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Review

Review of soil form and wetness indicators for wetland delineation in South Africa

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Wetland delineation in South Africa incorporates soil form and soil wetness indicators, requiring formal soil classification and description of soil redox morphology. The current wetland definition used administratively in South Africa focuses on saturated (hydric) soil signatures within plant root zones. Saturated soil horizons deeper than plant root zones fall outside the 50 cm criterion in the local approach as well as the accepted zone in USA literature. The field of hydropedology accommodates the classification of the various hydrologically active horizons and provides a tool for the handling of horizons with ephemeral wetness. This approach has been variably accepted by mandated authorities in South Africa. The South African soil classification system has evolved through three editions over the past 50 years while retaining the same redox morphology understanding. However, despite the concepts and context of redox morphology having been thoroughly technically adopted by soil scientists, this is not the case within the wetland research and management environment. This especially because the classification system is structured differently from other international systems, and the South African landscape is geologically ancient with mature soils, introducing challenges to resource assessment specialists who rely on international norms and approaches for wetland assessment. This paper reviews the various components of soil classification and redox morphology based on Fe and Mn minerals within the context of the South African soil classification system, the field of hydropedology and wetland delineation indicators. We provide a qualitative correlation between the various diagnostic horizons and materials in the system and their related redox morphology contexts that are relevant to wetland assessment, delineation, and protection in South Africa. This paper therefore aims to serve as a reference point for the description and correlation of various soil hydrological parameters used in formal assessments.

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INTRODUCTION

South Africa faces many water-related challenges thereby necessitating the need for the regulatory protection of its water resources. Since 1994, the country has increased its focus on the identification, description, and protection of watercourses (that include wetlands), as reflected specifically in the National Water Act (NWA) (Act No 36 of 1998), as well as other legislation and related administrative processes. Wetland delineation guidelines have been established in 'Appendix W6: Guidelines for delineation of wetland boundary and wetland zones' of the 'Resource Directed Measures for Protection of Water Resources. Volume 4: Wetland Ecosystems' published by the Department of Water Affairs and Forestry (DWAF, 1999). The Resource Directed Measures (RDM) (DWAF, 1999; Kotze and Marneweck, 1999) emphasise the presence of mottles and the expression of soil colour as key features in wetland identification and delineation. In 2005 the 'Wetland Delineation Guidelines, A Practical Field Guide' (WDG) (DWAF, 2005) followed, with emphasis on hydromorphic soils (soil form and soil wetness features within 50 cm of the soil surface) as two of the four wetland indicators (Van der Waals, 2019).

The definition of a wetland in the NWA (RSA, 1998), being narrow – with emphases on regular saturated conditions within the plant-root sphere, is in line with the approach followed in the USA where a large body of literature exists. This approach aligns well with the 50 cm criterion, especially in permanent wetland zones. In South Africa though, more ephemeral wetness conditions are practically accommodated in 'seasonal' and 'temporary' wetland zones, with reference often made to deeper fluctuating or saturated water conditions. The emerging discipline of hydropedology is better suited to dealing with shallow and deep interflow mechanisms (being temporary or seasonal expressions of wetness) feeding responsive (often permanent zone) soils. The conundrum presented by these aspects has not yet been adequately distilled in South African wetland practice.

The two soil-based indicators present a significant challenge due to the requirement for in-field interpretation of the soil form and wetness indicators. This interpretation demands a working knowledge of soil-forming factors and processes, which can be difficult for practitioners lacking a soil classification background. The varied interpretation of redox morphology by wetland practitioners and the three-edition evolution of the South African soil classification system further complicates a standardised approach.

This paper aims to provide (i) a dedicated review of the morphology expression determining the 'soil wetness indicator', and (ii) a correlation between existing soil classification system editions for determining the 'soil form indicator' for wetland delineation in South Africa to guide future guideline updates as well as equip wetland practitioners.

Wetland soil classification context

Section 1 (xxix) of the NWA (RSA, Act No 36 of 1998) defines wetlands as:

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

'Saturated soil', which can be measured through various well-established soil procedures (Pezeshki and DeLaune, 2012), forms the basis of extensive tacit regional South African knowledge. 'Saturation' is defined as the condition where all the soil pores are filled with water, while the 'degree of saturation' is the water content as a fraction of the soil pores expressed on a volumetric basis (Hillel, 1982). While direct measurement is challenging, the long-term effects can be assessed and described based on soil morphology resulting from the effect of anoxic conditions on iron chemistry. Anoxic conditions are prevalent in soils at levels ranging from 70% saturation (Van Huyssteen et al., 2005; Van Huyssteen et al., 2007; Mabuza and Van Huyssteen, 2019) to as low as 60% (Linn and Doran, 1984). Wetland soil identification is based on the effects of prolonged anaerobic conditions on Fe redox morphology (Vepraskas et al., 2006; Vepraskas and Lindbo, 2012).

Three wetland zones based on vegetation parameters are identified in the South African WDG, namely: 'permanent', 'seasonal' and 'temporary' (DWAF, 2005). The guideline provides broad soil wetness indicator criteria (soil colour and mottling), and specified soil forms that may occur in these zones (facultative rather than obligate approach). In contrast, underpinned by an extensive body of literature, wetland identification in the USA is based on the presence of the three parameters, namely, wetland hydrology, hydrophytic plants and hydric soils (Environmental Laboratory, 1987). Within this context, the Hydric Soil Indicators of the United States Department of Agriculture – Natural Resources Conservation Service (USDA–NRCS, 2010) were generated using extensive field information in specific geographic and wetland settings yielding specific wetland indicators.

Wetland soil classification challenges

The 2005 guidelines indicate that "The permanent zone will always have either a Champagne, Katspruit, Willowbrook or Rensburg soil forms present…" (DWAF, 2005 p. 7). However, the updated but unpublished draft circulated in 2008 states (emphasis from source): "***Champagne, Katspruit, Willowbrook or Rensburg soil forms <u>ALWAYS</u> denote wetlands***. These soil forms are diagnostic of wetland and are associated with permanently or seasonally saturated wetlands." The nuanced change in emphasis (facultative versus obligative) has far-reaching implications as many workers and regulating authorities alike erroneously align with the latter. The implication is that where, for instance, Rensburg soil forms regularly occur under bushveld (terrestrial) vegetation, they are often erroneously flagged by workers as constituting permanent wetland zones (Van der Waals, 2019). This and similar aspects yield far-reaching challenges for wetland delineation outcomes that carry administrative burdens or even criminal liabilities.

In practice, several limitations have been identified regarding the soil form indicator. Firstly, many wetland practitioners are not familiar with soil classification and the philosophy and structure of the Taxonomic System (TS; Soil Classification Working Group, 1991). This means that this indicator is seldomly used and reported in wetland reports.

Second, the classification of a soil form in the TS requires a profile description (auger or excavated profile) to a depth of 150 cm (or refusal at shallower depth). The 50 cm mottle depth criterion stipulated in the guideline often leads to field investigations assessing the upper section only and therefore, for expedience, foregoing a classification outcome. Therefore, if only the first 50 cm is considered, it is implied that landscape hydrological processes would not be assessed. The Natural and Anthropogenic System (NAS), published in 2018 (SCWG, 2018) provides for elucidating subsoil horizons and flow paths, taking into consideration the geologically ancient and varied nature of the South African landscape.

No systematic assessment and review of the soil form indicator has been undertaken to date. Job et al. (2018) refer briefly to the 2005 WDG in discussing soil indicators for wetland delineation and assessment. We have indicated since 2009, in unpublished reports and during oral presentations at wetland conferences (Van der Waals, 2009; 2012; 2013; 2014; Van der Waals and Rossouw; 2010; Van der Waals and Fairall, 2011; Van der Waals et al. 2012), that there are challenges with the consistent application of soil form criteria during wetland delineation assessments. Previous unpublished work culminated in a Water Research Commission (WRC) discussion document (Van der Waals, 2019) forming the basis of the current review.

Since the early 2000s, the discipline of hydropedology has developed rapidly in South Africa by generating a growing understanding of soil water flow mechanisms linked to morphological soil properties (Van Huyssteen et al., 2007; Le Roux et al., 2011; Van Tol et al., 2010a; 2010b; 2013a; 2013b). The hydrological functioning of soil forms was categorised by Van Tol et al. (2013a) with this process informing the expansion of soil classification into the NAS, with a subsequent proliferation of soil forms with specific hydrological criteria.

The Department of Water and Sanitation (DWS) issued a 'Guideline for Hydropedological Assessments and Minimum Requirements' in 2021 for wetland impact-related investigations. These guidelines and the associated approach have, however, not been widely adopted by other administrative authorities.

Informal discussions with wetland practitioners and feedback received during the presentation of wetland delineation and hydropedology courses have indicated that there is a critical need for a structured approach to soil form indicator alignment and elucidation, especially for workers not trained in soil science disciplines. The lack of broad uptake is ascribed to: (i) inadequate communication and elucidation of the concepts by the soil science fraternity, and (ii) a large degree of benign ignorance regarding the crucial value that adequate soil information can provide regarding landscape hydrological processes.

Agreement/divergence in USA versus SA approach

A comparison between the South African and USA approaches is useful due to the latter's extensive body of soil classification/wetland soil literature regarding wetland assessment and management for legislative wetland protection (National Research Council, 1995). The USDA Soil Taxonomy groups soils into 'orders' with suborders that include 'aquic soil conditions' (Soil Survey Staff, 2010). These conditions are identified as redoximorphic features based on specific morphological criteria of Fe/Mn, carbon (C), and sulphur (S) features and field tests.

Morphological features have been extensively reviewed (Meek and Grass, 1975; Patrick and Henderson, 1980; Schwab and

Lindsay, 1983; Veneman et al., 1988; Patrick and Jugsujinda, 1992; Lindsay, 1995; Bartlett and Ross, 2005; Lindbo et al., 2010). In a concise summary, Vepraskas and Lindbo (2012) describe the Fe/Mn-based redoximorphic features as consisting of: (i) redox depletions (reductive removal of Fe resulting in low chroma colours), (ii) redox accumulations (oxidation-related accumulation of Fe with associated high chroma colours), and (iii) reduced matrix (long-term reducing conditions resulting in low-chroma gley colours).

While based on a similar approach regarding expression, the WDG (DWAF, 2005) provides a broader categorisation of soil forms and soil morphological features associated with wetlands in SA, with many of these broader parameters not satisfying the criteria for 'aquic soil conditions'. The 2010 USDA–NRCS-defined 'aquic soil conditions', resultant from prolonged saturation, are essentially equivalent to 'permanent wetland zones' in the SA guidelines as identified through specific vegetation indicators (DWAF, 2005). This implies that areas identified according to current South African criteria as more ephemeral 'seasonal' and 'temporary' wetland zones may be much larger than if the USDA-NRCS criteria were used, limiting the applicability of USA-based literature.

Redoximorphic features are context-specific and hydric soil indicators are not easy to apply, therefore requiring regional calibration (Fiedler and Sommer, 2004; Ma et al., 2017). Lime presence and high salt contents in arid areas may even suppress or eliminate such features (Boettinger, 1994; Berkowitz and Sallee, 2011; Castañeda et al., 2017; King et al., 2019). This is also evident in South Africa, where the WDG approach better suits higher rainfall areas, particularly plinthic catena landscapes, compared to arid regions where the existing criteria lose relevance. The WDG do not allude to the geographic variation of specific features, save for dolomite and coastal sand dominated areas – a significant limitation due to the extensive geographical and edaphic variation in South Africa.

The structure of the South African Classification System, as outlined by Buol et al. (1997) and Laker (2003), differs significantly from the USDA Soil Taxonomy in that it specifies a set sequence of diagnostic horizons based on defined morphological features, including specified redoximorphic properties, to define a soil form. Laker (2003) emphasises the difference between continental, predominantly cold climate, elevated organic carbon soils due to recent glaciation with resultant pedologically young Northern Hemisphere landscapes, and the geologically old, hard and highly weathered subtropical to arid Southern African landscapes. The different settings yield highly diverging soils that are dealt with in the South African Classification System in a philosophically different, but regionally relevant manner for local landscape- and classification-based wetland and hydropedology interpretations (Van Huyssteen et al., 2007; Le Roux et al., 2011; Van Tol et al., 2010a; 2010b; 2013a; 2013b, Pretorius et al., 2020; Van Zijl et al., 2020).

