenal properties of the Land Type inventory makes them suitable for rapid disaggregation to develop hydrological hillslopes. This is because the Land Type inventory provides a rough ratio of soil types according to TMU down a given hillslope. To disaggregate Land Type data, group the soils in the Land Type inventory (examples in Figures 9 and 10) into hydrological soil classes, making use of Table 2 (Step 4). Hydrological soil classes (Step 4) can be provisionally assigned to TMU position and a hillslope association (catena) on the desktop, following the examples outlined below.

STEP 6: VERIFY HYDROLOGICAL SOIL CLASS AND HYDROLOGICAL HILLSLOPE(S) (FIELD STUDY)

Soil maps are the basis of hydropedological interpretation. Basic soil formation leaves signatures representative of the general conditions of formation (Section 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 hill crest to within the wetland, with soil auger observations (the most common way of exposing soil features), is required. 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. The deeper the soil horizon, the more important its role in hillslope hydrology. Water flows from soils into the underlying fractured rock and may return to the soils within the down slope hillslope. It may then return to the fractured rock system lower down and repeat the return to the soils further down slope. When these flowpaths are in the deep subsoil it is called deep interflow. Signs of recharge and return flow are discussed in Section 3. Short-term indicators (e.g. surface water) should be used with care. 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. Since soil pits are not permitted within wetlands, observations are restricted to the use of an auger.

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 (Turner, 1991). 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. To assign a hydrological soil type, soils are classified into hydropedological classes (Table 2). For increased detail, the results can be improved further by applying the interpretation of individual diagnostic horizons (Tables 3, 4 and 5). At an even higher level of detail, individual soil properties are interpreted. Quantification is covered in Section 5.

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. The surveyor should predict the hydrological response of the horizons, soils and hillslopes (Le Roux *et al.*, 2010, 2013; Van Tol *et al.,* 2013). The response of water flow in soil horizons, soils and hillslopes should be distinguished. Event-driven response is during the rain storm, e.g. infiltration. Post-event-driven response is active after the rain storm, e.g. drainage and active seeps after the rain. This response can last for weeks to months. Seasonal events are active for most of the rainy season. Post-seasonal events continue to respond into the dry season and some may be permanent (Section 3).

Support: See Section 3.

Reference: Methodology can be found for hydropedological surveys (Le Roux *et al.*, 2010, 2013), hillslopes (Van Tol *et al.*, 2013) and catchments (Van Zijl *et al.*, 2014). Turner (1991) gives information on soil description parameters.

STEP 7: DELINEATE WETLAND BOUNDARY (FIELD STUDY)

Current legislation in South Africa requires that wetlands be identified and afforded specific protection measures. Wetland soils fall within the responsive and shallow interflow hydrological types. 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 supporting hydrological interpretation as those outlined above. They must, however, occur sufficiently close to the surface to influence the wetland ecosystem. Step 8 outlines this in more detail. Taking into account the information gathered during Step 6, the following approach is recommended to delineate the wetland boundary.

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. Place successive cores in the same sequence as removed from the hole. Soil colour is quantified with a Munsell Colour Chart. 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 provided datasheet (Appendix 1), 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. On many sites, it is 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 hydrologic properties. 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. As recommended by the USACOE (2016) methodology, once 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 allows. The shape of the local landform can also affect the movement of water through the landscape and should be noted in the datasheet (Appendix 1).

It is recommended that a datasheet be filled out for each representative investigation plot, recording vegetation, soil, topography and visible hydrology. 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). 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.

Support: Appendix 1 datasheet.

References:

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, South Africa.

Kotze, D.C., Klug, J.R., Hughes, J.C. and 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.

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. Vicksburg, MS: U.S. Army Engineer Research and Development Centre.

U.S.D.A. 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. NRCS Wetland Science Institute, Louisiana.