REDOX MORPHOLOGY BACKGROUND

Iron oxides are the naturally occurring minerals responsible for the red, orange, yellow, and brown colours found in landscapes and used to infer pedogenic processes (Greenland and Hayes, 1978). The colours are the result of the redox chemistry of Fe (and Mn), with iron hydrolyses and the resulting polymers playing crucial roles in particle aggregation, flocculation, soil pH, and surface charge on soil particles.

Iron redox equilibria and chemistry have been reviewed extensively (Ponnamperuma, 1972; Lindsay, 1988; Schwertmann and Taylor, 1989; Bartlett and James, 1993; Bartlett and Ross, 2005; Cornell and Schwertmann, 2006; Vodyanitskii, 2010). In soil, iron chemistry is a thermodynamic process, driven by reduction and oxidation phases determining its chemical activity related to solubility and speciation. Under oxidised conditions (a function of both Eh and pH), Fe^{2+} donates electrons and is oxidised to Fe^{3+} with a subsequent decrease in solubility and increase in mineral stability (Lindsay, 1979). These minerals are the source of the colours indicative of narrowly defined redox conditions (Greenland and Hayes, 1978; Cornell and Schwertmann, 2006).

Under anaerobic respiration (oxidation of organic matter) conditions, Fe^{3+} acts as an electron acceptor and is reduced to soluble Fe^{2+} (Weber et al., 2006; Vodyanitskii, 2010). Such reduced conditions occur in anaerobic and waterlogged soil zones with high water potential (free water subject to gravity and exerting a positive pressure) and high electron input or scavenging (biological activity) – i.e. wetland soils. Ferrous iron, being soluble, can diffuse in solution and/or be transported with the soil solution and typically results in a low-chroma colour associated with Fe-depleted bleached/white/grey colour silica minerals.

The partial pressure of CO_2 and presence of reduced sulphur species often determine the dominant stable ferrous iron minerals, such as siderite ($FeCO_3$; Lindsay, 1979) or intermediate redox-sensitive minerals (Greenland and Hayes, 1978; Génin, 2004; Trolard and Bourrié, 2008; Ruby et al., 2010). Iron supply (or reserve) determines the extent to which Fe can be reduced with a subsequent matrix colour change (Bartlett, 1999; Rabenhorst and Parikh, 2000). This buffering effect is referred to as 'redox poise'.

Manganese, which occurs widely in natural environments, plays a large role in poising the redox potential, before Fe is reduced (Bartlett, 1999). Manganese undergoes solid state reduction/oxidation reactions, and Mn minerals can consume large proportions of the electrons generated during anaerobic respiration before soluble Mn^{2+} is produced (Swinkels et al., 1984; Bartlett, 1999; Vodyanitskii, 2009).

Iron/manganese minerals and colours in soils and wetland environments

Redox processes yield morphological indicators of specific and dominant soil and landscape conditions, wetland occurrence and hydrological functioning (Fiedler and Sommer, 2004; Chaplot and Walter, 2006; Vepraskas et al., 2006; Lin, 2012a, Lin, 2012b; Vepraskas and Lindbo, 2012). Since the late 1950s, these principles, along with associated soil colours, have been utilized in the South African soil classification system to conduct resource surveys for agricultural development (Loxton, 1962; Van der Eyk et al., 1969; Laker, 2003). Diagnostic horizons and distinctions at the family level within the South African Classification System explicitly include redoximorphic indicators (MacVicar et al., 1977; Soil Classification Working Group, 1991; Soil Classification Working Group, 2018).

The diverse range of contemporary and ancient weathering environments in the South African landscape are readily investigated and described based on the expression of coloured iron compounds (Schwertmann and Taylor, 1977; Greenland and Hayes, 1978; Fitzpatrick, 1988; Fey, 2010). Van Huyssteen et al. (1997; 2007) and Van Huyssteen and Ellis (1997) have indicated a strong correlation between the colour of soil horizons and the degree of wetness and/or duration of water saturation of soil horizons and soil forms in a hydrological sequence (from drier to wetter). The long-term climatic and hydrological characteristics of these landscapes are expressed through the Fe-minerals goethite (α-FeOOH), lepidocrocite (γ-FeOOH), hematite (Fe_2O_3), ferrihydrite ($(Fe^{3+})_2O_3{\cdot}0.5H_2O$), maghemite ($Fe_2O_3$, γ-Fe_2O_3), and magnetite (Fe_3O_4) (Greenland and Hayes, 1978).

Goethite is common in temperate, sub-tropical and tropical regions, imparting a yellow colour. Conversely, hematite is often inherited from parent materials, but is also formed in soils in warm regions with strongly weathered tropical soils, imparting a red colour. These soil sequences are common in the plinthic catena–dominated Highveld area in South Africa (Fey, 2010). Even when goethite is present, yellow colours in soils are often masked by finely-divided hematite that then dominates with a red colour (Schwertmann and Taylor, 1977). In cool humid regions, hematite is systematically replaced by goethite (Greenland and Hayes, 1978; Fey, 1981). Maghemite and magnetite are similar and are formed pedogenically in highly weathered environments (tropical and sub-tropical) and frequently occur as concretions, often magnetic, where they are accompanied by hematite and occasionally goethite. For the South African landscape, Fey (2010) provides a discussion on magnetic and non-magnetic concretions, while Fitzpatrick (1988) offers a dedicated discussion on iron minerals, including ferricretes, in the South African context. Goethite, hematite, maghemite and magnetite indicate well-drained and oxidised soil conditions.

Under moister, but nonetheless dominantly oxidised conditions, the dynamics of the hematite/goethite association is determined by association with other elements such as aluminium (Al). Masedo and Bryant (1989) report on the preferential reduction of hematite compared to goethite by microbes under high water table conditions and attributed the observation to a certain degree of AlOOH substituting for FeOOH over goethite. For investigations in South Africa, Fey (1981), Fitzpatrick and Schwertmann (1982), and MacVicar et al. (1984) reported on similar substitutions in a range of environments and concluded that the pedogenic environment determines the degree of Al-substitution and crystallinity of goethites. Van der Waals (2013) and Clarke et al. (2020) reported on soil colour variations between topsoil and subsoil horizons with a distinct lag in bleaching associated with bleached A horizons overlying yellow-brown apedal (goethite and hematite dominated) horizons, in line with the reports by the aforementioned authors.

Orange-coloured mottles associated with the mineral lepidocrocite are indicative of variable redox conditions where it can be a minor but common constituent of soil clays in humid temperate regions. It is less common in tropical soils where it is often replaced by maghemite (Greenland and Hayes, 1978). Schwertmann and Fitzpatrick (1977) indicated the presence of lepidocrocite under seasonally waterlogged (alternating oxidizing and reducing conditions), non-calcareous hydromorphic soils of the KwaZulu-Natal Province. Fitzpatrick et al. (1985) also identified lepidocrocite at concentrations exceeding 1% in soil samples from New Zealand, South Africa, and Australia, occurring as iron-rich precipitates from watercourses, as well as orange-coloured mottles, bands, crusts and pipestems in hydromorphic soils. Lepidocrocite is therefore associated with gleyed soil materials that occur in the poorly-drained areas of a humid temperate climate with abundant and slow water movement that yields reductomorphic conditions. Loeppert (1988) suggests that lepidocrocite dissolves more readily than goethite and hematite and preferentially forms the latter two under elevated CO_2 partial pressures, explaining why lepidocrocite is not observed in calcareous soils (Schwertmann and Thalmann, 1976).

Lepidocrocite often forms through the formation of an intermediate unstable mixed ferrous-ferric hydroxide or 'green rust' (Greenland and Hayes, 1978), with the specific green-coloured mineral named as 'fougerite' ($[Fe^{2+}_4Fe^{3+}_2(OH)_{12}][CO_3]\cdot 3H_2O$) in 2004 (Trolard, 2006; Trolard and Bourrié, 2008). It is believed that fougerite may be an important precursor to many ferric oxides in soil environments with stable state at Eh conditions of −0.5 to 0.5 V (moderate conditions of reduction) and pH conditions of 6 to 11 (Génin, 2004; Ruby et al., 2010).

Orange-brown-coloured ferrihydrite is formed by ferrous iron oxidation, a process that is catalytically accelerated by iron bacteria through rapid Fe hydrolysis, yielding a poorly crystalline colloidal precipitate referred to as 'hydrous ferric oxide' or 'brown amorphous ferric hydroxide' (Greenland and Hayes, 1978). Such iron oxyhydroxide minerals in aqueous environments are referred to as biogenic iron oxyhydroxides (BIOS) deposits (Weber et al., 2006; Chi Fru et al., 2012). These deposits are often observed where Fe- and Mn-rich anoxic water seeps from locally truncated landscapes, yielding an iridescent film on the water surface or orange-coloured algal strands. The former is often confused with hydrocarbon pollution but is distinguished by the crystalline nature of the film, as opposed to streaking in the case of hydrocarbons. The subsequent transformation of the Fe (and Mn) minerals depends on whether a drying or wetting/inundating trend dominates.

The lack of visible redox accumulations in periodically wet carbonate-dominated soils is attributed to the formation of siderite ($FeCO_3$) – a light-coloured iron carbonate mineral (Klein and Hurlbut, 1985). The increased accumulation of CO_2 under saturated conditions, with associated depletion of O_2, is correlated with the formation of higher siderite concentrations (Lindsay, 1979). Elevated levels of CO_2 can dissolve goethite, with concomitant precipitation of siderite. Upon aeration and oxidation, siderite dissolves, leading to the precipitation of amorphous Fe oxides (orange colours) that transforms to more stable Fe^{3+} oxides. While siderite is stable under poorly aerated conditions, the stable forms of iron in oxidised conditions with elevated CO_2 partial pressures are hematite and goethite (Loeppert, 1988), leading to a lack of bright-coloured mottling (lepidocrocite) in fluctuating wetness environments. Since the transformation of Fe minerals from less stable to more stable forms is a slow process, it is likely that repeated and regular anaerobic cycles may stabilise siderite as a mineral associated with other carbonate mineral deposits. In this sense, it may undergo substitution by magnesium (magnesite – $MgCO_3$) and even Mn to form rhodochrosite ($MnCO_3$) (Klein and Hurlbut, 1985).

Manganese minerals receive much less attention than Fe minerals when the expression of redox morphology is considered. Apart from the iridescent films where Mn plays a role associated with BIOS (Weber et al., 2006; Chi Fru et al., 2012) and its redox poise effect (Bartlett, 1999), Mn occurs as concretions and nodules as well as extensive manganocretes in some cases (Fitzpatrick, 1988, Beukes et al., 1999), often associated with redox accumulations in various mineral forms. In contrast with Fe, Mn is poorly hydrolysed and therefore occurs as oxides in soil (Vodyanitskii, 2009). However, carbonates can inhibit Mn oxidogenesis, and Mn may therefore occur associated with carbonate deposits (rhodochrosite).

Bartlett (1999) suggests that Mn minerals are highly capable of maintaining redox poise with variable electron fluxes. Recent studies conducted in selected soils of the Gauteng Province (Mudaly, 2015) have found that soil Mn content varies significantly and determines the extent of the redox poise, inhibiting Fe reduction in soils with high Mn content. This aspect significantly influences the expression of wetness differences between two adjacent geological zones in the Gauteng Province, the granite/gneiss of the Johannesburg Dome (low Mn content soils) (Robb et al., 2006) and the Chuniespoort Group dolomites (high Mn content soils) (Eriksson et al., 2006), even when vegetation parameters indicate local similarities. In the case of the latter, the Mn-induced poise of dolomite-derived soils is particularly significant.