STEP 8: IDENTIFY TERRESTRIAL AND WETLAND CONTROLS (FIELD STUDY)

Terrestrial and wetland controls are recorded and characterised at the same time as undertaking Step 6. Terrestrial and wetlands have most controls in common and these are discussed in Section 2. The controls are subsurface but often associated with surface topography. Subsurface controls include fractured rock with drainage resistance increasing with depth. Closer to the surface, soil horizons and saprolite are often laterally homogeneous but flow control varies in degree of permeability which can broadly be grouped into A/B, B/saprolite and saprolite/rock interfaces. Lateral flow in soil leaves distinctly different pedofeatures associated with the biological activity in soil in contrast to a lack of biological activity in saprolite and fractured rock.

The transition of a flowpath from terrestrial to wetland may be lateral and water follows the same flowpaths as in the terrestrial zone, with an increase in duration of flow obvious in soil flowpaths. Flow arriving in a fractured rock flowpath enters the wetland soil from below. Although this contribution is probably active in all wetlands, it may be the dominant link with terrestrial supply. Indicators are deep interflow, a very sharp transition from terrestrial signs of flowpaths to the wetland and permeable fractured rock. If flow enters predominantly from the side, the wetland soil serves as a clay plug. Flow from the terrestrial zone exceeds flow in the wetland and a seep line develops. The seep line is typically soil with reduction morphology.

Where the terrestrial flow path enters a wetland, the flow rate is controlled by outflow controls from the wetland. The above-listed controls also control the flow of water within and out of the wetland, but a few additional considerations must be taken into account (Section 2). Thus, the final hydroperiod of wetlands may not add up to the expected hillslope outputs, it may be wetter if an additional wetland control is in place. The exposure of soil morphology of several metres deep (using a soil auger) is useful for linking the flowpaths and important for identification of both terrestrial and wetland controls.

Support: The datasheet in Appendix 1 has a section for recording shape, location, and depth to impermeable surface. See also Section 2.

References: In addition to the three below, further references are listed at the end of the document.

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

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

Maherry, A., Marneweck, G., Kapangaziwiri, E., Mandlazi, N.P., Hackman, J., and Mwenge-Kahinda, J-M. 2016. Modelling of Wetland Processes Impacting Water Resources at a Catchment Scale. WRC Report No. 2191/1/16. Water Research Commission, Pretoria.

STEP 9: CHARACTERISE WETLAND HYDROLOGICAL RESPONSE (FIELD AND DESKTOP STUDY)

Characterise and map the spatial extent of wetland hydroperiod classes. Typical classes include temporary, seasonal and permanent. Permanently saturated wetland soils can be divided by organic carbon accumulation, namely peat wetlands (A) and other Champagne soils, reduction morphology including Katspruit and some Kroonstad and Fernwood soils (B).

Link to hillslopes (Section 5) and to rainfall event cycles (Section 3).

Link these to hillslope hydrological response and hydrograph, while considering the role of the control on the wetland outlet in driving the hydroperiod.

References: More information can be found in Ollis *et al.* (2013) and DWAF (2005).

STEP 10: FINALISE CONCEPTUAL HYDROLOGICAL RESPONSE MODEL FOR WETLAND AND WETLAND CATCHMENT (DESKTOP STUDY)

A model taking the hillslope characteristics into account and linking the terrestrial part of the hillslope hydrological response with the wetland response, can predict the potential water supply from terrestrial zones and rate the contribution to wetlands. To do this, the distribution of hydrological soil class and hillslopes are developed into an overall conceptual hydrological response model for the full wetland (Figure 8). This includes linking the event frequency of the final catchment hillslope classes to their relative influence on the wetland.