The reductive removal of Fe and Mn (sesquioxides) and weatherable minerals from soils leads to a relative accumulation of quartz minerals, resulting in a bleached or light-coloured soil matrix (Schaetzl and Anderson, 2005). These sesquioxide-depleted materials are called E horizons, while an albic horizon refers to a light-coloured horizon only (Buol et al., 1997; IUSS Working Group WRB, 2022). Large-scale reductive removal of Fe (and Mn) is often geologically described as pallid or kaolinized horizons/zones in lateritic profiles (McCrea et al., 1990; Schaetzl and Anderson, 2005; Chesworth, 2008). In many cases, the term 'pallid zone' refers to iron-depleted saprolite (McFarlane, 1976; Tardy, 1992; Marker et al., 2002) or 'gleyed saprolite' (Lambrechts and MacVicar, 2004). The term is occasionally used in reports on South African geology or geotechnical matters (Helgren and Butzer, 1977; McKnight, 1997; Vermaak, 2000) and its presence is used to provide context for the African Surface by Partridge and Maud (1987) and Marker et al. (2002).

There is uncertainty regarding the relict versus contemporary nature of Fe-related soil morphology, particularly for hard plinthic material in South Africa. Investigations yield varying results, with some features being identified as contemporary (Le Roux and Du Preez, 2006; 2008) and others as relict (Fitzpatrick, 1988; McKnight, 1997; Vermaak, 2000). According to Fitzpatrick (1988), the South African landscape is often characterised by ancient valleys with Fe-impregnated sediments, and the soils are often relicts of a historically stronger weathering environment. The more pronounced the formation and stability of the features, the more persistent they will be in a drying landscape. Fitzpatrick's (1988) view is that ferricretes formed under more humid historic conditions, and that the current dryer conditions favour their preservation. It is therefore quite certain that there is a mix of relict and contemporary features that are difficult to date and that require adequate elucidation during field investigations.

Redoximorphic/hydromorphic properties and classification (international categories)

Vepraskas and Lindbo (2012) provide a classification framework and detailed analysis of hydric soil properties based on aquic soil conditions for wetlands and hydric soils, within the USDA Soil Taxonomy categories (Soil Survey Staff, 2010). According to the USDA–NRCS (2010), hydric soils exhibit certain indicators such as Fe/Mn-, carbon- (C-) and sulphur- (S-) based features. Vepraskas and Lindbo (2012) state that Fe/Mn-based features, known as redoximorphic features, include:

1. Redox depletions (RD): characterised by the reductive removal of Fe, resulting in low-chroma colours.
2. Redox accumulations (RA): associated with oxidation-related accumulation of Fe, resulting in high-chroma colours. These accumulations can appear as nodules and concretions, soft masses (mottles) and pore linings surrounding root channels and structural cracks.
3. Reduced matrix (RM): a temporary feature, where the entire matrix has a low-chroma colour, but changes to a high-chroma colour upon exposure to air and subsequent oxidation of Fe^{2+} that was in solution.

Carbon-based features manifest as an accumulation of carbon under anaerobic conditions, leading to the development of dark colours, while sulphur-based features are characterised by the formation of H_2S gas under intensive reduction.

According to Vepraskas and Lindbo (2012), hydromorphic features occur, often localised in specific areas within many soils, under the following conditions: (i) presence of organic matter; (ii) presence of organisms actively respiring and oxidizing organic carbon; (iii) soil saturation; and (iv) anoxic conditions (absence of dissolved oxygen in water). The authors further provide seven conditional rules for the occurrence of hydromorphic features that align with the conditions listed above. However, in the first rule they stipulate that redox depletions occur in root growth zones where the four conditions are satisfied. It is implied that in deeper profile conditions, where roots are absent, the occurrence of depletions may not be associated with redoximorphic processes. This stipulation underpins the 50 cm depth criterion prescribed in the WDG approach.

The occurrence of depletions in deeper horizons without roots, such as grey gleyed (G) and plinthic horizons as well as lower-lying bleached eluvial (E) and albic horizons/pallid zones, requires selective application of the stipulation. In many landscapes, anoxic hillslope- or shallow groundwater drive redox depletions at depth in soils (Van Tol et al., 2010a; 2010b; 2013b; Le Roux et al., 2011). It is therefore proposed to rephrase the stipulation for South African conditions as follows: "Redox depletions often occur at depth, associated with oxygen-depleted water in hillslope flow paths or shallow groundwater in mature landscapes." The implications of the amended stipulation are evident in the soil classification parameters discussed later.

In the South African landscape, only limited instances would meet the strict reducing criteria within 50 cm for 'hydric soil' as defined above, and then only specific 'permanent' wetland zone soils. In practice, wetland delineators often refer to the presence of mottles and low-chroma colours in soils as indicative of wetland conditions, thereby including 'seasonal' and 'temporary' zones in this class. When compared to the approach outlined by the USDA–NRCS (2010), the South African situation somewhat exaggerates the significance of these features through the inclusion of non-hydric soils as wetlands. While this 'exaggeration' is pertinent to South African conditions and approaches, it highlights the need for a dedicated assessment of the hydromorphic property descriptions in the South African Classification System and their alignment with the various categorisations by Vepraskas and Lindbo (2012). The most suitable mechanism to deal with these deeper flow paths and more ephemeral wetness indicators is through the discipline of hydropedology.

HYDROMORPHIC PROPERTIES AND THE SOUTH AFRICAN CLASSIFICATION SYSTEM

A comprehensive evaluation of how hydromorphic properties are handled in the South African Classification System requires a systematic analysis of the different horizons and features. The starting point for the discussion of wetness indicators in the South African context will be the Taxonomic System (TS; SCWG, 1991), since this system was most recently in use and is the edition referenced by the WDG. When applicable, references will be made to the preceding Binomial System (BS; MacVicar et al., 1977) and the succeeding Natural and Anthropogenic System (NAS; Soil Classification Working Group, 2018).

Morphological parameters based on iron redox state (e.g., drainage status, soil colours, and various forms of reduced matrix) play a role in the classification, either by inclusion or exclusion, in 49 out of the 72 forms (or 68%) in the TS and in 23 out of the 41 forms (or 56%) in the BS.

Diagnostic chromic horizons

In this review, all horizons that are predominantly well-aerated (and therefore mainly 'terrestrial') are referred to as 'chromic' due to the dominance of oxidised iron minerals (goethite and hematite), resulting in high-chroma colours. This convention is followed regardless of whether the high-chroma colours are visible or not (masked by organic materials, high clay content, clay skins or cutans). Table 1 provides a summary of the colour criteria level and redox morphology features allowed for the chromic horizons as well as their wetland context.

Table 1. Diagnostic chromic (oxidic) horizons in the South African soil classification systems (Soil Classification Working Group, 1991; MacVicar et al., 1977; Soil Classification Working Group, 2018)

Diagnostic horizon	Colour criteria level	Mottles (redox accumulations) allowed	Concretions allowed	Wetland zone context
Red apedal B	Form	Yes, red mottles and a red matrix conditional	Yes	Terrestrial
Yellow-brown apedal B	Form	Yes, Fe/Mn mottling allowed to the point where soft plinthic B criteria start	Yes	Terrestrial
Red structured B	Form	Yes, to a limited extent if red/black mottles	Yes	Terrestrial
Podzol B	Form	Yes, determines classification of the underlying horizon	Yes	Terrestrial
Humic A	Form, darkened by organic carbon	No (humic A horizons are distinguished from wetter orthic A horizons with similar organic C levels through exclusion of redox morphology in the former)	Not specified	Terrestrial
Vertic A	Family	Yes	Yes	Terrestrial
Pedocutanic B	Family	Yes, determines classification of the underlying horizon	Yes	Terrestrial
Neocutanic B	Family	Yes, Fe/Mn mottling allowed to the point where soft plinthic B criteria start	Yes	Terrestrial
Neocarbonate B	Family	Yes, Fe/Mn mottling allowed to the point where soft plinthic B criteria start	Yes	Terrestrial

Apedal chromic horizons (yellow-brown apedal B, red apedal B, neocutanic B)

These chromic horizons are included in the BS and TS, with refined colour boundaries and additional descriptions and field identification criteria in the NAS. They are classified based on colour criteria, predominantly red and yellow to yellow-brown due to the dominance of hematite and goethite, along with limited expression of mottles (redox accumulations/depletions). The threshold for the presence of mottles to exclude a soft plinthic horizon (10% by volume with distinct grey colours) is relevant. The diagnostic neocutanic colour variation is often incorrectly interpreted as redox morphology.

Structured chromic horizons (vertic A, red structured B, pedocutanic B)

The vertic A, red structured and pedocutanic horizons in the BS were retained in the TS and NAS with additional descriptions and field identification criteria. For the vertic A and pedocutanic B, the colour (chromic) criteria are distinguished at family level, as is the presence of carbonates for all three horizons. The red structured horizon has strict criteria regarding the presence of redox morphology (only limited red mottles in a red matrix allowed), whereas the vertic A and pedocutanic B horizons have a wider tolerance before changing to a different diagnostic horizon (predominantly the G horizon).

Chromic horizons containing carbonate

In the BS, apedal soils containing carbonates were categorised under the chromic apedal (yellow-brown, red, neocutanic) B horizons as eutrophic families. Hard carbonate and dorbank materials were included under the Mispah soil form if shallow, and as unspecified materials in other forms if present as a third horizon. In the TS, the chromic horizons containing carbonate were separated from non-carbonate horizons by introducing a neocarbonate B horizon (visible effervescence with 10% HCl solution but dominated by chromic colours). Horizons dominated by carbonate morphology (soft carbonate and hard carbonate as opposed to chromic) were added as second and third horizon options. This resulted in a proliferation of soil forms, with further additions in the NAS as specific combinations occurring at depth in natural profiles were incorporated. New additions in the NAS include the identification of the gypsic horizon, which was previously grouped together with carbonate horizons in the TS. It is important to note that the carbonate horizons may contain mottles, and the threshold for redox morphological features is identified at the family level.

Podzol horizons

In the BS, the original 'ferrihumic' horizon was described and included as a third horizon underneath E horizons, while in the TS, the name was changed to 'podzol' and also accommodated as a second horizon underneath an orthic horizon. The approach of the TS was largely retained in the NAS. Podzol horizons allow for the presence of mottles up to the threshold for a soft plinthic horizon (10% by volume with associated distinct grey colours). Additionally, the podzol accommodates the transition between an overlying E (or bleached orthic A) and underlying materials that may exhibit redoximorphic features.

Humic horizons

Humic horizons are included in the BS, TS, and NAS as surface horizons enriched with organic carbon, formed under well-drained conditions in cool, high-moisture environments (rainfall and mist). In the BS and TS, the presence of redox morphology is strictly prohibited throughout the profile for classification. However, in the NAS, this criterion was relaxed to allow for the presence of redox morphology associated with deeper subsoil horizons – in alignment with the amendment of the rule proposed by Vepraskas and Lindbo (2012).

Diagnostic hydromorphic horizons

In this section, 'hydromorphic' refers to any form of Fe accumulation or depletion resulting from alternating reducing/oxidising conditions, as well as the accumulation of organic matter under dominantly anaerobic conditions due to water. The horizons and features include materials that may be considered relict but still exhibit the morphology of Fe depletions/accumulations. In the South African landscape, many horizons dominated by redox depletions and organic carbon build-up occur in profiles where water enters predominantly through lateral hillslope additions (shallow and/or deep), rather than as the result of a high regional water table.

Peat topsoil horizon (NAS)

In the BS and TS, the peat topsoil horizons (containing more than 20% organic carbon) were classified by default as organic O horizons. However, recent research (Grundling and Grobler, 1995; Grundling et al., 1998; Grundling et al., 2000) identified their absence in the Classification System. The NAS introduced these materials in accordance with international standards set by the International Mire Conservation Group (IMCG) and the International Peat Society (IPS), which define a threshold of 30% organic matter for classifying an area as a peatland (Joosten and Clarke, 2002). Peat materials align with the carbon-based features specified by Vepraskas and Lindbo (2012) for hydric soils, because their formation is dependent on prolonged water saturation and may contain lenses of other materials exhibiting reductomorphic features (such as redox depletions and reduced matrix).

Organic topsoil horizon (BS/TS/NAS)

The organic topsoil horizon (10% to 20% organic carbon), referred to as the organic O horizon in the BS and TS, was retained in the NAS to encompass soils enriched with organic matter that do not meet the criteria for peat classification. These soils, referred to as 'peat soils', have lower carbon levels due to less accumulation, degradation, or mixing, either within the matrix or in lenses, with mineral soil material. They share similar formation conditions with peat and thus conform to the carbon-based features specified by Vepraskas and Lindbo (2012) for hydric soils. Hydromorphic features in the form of redox depletions and a reduced matrix are commonly observed in these soils.

Gley horizon (NAS)

In the TS, the horizon definition of the G includes the phrase "… is saturated for long periods …". This implies that the 'morphological' approach used in the BS was replaced by an 'empirical measurement' approach in the TS, which involves inferring the duration of saturation – a factor that is not easily measured in the field. The NAS provides criteria and practical guidance for identifying and determining 'prolonged saturation'. In the BS, 'gleyed material' under the Champagne (Organic O horizon) was changed to an 'unspecified' horizon in the TS. Other gleyed materials were classified as the G horizon in both the BS and TS. In the NAS, these horizons, along with horizons at depth that were classified as 'unspecified material with signs of wetness' that meet the criteria for the G horizon, are grouped together as 'Gley'. The primary criterion is the dominance of grey, low-chroma colours resulting from prolonged saturation in a grey matrix. Mottles (redox depletions and accumulations) are permitted up to the thresholds for a soft plinthic horizon. The G horizon aligns with the Fe/Mn (redox depletions, redox accumulations, and occasionally reduced matrix) criteria stipulated by Vepraskas and Lindbo (2012) for hydric soils.

Gleyic horizon (NAS)

The BS included the gleycutanic horizon, which was incorporated into the G horizon in the TS. However, field workers expressed the need for a structured G-type horizon that exhibits contrasting colours between ped interiors and exteriors to account for variations observed during soil surveys. In response, the Soil Classification Working Group (SCWG) decided to introduce a new horizon in the NAS called the gleyic horizon, which encompasses the previously defunct gleycutanic horizon as well as the observed field variations of the G horizon. The gleyic horizon is characterised by the same redoximorphic features as the G horizon, but differ in that distinct redox accumulations are observed within peds, while redox depletions are evident on ped surfaces due to regular preferential water flow in these pores. Although a direct correlation between gleyic colour patterns and stagnic colour patterns, as described in the WRB (IUSS Working Group WRB, 2022), for the gley and gleyic horizons, respectively, did not emerge, the WRB approach was used as a rough guideline. The gleyic horizon adheres to the Fe/Mn (redox depletions, redox accumulations) criteria specified by Vepraskas and Lindbo (2012) for hydric soils.

Albic horizon (NAS)

- In the BS and TS, the E horizon is defined as a bleached horizon characterised by sesquioxide and clay depletion at the master horizon level. The diagnostic criteria for clay removal in the TS were not as strict, largely ignored, and subsequently found inaccurate in many E horizons (Turner et al., 2023). During the development of the NAS, the SCWG made the decision to discard the textural criteria for the E horizon and retain only the colour and reductomorphic criteria. As a result, the E horizon was renamed the albic horizon. Albic horizons conform to the Fe/Mn (redox depletions, redox accumulations, and occasionally reduced matrix) criteria for hydric soils as specified by Vepraskas and Lindbo (2012).
- Originally, the E horizon was defined to occur only beneath an A horizon. However, with the removal of textural and horizon sequence criteria, subsoil materials with a bleached matrix could also be classified as albic horizons. This intentional change allows for the specification of horizons that were previously classified as 'unspecified material with signs of wetness' as albic, as long as they meet the colour criteria. The classification of subsoil albic materials now includes pallid or kaolinized horizons (excluding unconsolidated materials) that may exist as subsoil horizons/materials or as layers beneath the classifiable soil profile. The colouration observed in pallid zones is interpreted as an indication of a reduced and Fe-depleted matrix, aligning with the hydric soils criteria set by Vepraskas and Lindbo (2012).
- In the TS, the Fernwood form was redefined from a regic sand to a soil with a deep E horizon. Consequently, the concept of a regic sand in the BS has been modified to include thick eluvial horizons (E – Fernwood) and thick aeolian deposits (Namib) in the TS. This approach was maintained in the NAS, with the change being limited to colour criteria for the albic horizon (indicating eluviation-dominant processes).
- E horizons with low clay content are typically associated with underlying podzol horizons. Since these horizons form through podzolization (complexation) processes rather than prolonged saturation, they do not meet the redox morphology criteria for hydric soils mentioned above.
- The E (albic) horizon is often interpreted as an indication of lateral water flow paths in landscapes (Van Tol et al., 2013b). However, data by Turner et al. (2023) suggests that not all surface albic horizons in the database exhibit characteristics of lateral flow paths. Given the wide variation observed in these horizons, special care must therefore be taken during field surveys and interpretation exercises to contextualise them properly and make inferences about their hydrological functioning.

Soft plinthic horizon (BS/TS/NAS)

The soft plinthic horizon remains consistent in the BS, TS, and NAS. It is characterized by the presence of high-chroma mottles (redox accumulations) comprising more than 10% of the volume, with or without the formation of hardened concretions, as well as grey colours (redox depletions) within or immediately below it.

This horizon indicates a fluctuating water table, either horizontally or through pulses of water in subsoil return flow zones. It aligns well with the Fe/Mn morphology concepts proposed by Vepraskas and Lindbo (2012), although it differs from 'Rule 1' as discussed above. In South Africa, this morphology is widely and correctly used as an indicator of wetland conditions, particularly when it occurs within 50 cm of the soil surface (DWAF, 2005).

Hard plinthic horizon (TS/NAS)

The hard plinthic horizon has been retained in the NAS as described in the BS and TS. These horizons have sparked debates in South Africa regarding their origin, whether they are relics from past higher rainfall climates or contemporary features under the current climate (SCWG, 2018). While there is a general consensus that they are relics, they still contribute to the hydrological functioning of specific landscapes by acting as aquacludes (McKnight, 1997; Vermaak, 2000). Ferricrete materials make up some of the ejecta from the Tswaing Crater event dated at approximately 220 000 years BP (Reimold, 2006), indicating that these horizons were formed and in place in the specific geological and landscape context at the time of the impact. In the Johannesburg Dome area, they form significant portions of the landscape, either as subsoil materials overlying distinct pallid/kaolinized zones or as outcrops in certain landscape positions (McKnight, 1997; Vermaak, 2000). Although in most landscapes these materials may be relics and do not align with the current hydric soil indicators proposed by Vepraskas and Lindbo (2012), they play a crucial role in influencing the expression of such features in other parts of the soil profile, including overlying horizons.

Unconsolidated material with signs of wetness (TS/NAS)

The inclusion of unconsolidated materials in the BS aimed to classify landscapes where the parent materials of the classified profile consist of large volumes of transported material (alluvial and/or colluvial), lacking clear evidence of pedogenesis. These occur predominantly in the Cape Fold Mountains (Botha and Partridge, 2000; Partridge et al., 2006), but they can also be observed in other regions where suitable environmental conditions exist due to topographical variations. Botha et al. (1994) and Botha (1996) describe palaeosol profiles within such materials in the KwaZulu-Natal Province, which exhibit episodes of alteration. In the TS, the concept of 'signs of wetness' was introduced to the diagnostic horizon criteria and retained in the NAS as 'unconsolidated material with wetness'. These signs primarily manifest as grey, low-chroma colours associated with redox morphology, which overlaps with the properties of pallid/kaolinized materials that could be classified as albic horizons in the NAS. This inclusion serves as a transitional arrangement, because further research is necessary to determine their distribution, diagnostic criteria, and measurable properties. The described redox morphology aligns with the Fe/Mn (redox depletions, redox accumulations, and occasionally reduced matrix) hydric soil criteria proposed by Vepraskas and Lindbo (2012).

Hydromorphic properties within diagnostic horizons

In the TS (and retained in the NAS), the inclusion of hydromorphic properties is explicitly incorporated within various diagnostic horizons to distinguish them at the family level. In the TS, these properties are referred to as 'signs of wetness', while in the NAS, they are simply termed 'wetness'. These features are described as (Soil Classification Working Group, 1991 p. 42): "… grey, low chroma colours, sometimes with blue or green tints, with or without sesquioxide mottling. The latter, if present, may be yellowish brown, olive brown, red or black." These wetness-related characteristics are observed within 1.5 meters of the soil surface and encompass a wide range of redox states. Their occurrence and form align with diagnostic horizon classification based on properties other than hydromorphic properties. Table 2 summarises the SA diagnostic horizons featuring redoximorphic characteristics, which correlate with the classifications of Vepraskas and Lindbo (2012). Where these horizons occur as third horizons or deeper they fall below the WDG 50 cm depth criterion, thereby often falling outside of the wetland zone soils but still performing critical roles in landscape hydrology as described in a hydropedology context.

The horizons that encompass these distinctions are:

1. Soft carbonate B (with wetness) (TS/NAS): In this case, the presence of high-chroma mottles is limited due to the prevalence of high-pH soil conditions and the existence of amorphous siderite (as discussed above).
2. Lithocutanic B (TS)/Lithic (NAS): Within the context of weathered and weathering rock, this category encompasses the concepts of saprolithic, geolithic, and gleylithic horizons. Redox morphology often arises due to the presence of water, but it can be difficult to differentiate it from geogenic mottling, which occurs as a result of weathering processes that release Fe and Mn from primary minerals, leading to the formation of apparent redox accumulations. These features exhibit heterogeneity, making it necessary to interpret their adherence to Vepraskas and Lindbo's stipulations (2012) on a site-specific basis. Currently, no comprehensive investigations have been conducted to assess these features on a geographically representative scale in South Africa.
3. Alluvial horizon (NAS) (with wetness – grey matrix colours): The equivalent of this horizon in the BS and TS was referred to as the stratified alluvium horizon. However, in the NAS, the characteristics have been retained with a name change to 'alluvial.' This horizon is characterized by pedologically young, recently deposited material, where stratification has not been eliminated through pedogenesis. The deposition process is such that saturation actively influences or has influenced the expression of morphology, resulting in the development of grey matrix colours (indicating redox depletions) preceding the formation of redox accumulations. When confirmed, these features are classified at the family level and adhere to the criteria outlined by Vepraskas and Lindbo (2012).
4. Prismacutanic (BS/TS/NAS) (continuous black cutans on ped faces): The prismacutanic horizon is frequently observed in landscapes where it transitions into G/gley horizons, necessitating the establishment of distinct criteria to effectively differentiate between the two (Stolk and Van Huyssteen, 2019). In the case of the prismacutanic horizon, if morphological characteristics qualifying as a gley horizon are also present, the prismatic structure is considered dominant for classification purposes only when the structural units are uniformly coated with dark organic compounds (MacVicar and Loxton, 1967). In this context, the horizon will primarily exhibit Fe/Mn redox morphology, and horizons meeting this criterion conform to both the redox morphology and carbon-based categories for hydric soils according to Vepraskas and Lindbo (2012).
5. Materials occurring beneath a placic pan (TS): In the NAS, these materials are referred to as 'Occurrence of gley in or below a podzol horizon' and align with the earlier description of Gley.