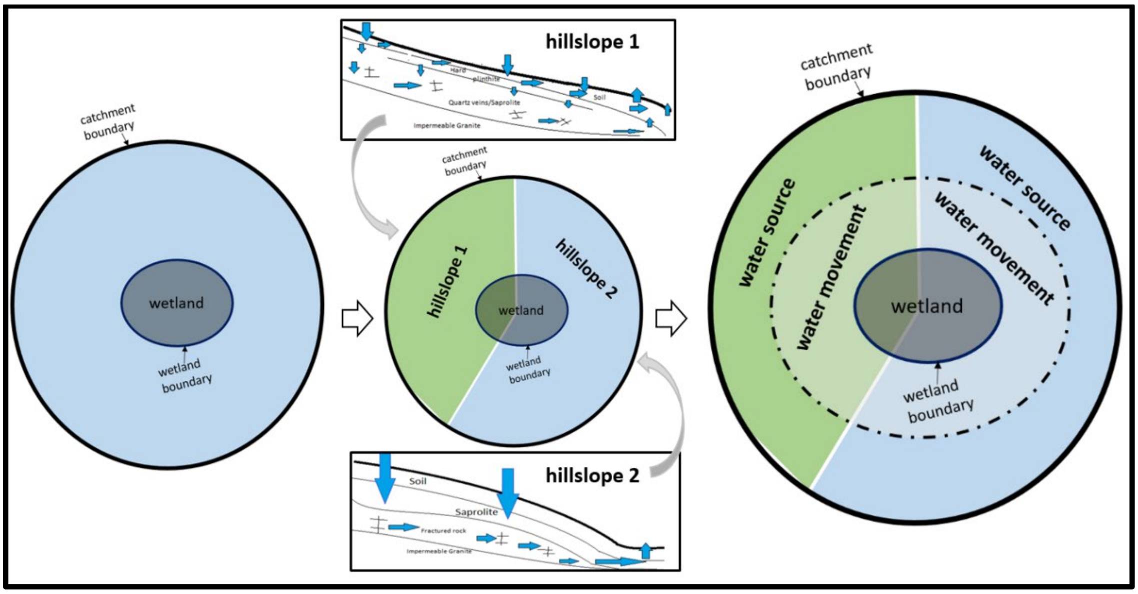


Figure 8. *Summary of components leading to a final conceptual hydrological response model for the entire wetland.*

This can contribute to identification of key water source areas driving wetland function and assessment of alteration from natural response (volume and timing).

Based on a hydropedological assessment of the wetland catchment:

- the location, timing and quantity of non-riverine, overland and sub-surface water delivery to the wetland can be described in more detail, and
- the key impacting land uses can be identified with higher confidence.

This can be used in the reserve determination for a wetland, and in estimating the impact of land-use change on either recharge or interflow, and ultimately on the water regime of the wetland.

PART 2

7. GUIDELINES PART 2: ASSESSMENT OF IMPACTS ON HILLSLOPE WATER SOURCE AND FLOWPATHS, AND EFFECTS ON THE WETLAND

These guidelines align with wetland condition assessment methodology in South Africa (WET-Health; MacFarlane *et al*., 2009) in identifying two fundamental units of assessment:

- the wetland hydrogeomorphic (HGM) unit, and
- the associated wetland catchment.

While WET-Health outlines a comprehensive methodology to assessment of hydrology, geomorphology, vegetation and water quality, these guidelines focus only on wetland hydrology, in particular for wetlands driven by lateral water inputs. They are intended to complement the WET-Health methodology through providing more in-depth assessment and supporting information to characterise, manage and conserve hillslope water resources and the wetlands they supply.

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*., 2009) 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, different land uses are mapped. 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.

Once the extent of different land use types is established within the catchment, each land use is ascribed an intensity score. The intensity of impact is estimated by evaluating the degree of hydrological alteration that results from a given activity. It can also be measured against the degree to which the water source (recharge area) or flow path has been impacted (Tables 12 and 13). Intensity, therefore, can be measured against:

- a 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) (Tables 12 and 13); and

- vulnerability of the HGM wetland type to the land use (based on water input source and local climate broadly divided by WET Health into 5 groups according to MAP:PET ratio).