Table 2. Diagnostic horizon correlation between the three South African classification editions and the Vepraskas and Lindbo (2012) hydromorphic features

Form level BS – diagnostic horizon	Form level TS – diagnostic horizon	Form level NAS – diagnostic horizon	Hydromorphic features (Vepraskas and Lindbo, 2012)				Wetland zone / subsoil horizon character context
			C-based	Redox depletion (RD)	Redox accumulation (RA)	Reduced matrix (redox morphology)	
Organic C	Organic O	Peat topsoil horizon	XX	X	-	X	Permanent
		Organic horizon	XX	X	-	X	Permanent
G	G	Gley horizon	-	XX	X	XX	Seasonal/permanent
Gleycutanic		Gleyic horizon	-	XX	XX	X	Seasonal/permanent
E	E	Albic	-	XX	X	XX (occasionally)	Seasonal (context specific)
E (on Podzol)	E (on Podzol)	Albic	-	-	-	-	Temporary/terrestrial
Soft plinthic	Soft plinthic	Soft plinthic	-	X	XX	X	Seasonal
Hard plinthite	Hard plinthite	Hard plinthite	-	X	XX	X	Relict, terrestrial / seasonal
-	Unspecified material with signs of wetness	(Gley/Gleyic/Albic/Soft plinthic – now specified)	-	XX	X	-	Seasonal
-	Unconsolidated material with signs of wetness	Unconsolidated material with wetness	-	XX	X	X	Seasonal
	Family level TS – diagnostic horizon	**Family level NAS – Diagnostic horizon**					
-	Soft carbonate B (with signs of wetness)	Soft carbonate (with wetness)	-	XX	(Note pH influence)	X	Temporary/seasonal
-	Lithocutanic B (with signs of wetness)	Lithic (saprolithic, geolithic, gleylithic – features vary)	-	XX	X	X	Temporary/seasonal
-	Stratified alluvium (with signs of wetness)	Alluvial horizon (with wetness)	-	XX	X	-	Temporary/seasonal
-	Prismacutanic B (continuous black cutans on ped faces)	Prismacutanic (continuous black cutans on ped faces)	XX	X (only if C-based present)	-	-	Seasonal
	Family criteria (specific)		-	-	-	-	
-	Materials occurring beneath a placic pan	NAS: "Occurrence of gley in or below a podzol horizon"	-	XX	X	X	Temporary/seasonal

X: possibly present; XX: definitely present; ('Signs of wetness' / 'With wetness': = redoximorphic features)

CORRELATION OF SOUTH AFRICAN SOIL CLASSIFICATION SYSTEM EDITIONS

The three South African soil classification editions are linked by a common structure and philosophy, as discussed earlier regarding redox morphology, thereby making correlation between editions possible. The correlation between the Binomial System (BS – MacVicar et al, 1977), Taxonomic System (TS – SCWG, 1991) and Natural and Anthropogenic System (NAS – SCWG, 2018) is provided in Table 3 (diagnostic topsoil horizons) and Table 4 (diagnostic subsurface horizons underlying orthic A topsoil horizons) followed by expanded elucidation notes.

Correlation of Binomial System with Taxonomic System

In a dedicated review of the South African soil classification system, Laker (2003) discusses the history and evolution of the Binomial System to the Taxonomic System. The extensive Land Type inventory soil profile database also uses the Binomial System.

For many of the Binomial System soil forms, the translation to the equivalent in the Taxonomic System is a direct correlation in that all the criteria (diagnostic horizon definitions and diagnostic horizon sequences) remain essentially the same. However, the 43 forms in the Binomial System were expanded to 71 forms in the Taxonomic System, with each of the added forms constituting the addition of new diagnostic horizons (and criteria). The main expansion was the splitting of apedal horizons as a group into those with and without lime. A limited number of diagnostic horizons' criteria were amended, and this yielded new soil forms or even the deletion of two Binomial System forms. The concept of E vs regic sand horizons (Fernwood soil form) was clarified with clear distinctions between the Namib (regic sand) and Fernwood (E) forms in the Taxonomic System (as discussed earlier).

Correlation of Taxonomic System with Natural and Anthropogenic System

The Land Type data mapping project was completed by the early 2000s (Land Type Survey Staff, 1972–2002). It includes detailed descriptive and analytical information for over 2 500 modal profiles, and approximately 15 000 profiles that are less comprehensively described and analysed, identifying new soils and variations (Van Zijl et al., 2020). In addition, increasing interest in soil classification developed from environmental and hydrological applications as opposed to a previously dominantly agricultural emphasis. Soil hydrological properties are integrally linked to the philosophy of the science and describing the genesis of soils. The result was that the 'pedological sphere of interest' was expanded by the Soil Classification Working Group to include mechanisms for classification of horizons that underlie soil forms that already have 2 or 3 diagnostic horizons (and therefore an established name) in an open-ended system. This was done to accommodate new horizon sequences (and therefore new forms) within a structure where the links with the Taxonomic System remained to provide well-known points of reference. In this sense, much of the TS system regarding procedures and approaches was retained.

Table 3. Correlation matrix between the Binomial, Taxonomic and Natural and Anthropogenic Systems soil forms for specified diagnostic topsoil horizons

Topsoil horizon	Subsoil horizons and soil form – Binomial System (1977)			Subsoil horizons and soil form – Taxonomic System (1991)			Subsoil horizons and soil form – Natural and Anthropogenic System (2018)		
	Second horizon/ material	**Third horizon/ material**	**Binomial System soil form**	**New second subsoil horizon**	**New third subsoil horizon**	**Taxonomic System soil form**	**New second subsoil horizon**	**New third subsoil horizon**	**NAS soil form**
Peat			**New in NAS**				Gley	-	**Mfabeni**
							Albic	-	**Nhlangu**
							Hard carbonate	-	**Muzi**
							Hard rock	-	**Kromme**
Organic	Gleyed material	-	**Champagne**	Unspecified	-	**Champagne**	Gley	-	**Champagne**
			New in NAS				Albic	-	**Manguzi**
							Hard carbonate	-	**Makhasana**
							Hard rock	-	**Didema**
Humic	Yellow-brown apedal B	Red apedal B	**Kranskop**	Yellow-brown apedal B	Red apedal B	**Kranskop**	Yellow-brown apedal	Red apedal	**Kranskop**
		-			**New in NAS**			Gleyic	**Dartmoor**
								Soft plinthic	**Eland**
								Lithic	**Longtom**
			Magwa		Unspecified	**Magwa**	Yellow-brown apedal (thick)		**Magwa**
	Red apedal B	-	**Inanda**	Red apedal B	Unspecified	**Inanda**	Red apedal (thick)		**Inanda**
			New in NAS				Red apedal	Gleyic	**Highmoor**
								Soft plinthic	**Netherley**
								Lithic	**Gangala**
		New in TS		Pedocutanic B	Unspecified	**Lusiki**	Pedocutanic		**Lusiki**
				Neocutanic B	Unspecified	**Sweetwater**	Neocutanic (thick)		**Sweetwater**
			New in NAS				Neocutanic	Soft plinthic	**Umvoti**
							Neocutanic	Lithic	**Henley**
	Lithocutanic B	-	**Nomanci**	Lithocutanic B	-	**Nomanci**	Lithic		**Nomanci**
			New in NAS				Hard rock		**Graskop**
Vertic	G	-	**Rensburg**	G	-	**Rensburg**	Gley		**Rensburg**
			New in NAS				Pedocutanic (thick)		**Glen**
							Soft Carbonate	Gley	**Zondereinde**
							Soft carbonate	Hard carbonate	**Dwaalboom**
							Soft carbonate	Lithic	**Bakwena**
							Hard carbonate		**Waterval**
							Alluvial (thick)		**Mkuze**
	Not specified	-	**Arcadia**	Unspecified	-	**Arcadia**	Lithic		**Arcadia**
			New in NAS				Hard rock		**Rustenburg**
Melanic	G	-	**Willowbrook**	G	-	**Willowbrook**	Gley		**Willowbrook**
			New in NAS				Red structured	Lithic	**Stanger**
	Pedocutanic B	Not specified	**Bonheim**	Pedocutanic B	Unspecified	**Bonheim**	Pedocutanic (thick)		**Bonheim**
			New in NAS				Pedocutanic	Gleyic	**Lauriston**
							Pedocutanic	Alluvial	**Potsdam**
							Pedocutanic	Lithic	**Darnall**
	Lithocutanic B	-	**Mayo**	Lithocutanic B	-	**Mayo**	Lithic		**Mayo**
	Neocutanic B	-	**Inhoek**	Unspecified	-	**Inhoek**	Neocutanic (thick)		**Abbotspoort**
	Stratified alluvium		**Inhoek**			**Inhoek**	Alluvial (thick)		**Inhoek**
	Hard rock, hardpan ferricrete, hardpan calcrete, hardpan silcrete or dorbank		**Milkwood**	Hard rock	-	**Milkwood**	Hard rock		**Milkwood**
				Soft carbonate B	-	**Steendal**	Soft carbonate		**Steendal**
				Hardpan carbonate	-	**Immerpan**	Hard carbonate		**Immerpan**
	Soft plinthic B	-	**Tambankulu**	Soft plinthic B	-	**Discontinued**			**Discontinued**

Table 4. Correlation matrix between the Binomial, Taxonomic and Natural and Anthropogenic Systems for soil forms with Orthic topsoil horizons

Subsoil horizons and soil form – Binomial System (1977)			**Subsoil horizons and soil form – Taxonomic System (1991)**			**Subsoil horizons and soil form – Natural and Anthropogenic System (2018)**		
Second horizon/ material	**Third horizon/ material**	**Binomial System soil form**	**New second subsoil horizon**	**New third subsoil horizon**	**Taxonomic System soil form**	**New second subsoil horizon**	**New third subsoil horizon**	**NAS soil form**
G	-	**Katspruit**	G	-	**Katspruit**	Gley		**Katspruit**
E	G	**Kroonstad**	E	G	**Kroonstad**	Albic	Gley	**Kroonstad**
	Soft plinthic B	**Longlands**		Soft plinthic B	**Longlands**		Soft plinthic	**Longlands**
	Hard plinthic B	**Wasbank**		Hard plinthic B	**Wasbank**		Hard plinthic	**Wasbank**
	Yellow-brown apedal B	**Constantia**		Yellow-brown apedal B	**Constantia**		Yellow-brown apedal	**Constantia**
	Ferrihumic B / unconsolidated material	**Lamotte**		Podzol B with placic pan	**Tsitsikamma**		Podzol with placic pan	**Tsitsikamma**
				Podzol B / uncon. mat. with signs of wetness	**Lamotte**		Podzol / uncon. mat. with wetness	**Lamotte**
				Podzol B / uncon. mat. no signs of wetness	**Concordia**		Podzol	**Concordia**
	Ferrihumic B / saprolite	**Houwhoek**		Podzol B / saprolite	**Houwhoek**		Podzol/lithic	**Houwhoek**
	Prismacutanic B	**Estcourt**		Prismacutanic B	**Estcourt**		Prismacutanic	**Estcourt**
	New in TS			Pedocutanic B	**Klapmuts**		Pedocutanic	**Klapmuts**
	Neocutanic B	**Vilafontes**		Neocutanic B	**Vilafontes**		Neocutanic	**Vilafontes**
	-	**New in TS**		Neocarbonate B	**Kinkelbos**		Neocarbonate	**Kinkelbos**
	Lithocutanic B	**Cartref**		Lithocutanic B	**Cartref**		Lithic	**Cartref**
	Red apedal	**Shepstone**		-	**Discontinued**		Red apedal	**Shepstone**
				New in NAS			Hard rock	**Iswepe**
Regic sand	-	**Fernwood**		Unspecified	**Fernwood**		(Thick horizon)	**Fernwood**
Soft plinthic B	-	**Westleigh**	Soft plinthic B	-	**Westleigh**	Soft plinthic		**Westleigh**
New in TS	-	**(Mispah)**	Hard plinthic B	-	**Dresden**	Hard plinthic		**Dresden**
Yellow-brown apedal B	Soft plinthic B	**Avalon**	Yellow-brown apedal B	Soft plinthic B	**Avalon**	Yellow-brown apedal	Soft plinthic	**Avalon**
	Hard plinthic B	**Glencoe**		Hard plinthic B	**Glencoe**		Hard plinthic	**Glencoe**
	Gleycutanic B	**Pinedene**		Unspec. mat. with signs of wetness	**Pinedene**		Gleyic	**Pinedene**
							Albic	**Kransfontein**
	Red apedal B	**Griffin**		Red apedal B	**Griffin**		Red apedal	**Griffin**
	Not specified	**Clovelly**		**New in NAS**			Neocutanic	**Palmiet**
				Soft carbonate	**Molopo**		Soft carbonate	**Molopo**
				Hardpan carbonate	**Askham**		Hard carbonate	**Askham**
				Unspecified	**Clovelly**		Lithic	**Clovelly**
							Hard rock	**Carolina**
							(Thick horizon)	**Ermelo**
		Lime containing Clovelly	All yellow-brown apedal horizons containing lime are re-classified as neocarbonate horizons irrespective of colour in TS. Refer to neocarbonate horizon.					
Red apedal B	Soft plinthic B	**Bainsvlei**	Red apedal B	Soft plinthic B	**Bainsvlei**	Red Apedal	Soft plinthic	**Bainsvlei**
	Not specified	**Hutton**	Red Apedal	Hard plinthic B	**Lichtenburg***		Hard plinthic	**Lichtenburg**
				Unspec. mat. with signs of wetness	**Bloemdal**		Gleyic Albic	**Bloemdal**
				New in NAS			Neocutanic	**Tongwane**
				Soft carbonate	**Kimberley**		Soft carbonate	**Kimberley**
				Hardpan carbonate	**Plooysburg**		Hard carbonate	**Plooysburg**
				Dorbank	**Garies**		Drobank	**Garies**
				Unspecified	**Hutton**		Lithic	**Nkonkoni**
							Hard rock	**Vaalbos**
							(Thick horizon)	**Hutton**
		Hutton containing lime	All red apedal horizons containing lime are re-classified as neocarbonate horizons irrespective of colour in TS. Refer to neocarbonate horizon.					
Red structured B	-	**Shortlands**	Red structured B		**Shortlands**	Red structured	Lithic	**Magudu**
						Red structured	Hard rock	**Nshawu**
						Red structured (thick)		**Shortlands**
New in TS	-	-	Podzol B with placic pan		**Jonkersberg**	Podzol with placic pan		**Jonkersberg**
			Podzol B / uncon. mat. with signs of wetness		**Witfontein**	Podzol	Uncon. mat. with wetness	**Witfontein**
			Podzol B / uncon. mat. no signs of wetness		**Pinegrove**	Podzol		**Pinegrove**
			Podzol B / saprolite		**Groenkop**	Podzol	Lithic	**Groenkop**

*The Lichtenburg form was not originally included in the TS but was later accepted by the SCWG as an additional form.

Table 4 Continued. Correlation matrix between the Binomial, Taxonomic and Natural and Anthropogenic Systems for soil forms with Orthic topsoil horizons

Subsoil horizons and soil form – Binomial System (1977)			Subsoil horizons and soil form – Taxonomic System (1991)			Subsoil horizons and soil form – Natural and Anthropogenic System (2018)		
Second horizon/ material	**Third horizon/ material**	**Binomial System soil form**	**New second subsoil horizon**	**New third subsoil horizon**	**Taxonomic System soil form**	**New second subsoil horizon**	**New third subsoil horizon**	**NAS soil form**
Prismacutanic B	-	**Sterkspruit**	Prismacutanic B	-	**Sterkspruit**	Prismacutanic	(Thick horizon)	**Stekspruit**
							Gleyic	**Idutywa**
							Pedocutanic	**Heilbron**
							Alluvial	**Utrecht**
							Lithic	**Sandile**
							Hard rock	**Cookhouse**
Pedocutanic B	Unconsolidated material	**Valsrivier**	Pedocutanic B	Uncon. mat. no signs of wetness	**Valsrivier**	Pedocutanic	(Thick horizon)	**Valsrivier**
							Hard rock	**Spioenberg**
				Uncon. mat. with signs of wetness	**Sepane**		Gleyic	**Sepane**
							Alluvial	**Queenstown**
	Saprolite	**Swartland**		Saprolite	**Swartland**		Lithic	**Swartland**
Neocutanic B	None specified	**Oakleaf**	Neocutanic B	Unspec. mat. with signs of wetness	**Tukulu**	Neocutanic	Gleyic Albic	**Tukulu**
				New in NAS			Pedocutanic	**Erin**
							Neocarbonate	**Makgoba**
				Soft carbonate	**Etosha**		Soft carbonate	**Etosha**
				Hardpan carbonate	**Gamoep**		Hard carbonate	**Gamoep**
				New in NAS			Gypsic	**Soutvloer**
				Dorbank	**Oudtshoorn**		Dorbank	**Oudtshoorn**
				New in NAS			Uncon. mat. with wetness	**Tshiombo**
							Alluvial	**Quaggafontein**
							Lithic	**Tubatse**
							Hard rock	**Bethesda**
				Unspecified	**Oakleaf**		(Thick horizon)	**Oakleaf**
			Oakleaf containing lime	All neocutanic horizons containing lime are re-classified as neocarbonate horizons irrespective of colour in TS. Refer to Neocarbonate horizon.				
New in TS	Lime containing Clovelly / Hutton / Oakleaf with effervescence with 10% HCl solution only		Neocarbonate B	**New in NAS**		Neocarbonate	Pedocutanic	**Palala**
				Soft carbonate	**Addo**		Soft carbonate	**Addo**
				Hardpan carbonate	**Prieska**		Hard carbonate	**Prieska**
				New in NAS			Gypsic	**Sendelingsdrif**
				Dorbank	**Trawal**		Dorbank	**Trawal**
				Unspec. mat. with signs of wetness	**Montagu**		Uncon. mat. with wetness	**Montagu**
				New in NAS			Alluvial	**Motsane**
							Lithic	**Burgersfort**
							Hard rock	**Hofmeyr**
				Unspecified	**Augrabies**		(Thick horizon)	**Augrabies**
New in NAS						Soft carbonate	Uncon. mat. with wetness	**Kolke**
							Hard carbonate	**Olienhout**
							Gypsic	**Koiingnaas**
New in TS	Clovelly, Hutton or Oakleaf with visible lime		Soft carbonate		**Brandvlei**	Soft carbonate		**Brandvlei**
Lithocutanic B		**Glenrosa**	Lithocutanic B		**Glenrosa**	Lithic		**Glenrosa**
Hard rock, hardpan ferricrete, hardpan calcrete, hardpan silcrete or dorbank		**Mispah**	Hard rock		**Mispah**	Hard rock		**Mispah**
			Hardpan carbonate		**Coega**	Hard carbonate		**Coega**
			New in NAS			Gypsic		**Rooiberg**
			Dorbank		**Knersvlakte**	Dorbank		**Knersvlakte**
Stratified alluvium		**Dundee**	Stratified alluvium		**Dundee**	Alluvial		**Dundee**
New in NAS						Uncon. mat. Wetness		**Lepellane**
Regic sand		**(Fernwood)**	Regic sand		**Namib**	Regic sand	(Thick horizon)	**Namib**
New in TS			Man-made soil deposit		**Witbank**	Transported technosols		**Witbank**
Anthrosols – New in NAS						Physically disturbed anthrosols		**Grabouw**
						Chemically polluted technosols		**Industria**
						Hydric technosols		**Stilfontein**
						Anthropogenic open excavation technosols		**Cullinan**
						Archaeological technosols		**Maropeng**
						Urban technosols		**Johannesburg**

*The Lichtenburg form was not originally included in the TS but was later accepted by the SCWG as an additional form.

The Lepellane soil form was added in the Natural and Anthropogenic System, as an interim measure, to accommodate widely occurring truncated profiles in depositional environments with unconsolidated transported materials that exhibit distinct redox morphological features. The expansion of the anthropogenic soils also includes the Stilfontein Technosol with hydric properties.

During the conceptualisation of the newest version, a decision was made by the SCWG to retain as much of the Taxonomic System structure as practically possible, with expansion of diagnostic horizons at depth to accommodate the anticipated increased application in the fields of, amongst others, hydropedology. This required the introduction of a naming convention requiring three diagnostic horizons, thereby retaining most of the well-known and established soil forms. However, many well-known soil forms with only two diagnostic horizons in the Taxonomic System were also retained in 'modal' forms with the requirement of a 'thick' subsoil horizon stretching to the minimal depth limitation of 1.5 meters. These include the Magwa, Inanda, Sweetwater, Fernwood, Hutton, Shortlands, Sterkspruit, Valsrivier, Oakleaf, Augrabies, and Dundee. Shallower soils will invariably key out as another form, with the relevant depth-limiting material constituting the third diagnostic horizon in the new soil form. In this regard the 'Unspecified' horizons were discarded and replaced with specified materials, therefore necessitating the specifying of possible subsoil materials and subsequently yielding the expansion of diagnostic horizon options. As the system has been expanded initially to 145 forms with a clear Taxonomic System–based framework, a more detailed discussion will not be provided here.

A significant improvement in the Natural and Anthropogenic System over the Binomial System and Taxonomic System is the provision of dedicated field and laboratory identification sections to enhance the morphologically based criteria.

Correlation of the TS with Fey (2010)

Fey (2010) provides a very handy and detailed explanation of the genesis of diagnostic horizons and materials in the South African context. Correlation of the Taxonomic System and Natural and Anthropogenic System with Fey (2010) is not explored here as: (i) the Fey classification has a geochemical focus, and (ii) it considers the presence of E horizons often as extensions of the A horizons with depth due to clay dispersion and eluviation, podzolization and/or ferrolysis processes. The E horizon has therefore not been elevated to a soil group. While the geochemical classification fits specified surface and subsurface horizon concepts, it combines E (albic) horizons with A horizons and therefore excludes distinct E horizon–characterised soils from diagnostic categories. Whereas this approach is not rejected based on merit, in this correlation exercise it is not further entertained as the consideration of E (albic) horizons has become essential for wetland and hydropedology purposes.

WETLAND AND HYDROLOGICAL SOIL FORM CLASSIFICATION IN SOUTH AFRICA

A critical assessment of the soil form indicator in wetland delineation is a function of the integration of redox morphology and hydropedology principles and applications within the formal soil classification structure. Table 5 provides a list of the soil forms in the TS and their various categories related to the wetland and hydrological classification. The sequence of soil forms is structured within: (i) the categories stipulated in the WDG, (ii) the level (form versus family) at which wetness criteria are accommodated, and (iii) the dominant determining features used for a revised form indicator classification. The soil form name sequence within the sections aligns with the sequence in the TS soil form key.

Wetland delineation guidelines (WDG)

The guidelines provide a categorisation of soil forms that may occur in terrestrial, temporary wetland, seasonal wetland and permanent wetland zones (Table 5). It is important to note that the WDG state that the specific soil forms 'may' occur associated with wetlands; in other words, a facultative approach as opposed to an 'obligative' approach. The implication is that the presence of the specific soil form does not necessarily indicate the presence of a wetland, with the implied additional scrutiny required to determine the hydrological functioning of the specific soil in the landscape.

Soil form hydrological classification

The hydrological classification of South African soil forms in the Taxonomic System was conducted by Van Tol et al. (2013a) with the specific categories provided in Table 5. This exercise was made possible by the fact that South Africa is characterised predominantly by mature soils in old geological settings (Laker, 2003; Fey, 2010), therefore providing distinct sequences (catenae) that allow for hydrological contextualisation and description. The categories are: recharge soils, interflow in the A/B horizon interface, interflow on the soil/rock interface, and responsive soils.

It follows that, due to the shallow position of the A/B horizon interflow features in the profile (often within 50 cm of the surface), many of these soils will be flagged as seasonal/temporary wetland zone soils in the WDG. Due to the facultative nature of the approach as discussed above, it is apparent that the hydrological classification does not always align with the WDG categorisation. Additional in-situ elucidation is required to determine the specific wetland category.

Revised wetland soil form indicator

A dedicated assessment of the soil form horizon sequences, their hydrological functioning and their dominant hydromorphic features used for diagnostic horizon classification, yields a revised wetland soil form indicator. In this case the classification is again facultative, and the specific local classification will require regional contextualisation.