The WET-Health methodology provides a list of land uses grouped according to whether they lead to an increase or decrease in water reaching the wetland, and rates them according to the significance of their effect on water quantity. The overall magnitude of reduction in quantity of inflows to the wetland is the sum of all the magnitudes for all of the different land use types across all hydrological hillslopes within the wetland catchment.

WET-Health provides a list of land use activities which reduce the quantity of water flowing into a wetland. These include abstraction of water for irrigation and dams, timber plantations, sugarcane and other perennial crops, and woody alien plants. 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.

WET-Health also provides a list of land use activities which increase the quantity of water flowing into a wetland. These include sewerage discharges, storm water and irrigation return flows, and inter-basin transfer schemes. 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 is the infiltration of storm water, and therefore the greater the surface runoff and increase in flood peaks. This has an especially negative affect 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 8. *Risk of local activities impacting on the functions of hydrological soil classes*

Soil feature	Flow process affected	Impact on hydrological response	Risk level
Recharge areas			
Recharge soil	Recharge of soil, fractured rock and groundwater	Surface sealing convert recharge into peak flow and runoff.	High
Fractured rock outcrops	Recharge fractured rock and groundwater	Surface sealing convert recharge into peak flow and runoff.	High
Interflow areas			
Midslope E horizon or bleached A horizon not overlying interflow subsoils	Evapotranspiration, hillslope geophysical properties	Local losses, foreign gains (translocating soils' space-time continuum on the interaction with water, i.e. from midslope interflow to wetland recharge).	Low
Footslope E horizon, bleach A horizon not on interflow subsoils	Shallow flow path returning to soil	Event and post-event flow.	Moderate
Soft plinthic B horizon	Slope 0-1% following from steep slope	Flow from rain recharge. Mainly local. Post-event.	Low
	Slope 2% and higher	Possible return flow.	Moderate
Hard plinthic B	Interflow in deep subsoil or return flow to subsoil, topsoil or even soil surface	Post-event and post-seasonal in wet years.	Moderate
Reducing morphology below 500 mm	Return or recharge flow to subsoil	Seasonal to permanent.	High
Redox morphology below 500 mm	Rainfall or return flow to subsoil	Post-event to seasonal.	High

Table 9. *Risk of local activities impacting on the functions of hydrological hillslope types*

Hydropedological hillslope type	Activities with high impact	Comments	Risk to wetland
1 Recharge-interflow-wetland	Seal recharge zone. Disturb deep interflow zone	Ratio of recharge:interflow < 1:1. Ratio of recharge:interflow >1:1. Soil interflow disturbed.	High Moderate High
2 Interflow-wetland	Disturb interflow zone	Depth of interflow determines contribution to wetland. Crest and upper midslope. Impact increase down slope.	Low
3 Recharge-interflow	Seal recharge zone	Depth of flow important. Interflow ET prone.	High
4 Recharge-wetland	Seal recharge zone	Buffer zone for hydrological purposes questioned.	High
5 Recharge to midslope	Disturb midslope fractured rock to soil return flow	Seeps are associated. It may repeat itself several times down slope.	Moderate
6 Quick interflow	Disturb interflow zone	Not a significant role player in generating flow.	Low

Approaching an assessment in this way links wetland degradation to specific causes and locations within the wetland catchment, leading to informed decision-making and selection of management interventions. The approach outlined throughout this document is useful preparation for a further step of modelling of water inputs, for example with the ACRU-Int model, which may require more resources and time, but offers a more accurate assessment of the hydrological impacts.

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Appendix 1: Example wetland delineation data sheet

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 **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 below surface:________cm
☐ Recent sediment deposits ☐ Salt crust ☐ Algal mat ☐ Aquatic invertebrates ☐ Water-stained leaves ☐ Water marks

☐ Evidence of shallow bedrock/other impermeable 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	OBL/FACW/FAC	% Cover
1			
2			
Etc.			

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

SOIL MORPHOLOGY INDICATOR

Soil Profile Description:

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