The determining features for the classification provided in Table 5 are broadly:

- Determining diagnostic horizon
- Emphasis on G horizon colours and/or their presence as elucidated in the WDG and the redox morphology review conducted earlier
- Emphasis on E horizon colours in general and also specifically grey versus yellow colours in the moist state as elucidated in the WDG and the redox morphology review conducted earlier
- Broad occurrence context and features
- Soil classification system context

It follows that the myriad of determining features are too numerous, with too many permutations to be considered, to be adequately accommodated at a national level. Further work is currently being conducted on the regional contextualisation of the specific soil form and redox morphology features in specific soil hydrological contexts. The aspects considered for each form, or group of forms, are:

1. Champagne: It is accurately described as occurring in permanent wetland zones as it occurs in peatlands and marshes (Fey, 2010). The same applies to the additional soil forms with organic and peat topsoils in the NAS. It is important to note that the Champagne soil form is implied to include 'peat and peat soils' as identified in Activity 24 of Listing Notice 2 of 2014 (Amendment of the Environmental Impact Assessment Regulations) of the National Environmental Management Act (Act No. 107 of 1998). This reference includes large areas as well as lenses of such soils often occurring in specific landscapes. In its natural state the Champagne soil form is therefore an **obligate** wetland soil.

Table 5. Correlation of South African soil forms with various wetness categorisations (main groups separated by double lines)

Taxonomic System soil form	Wetness at level	Facultative soil form indicator (DWAF, 2005)	Hydrology (Van Tol et al., 2013a)	Revised wetland soil form indicator (facultative)[‡]
Champagne	Form	Permanent	Responsive	Permanent
Willowbrook	Form	Permanent	Responsive	Fluctuating/seasonal
Katspruit	Form	Permanent	Responsive	Permanent
Rensburg	Form	Permanent	Responsive	Fluctuating/seasonal
Kroonstad	Form	Seasonal/temporary	Interflow A/B	Fluctuating/seasonal
Longlands	Form	Seasonal/temporary	Interflow A/B	Fluctuating/seasonal
Wasbank	Form	Seasonal/temporary	Interflow A/B	Terrestrial
Lamotte	Form	Seasonal/temporary	Interflow soil/bedrock	Fluctuating/seasonal
Estcourt	Form	Seasonal/temporary	Interflow A/B	Terrestrial
Klapmuts	Form	Seasonal/temporary	Interflow A/B	Terrestrial
Vilafontes	Form	Seasonal/temporary	Interflow A/B	Terrestrial
Kinkelbos	Form	Seasonal/temporary	Interflow A/B	Terrestrial
Cartref	Form	Seasonal/temporary	Interflow A/B	Terrestrial
Fernwood	Form	Seasonal/temporary	Interflow A/B*	Terrestrial
Westleigh	Form	Seasonal/temporary	Interflow soil/bedrock	Fluctuating/seasonal
Dresden	Form	Seasonal/temporary	Interflow soil/bedrock	Fluctuating/seasonal
Avalon	Form	Seasonal/temporary	Interflow soil/bedrock	Terrestrial
Glencoe	Form	Seasonal/temporary	Interflow soil/bedrock	Terrestrial
Pinedene	Form	Seasonal/temporary	Interflow soil/bedrock	Terrestrial
Bainsvlei	Form	Seasonal/temporary	Interflow soil/bedrock	Terrestrial
Bloemdal	Form	Seasonal/temporary	Interflow soil/bedrock	Terrestrial
Lichtenburg*	Form	Seasonal/temporary	Recharge	Terrestrial
Witfontein	Form	Seasonal/temporary	Interflow soil/bedrock	Fluctuating/seasonal
Sepane	Form	Seasonal/temporary	Interflow soil/bedrock	Fluctuating/seasonal
Tukulu	Form	Seasonal/temporary	Interflow soil/bedrock	Fluctuating/seasonal
Montagu	Form	Seasonal/temporary	Interflow soil/bedrock	Fluctuating/seasonal
Inhoek	Family	Seasonal/temporary	Recharge	Fluctuating/seasonal
Tsitsikamma	Family	Seasonal/temporary	Recharge	Terrestrial
Houwhoek	Family	Seasonal/temporary	Recharge	Terrestrial
Molopo	Family	Seasonal/temporary	Recharge	Terrestrial
Kimberley	Family	Seasonal/temporary	Recharge	Terrestrial
Jonkersberg	Family	Seasonal/temporary	Recharge	Fluctuating/seasonal
Groenkop	Family	Seasonal/temporary	Recharge	Fluctuating/seasonal
Etosha	Family	Seasonal/temporary	Recharge	Terrestrial
Addo	Family	Seasonal/temporary	Recharge	Terrestrial
Brandvlei	Family	Seasonal/temporary	Recharge	Fluctuating/seasonal
Glenrosa	Family	Seasonal/temporary	Recharge	Terrestrial
Dundee	Family	Seasonal/temporary	Recharge	Fluctuating/seasonal
Kranskop	-	Terrestrial	Recharge	Terrestrial
Magwa	-	Terrestrial	Recharge	Terrestrial
Inanda	-	Terrestrial	Recharge	Terrestrial
Lusiki	-	Terrestrial	Recharge	Terrestrial
Sweetwater	-	Terrestrial	Recharge	Terrestrial
Nomanci	-	Terrestrial	Recharge	Terrestrial
Arcadia	-	Terrestrial	Recharge	Terrestrial
Bonheim	-	Terrestrial	Recharge	Terrestrial
Steendal	-	Terrestrial	Recharge	Terrestrial
Immerpan	-	Terrestrial	Recharge	Terrestrial
Mayo	-	Terrestrial	Recharge	Terrestrial
Milkwood	-	Terrestrial	Recharge	Terrestrial
Constantia	-	Terrestrial	Interflow A/B	Terrestrial
Concordia	-	Terrestrial	Recharge	Terrestrial
Griffin	-	Terrestrial	Recharge	Terrestrial
Askham	-	Terrestrial	Recharge	Terrestrial
Clovelly	-	Terrestrial	Recharge	Terrestrial
Plooysburg	-	Terrestrial	Recharge	Terrestrial
Garies	-	Terrestrial	Recharge	Terrestrial
Hutton	-	Terrestrial	Recharge	Terrestrial
Shortlands	-	Terrestrial	Recharge	Terrestrial
Pinegrove	-	Terrestrial	Recharge	Terrestrial
Sterkspruit	-	Terrestrial	Recharge	Terrestrial
Valsrivier	-	Terrestrial	Recharge	Terrestrial
Swartland	-	Terrestrial	Recharge	Terrestrial
Gamoep	-	Terrestrial	Recharge	Terrestrial
Oudtshoorn	-	Terrestrial	Recharge	Terrestrial
Oakleaf	-	Terrestrial	Recharge	Terrestrial
Prieska	-	Terrestrial	Recharge	Terrestrial
Trawal	-	Terrestrial	Recharge	Terrestrial
Augrabies	-	Terrestrial	Recharge	Terrestrial
Coega	-	Terrestrial	Recharge	Terrestrial
Knersvlakte	-	Terrestrial	Recharge	Terrestrial
Mispah	-	Terrestrial	Recharge	Terrestrial
Namib	-	Terrestrial	Recharge	Terrestrial
Witbank	-	Terrestrial	Recharge	Terrestrial

* Due to the thickness of the E horizon in the Fernwood form and absence of an underlying B horizon the hydrology classification is better suited as 'interflow on the soil/rock interface'; [‡] Underlined categories indicate a change from the WDG Soil Form Indicator category

2. Willowbrook, Katspruit and Rensburg: These soil forms are characterised by a subsoil G horizon which is often taken to indicate a localised water table. The work by Le Roux et al. (2011) and Van Tol et al. (2010a; 2010b; 2013a; 2013b) has shown that G horizons are associated with return flow from hillslope hydrological processes and are therefore often associated with wetland features. However, the formation of vertic (and to a degree melanic) horizons are dependent on a set of drivers that are not necessarily linked to wetland features. The formation of 2:1 swelling and non-swelling clays dominating these two horizons occur in environments, both in depressions and flat areas of basic igneous geology, that yield specific weathering products under humid conditions, leading to the neoformation of such clays under seasonal conditions of drying and saturation of the soil solution. In many environments, therefore, vertic and melanic horizons are indicative of seasonal wetness at most. Whereas Katspruit soil forms are accepted as occurring in permanent wetland zones (mostly obligate), Rensburg and Willowbrook soils are not and therefore mostly **facultative**.
3. Soils where E horizons are emphasised: These soils include the Kroonstad, Longlands, Lamotte, Estcourt, Klapmuts, Vilafontes, Kinkelbos and Cartref forms. The categorisation of these E horizons as exhibiting lateral flow and hydromorphic properties depends on in-field observations and landscape context. A distinction is made in many cases at family level regarding 'grey' or 'yellow' colours in the moist state with the greyer materials generally indicating wetter conditions. In most settings, however, many of these soils are 'terrestrial' rather than 'wetland' due to their geogenic origin as opposed to a hydromorphic origin. In this regard the distribution of quartz-dominated geology as well as the ancient nature of the South African landscape and its varied historical climates play significant roles. Fernwood soils are therefore **facultative** wetland soils (as affirmed in Pretorius et al., 2020 for Maputaland soils).
4. Fernwood soil form: These are not necessarily indicative of wet conditions (as in the case of dunes) but are included in the wetland guidelines as being part of the temporary/ seasonal zone. Due to the nature of the E horizon it is categorised as Interflow A/B by Van Tol et al. (2013b) but the deep profile in many environments yields a 'terrestrial' soil in the revised approach. Regional contextualisation could provide more suitable distinction as the Fernwood soils immediately east of Mkuze (600 mm p.a rainfall) are not very wet (Land Type Survey Staff, 1986a), but those at KwaMbonambi (>1 000 mm p.a. rainfall) may well be seasonally wet (Land Type Survey Staff, 1986b). Soils with E horizons are **facultative** wetland soils (as affirmed in Pretorius et al., 2020, for Maputaland soils).
5. Plinthic soils: These include the shallow plinthic soils of the Westleigh and Dresden forms and the thicker soils of the Avalon, Bainsvlei, Pinedene, Bloemdal, Glencoe and Lichtenburg forms. Soils with plinthic horizons (or low-chroma colours without distinct mottling) indicate subsoil fluctuating perched water conditions. It follows that if the mottling features are within 50 cm of the surface, these soils will be flagged as seasonal/temporary wetland soils if the specific depth criterion is used. Conversely, the deeper plinthic horizons will not be flagged using the depth criteria, especially due to a chromic horizon occurring within such a zone – therefore yielding a 'terrestrial' category. However, the WDG guidelines indicate all of these soils as potentially occurring in seasonal/temporary wetlands with a hydropedology (Van Tol et al, 2013a) approach emphasising the deeper interflow character. Fey (2010) discusses the plinthic soils and their specific colour sequences of red, yellow, grey and dark, along an increasing wetness gradient. These sequences are readily used as indicators by wetland workers during delineation exercises. Thicker plinthic soils are normally terrestrial, whereas thinner soils are **facultative** wetland depending on the chromic nature and thickness of the surface horizons.
6. Soils with 'signs of wetness' at depth: These include soils of the Montagu, Witfontein, Sepane and Tukulu forms. The Montagu and Tukulu soils, often occurring in broad depositional landscapes, have chromic B horizons overlying the TS diagnostic horizon 'unspecified material with signs of wetness'. In the NAS these horizons have been specified as gley, gleyic or albic horizons with additional soil forms added. The Witfontein and Sepane forms have chromic horizons overlying 'unconsolidated material with signs of wetness'. The retention of the latter in the NAS is a transitional arrangement with the aim of further elucidation and description. The interpretation of these soil forms in terms of wetland occurrence is similar to the plinthic soils above, with a bias towards seasonal wetlands.
7. Alluvial soils with family level wetness criteria: The Inhoek and Dundee soil forms have alluvial stratification horizons that may or may not be associated with wetland conditions. These are readily associated with riparian zones and the presence of redoximorphic features yields families that are associated with seasonal/fluctuating wetland conditions. In a hydropedology setting these are categorised as recharge soils.
8. Podzolic soils with placic pan / saprolite: Podzolic horizons are not indicative of redox morphology. Podzol soils with wetness features in subsoil horizons/materials at family level are listed in the WDG as seasonal/temporary. The hydropedology categorisation is not entirely in agreement and indicates these soils as 'recharge', especially if wetness signs are absent. In a revised categorisation the deeper E/podzol profiles are classified as 'terrestrial' and the shallower profiles (without an E) as fluctuating/seasonal due to the closer proximity of the features to the surface.
9. Glenrosa soil forms: The Glenrosa soil form is indicated as seasonal/temporary in the WDG but is considered 'recharge' and 'terrestrial' in the hydropedology and revised categorisation, respectively. This approach was decided upon due to the very wide occurrence of the soil form and the very low occurrence of Glenrosa families with hydromorphic features. Further underpinning this approach is the difficulty in distinguishing between geogenic- and hydromorphic-related mottling, with the former often preferred in weathered rock environments.
10. Carbonate soils with redox morphology at family level: Several lime-containing soils (Molopo, Kimberley, Etosha and Addo) have chromic horizons overlying carbonate-rich materials with the option of redox depletions at family level. The lack of high-chroma mottles in carbonate horizons was addressed earlier. While these soils are categorised as seasonal/temporary in the WDG, they are 'recharge' and 'terrestrial' in the hydropedology and revised categories, respectively. The Brandvlei form, having a shallower carbonate horizon with the same family criteria, is categorised as seasonal/temporary and fluctuating/seasonal in the WDG and revised categorisation, respectively, even though it is considered 'recharge' from a hydropedology perspective. This aspect is a regional differentiation as it is often associated with arid pan depression environments.

Geographical context limitations

The revision of the soil form categories above regarding wetland character emphasises the importance of regional contextualisation. It follows that certain soil forms can be associated with wetland conditions in specific geographical, topographical and/or geological contexts while they may not in others (as addressed in Pretorius et al., 2020). Therefore, a set range of soil forms cannot satisfy wetland criteria throughout South Africa and regional contextualisation and representation is critical. A distinct possibility is the interrogation of the Land Type database along specific criteria with the regionalisation of wetland features and specific soil forms. Van der Waals (2019) indicated preliminary results regarding such an exercise, but the approach requires refinement and identification of the most suitable area delineation criteria.

Many wetland workers focus on geographically distinct areas and have developed significant sets of vegetation and wetland context data for the respective areas. It is envisaged that a structured Land Type interrogation, with focused extraction and categorisation of existing soil form occurrence information, could be combined with data available from other disciplines to generate specific regional wetland delineation and assessment guidelines.

The Binomial System has as a subdivision of the soil forms a lower-level classification of several 'soil series'. The Taxonomic System replaced the series categories with more general, and often wetness-focused, 'soil family' criteria. It is important to note that most of the nuances in categorisation discussed above have regional variation at their core. It is therefore likely that regionalisation of wetland criteria could provide meaningful differentiation between soils of the same form, an aspect that is not possible within one national set of criteria. The differentiation of soil forms on a geographical basis would require an additional level of classification as a possible 'geographical series' at a lower level or as a soil property categorisation in groups at a higher level – similar in approach to that of Fey (2010). There is, however, a lack of consensus in the Soil Classification Working Group regarding the future development along this line. It is proposed that a user-defined approach should inform future categories with the main users being (i) agriculture, (ii) wetland and (iii) hydropedology practitioners. A bonus would be a common approach and soil naming that satisfies the requirements of the various users.

CONCLUSIONS

The field of wetland science has evolved, with a focus on identifying characteristic indicator soil properties. Much of the international literature on this subject originates from the USA, where a structured approach to wetland identification and protection is prescribed. Hydric soil indicators (USA) and soil form and redox morphology (redoximorphic) indicators (SA) are central to the process, exhibiting both significant overlap and divergence. While distinct differences exist in soil and landscape contexts, the fundamental principles of redox morphology chemistry and drivers are universally applicable.

Traditionally, wetland practitioners have primarily relied on the presence of mottles to identify wetland soils, without explicitly considering soil form and redoximorphic context. The South African soil classification system acknowledges mottling in predominantly well-aerated soils, as well as those experiencing varying degrees and durations of anaerobic conditions. This review addresses these issues by systematically organising redox morphology and soil classification categories, aiming to provide a solid foundation for future wetland work and research.

The South African landscape is geologically ancient and complex, offering valuable insights into hydrological and pedological contexts through the expression of soil morphology and iron mineral colours. The South African soil classification systems were developed based on this understanding, and together with the descriptions of redox morphology in different horizons and materials, they provide a highly suitable framework for describing landscape hydrological processes in wetland assessment and conservation. The evolution of the three editions of the soil classification system has resulted in a growing and expanding framework for the classification and interpretation of the soil resource.

The field of hydropedology is gaining recognition as a powerful tool for wetland assessment and conservation, as it integrates geographically linked soil morphology, landscape hydrology, and knowledge of wetland expression. However, further research is needed to contextualise specific geographical areas and their hydrological, soil, and morphological expressions. In this regard, correlating the classification system with the relevant redox morphology contexts geographically will establish a solid foundation.

It is concluded and recommended here that:

1. The criteria provided by Vepraskas and Lindbo (2012) are suitable for wetland delineation and assessment in South Africa with the added understanding that hillslope processes are critically important in the field of hydropedology and the understanding of wetland drivers.
2. The South African wetland delineation guidelines should be updated and tailored to regional contexts, taking into account the available Land Type data and other relevant soil survey information. Regional variations and specific characteristics should be considered to improve the accuracy and applicability of these guidelines.
3. The understanding of 'mottling' within the South African wetland community should be expanded to incorporate existing knowledge and approaches published in formal soil and wetland literature, as well as the information provided in the formal soil classification system. This will enhance the understanding and interpretation of mottling in relation to wetland assessments and classifications.
4. The training of wetland scientists and practitioners should incorporate the latest knowledge and resources regarding soil information and the soil classification system. This will ensure that field workers are equipped with the necessary understanding and skills to effectively utilise available soil information resources in their work.

AUTHOR CONTRIBUTIONS

JH van der Waals, DG Paterson and DP Turner conceptualised and designed the paper and provided detailed contributions on soil mineralogy, redox morphology and related contexts of diagnostic horizons and soil materials, soil classification correlation and interrogation of the various systems.

PS Rossouw and CW van Huyssteen provided detailed in-field contributions on soil mineralogy, redox morphology and related contexts of diagnostic horizons and soil materials, with CW van Huyssteen providing guidance on the classification systems' correlation with USDA approaches.

A Grundling aided in the conceptualisation and design of the review paper.

All the authors conducted critical revision at various stages of manuscript preparation.

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REFERENCES

BARTLETT RJ and JAMES BR (1993) Redox chemistry of soils. *Adv. Agron.* **50** 151–208. https://doi.org/10.1016/S0065-2113(08)60834-2

BARTLETT RJ (1999) Characterizing soil redox behaviour. In: Sparks DL (ed.) *Soil Physical Chemistry* (2nd edn). CRC Press, Boca Raton.

BARTLETT RJ and ROSS DS (2005) Chemistry of redox processes in soils. In: Tabatabai MA and Sparks DL (eds.) *Chemical Processes in Soils*. SSSA Book Series. https://doi.org/10.2136/sssabookser8.c9

BERKOWITZ J and SALLEE J (2011) Investigating problematic hydric soils using water table measurements, IRIS tubes, soil chemistry, and application of the Hydric Soils Technical Standard. *Soil Sci. Soc. Am. J.* **75** (6) 2379–2385. https://doi.org/10.2136/sssaj2011.0040

BEUKES NJ, VAN NIEKERK HS and GUTZMER J (1999) Post Gondwana African land surfaces and pedogenetic ferromanganese deposits on the Witwatersrand at the West Wits Gold Mine, South Africa. *S. Afr. J. Geol.* **102** (1) 65–82. https://hdl.handle.net/10520/EJC-94d379bf3

BOETTINGER JL (1994) Aquisalids (Salorthids) and other wet saline and alkaline soils: problems identifying aquic conditions and hydric soils. *Aquic conditions and hydric soils – the problem soils Proceedings of a symposium*, 14 November 1994, Seattle, USA.

BOTHA GA, WINTLE AG and VOGEL JC (1994) Episodic late Quaternary palaeogully erosion in northern KwaZulu-Natal, South Africa. *Catena* **23** 327–340. https://doi.org/10.1016/0341-8162(94)90076-0

BOTHA GA (1996) Cyclical colluvial accretion on bedrock pediments during the Late Quaternary in northern KwaZulu-Natal, South Africa. *Z. Geomorph.* Suppl. Bd. **103** 85–102.

BOTHA GA and PARTRIDGE TC (2000) Colluvial deposits. In: Partridge TC and Maud RR (eds.) *The Cenozoic of Southern Africa*. Oxford University Press, New York.

BUOL SW, HOLE FD, MCCRACKEN RJ and SOUTHARD RJ (1997) *Soil Genesis and Classification* (4th edn). Iowa State University Press, Ames. 527 pp.

CASTAÑEDA C, LUNA E and RABENHORST M (2017) Reducing conditions in a soil of Gallocanta Lake, NE Spain. *Eur. J. Soil Sci.* **68** (2) 249–258. https://doi.org/10.1111/ejss.12407

CHAPLOT V and WALTER C (2006) Improving the spatial prediction of soils at local and regional levels through a better understanding of soil-landscape relationships: soil hydromorphy in the Armorican massif of western France. *Dev. Soil Sci.* **31** 507–520. https://doi.org/10.1016/S0166-2481(06)31038-0

CHESWORTH W (2008) *Encyclopaedia of Soil Science*. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-3995-9

CORNELL RM and SCHWERTMANN U (2006) *The Iron Oxides: Structure, Properties, Reactions, Occurrences and Uses* (2nd edn). Wiley-VCH, Weinheim. 703 pp. ISBN: 978-3-527-60644-3

CHI FRU E, PICCINELLI P and FORTIN D (2012) Insights into the global microbial community structure associated with iron oxyhydroxide minerals deposited in the aerobic biogeosphere. *Geomicrobiol. J.* **29** 587–610. https://doi.org/10.1080/01490451.2011.599474

CLARKE C.E, LE ROUX JL, ELLIS F, DE CLERCQ WP and VAN DER WAALS JH (2020) Pedogenesis of bleached topsoils occurring on weakly structured, high chroma subsoils in South Africa. *Catena* **193** 104634

DWAF (Department of Water Affairs and Forestry) (1999) Resource Directed Measures for Protection of Water Resources. Volume 4: Wetland Ecosystems. DWAF, Pretoria https://www.dws.gov.za/Documents/Policies/WRPP/Wetland%20Ecosystems.htm (Accessed 27 April 2023)

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

ENVIRONMENTAL LABORATORY (1987) *Corps of Engineers Wetland Delineation Manual*. Technical Report Y-87-1. U.S. Army, Corps of Engineers, Washington, DC.

ERIKSSON PG, ALTERMANN W and HARTZER FJ (2006) The Transvaal Supergroup and its precursors. In: Johnson MR, Anhaeusser CR and Thomas RJ (eds) *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria. 237–260.

FEY MV (1981) Hypothesis for the pedogenic yellowing of red soil materials. *Proceedings of the 10th National Congress of the Soil Science Society of Southern Africa, East London*. Technical Communication No. 180. Department of Agriculture, Pretoria. 130–136.

FEY MV (2010) *Soils of South Africa: Their Distribution, Properties, Classification, Genesis, Use and Environmental Significance*. Cambridge University Press, Cape Town. 287 pp.

FIEDLER S and SOMMER M (2004) Water and redox conditions in wetland soils–their influence on pedogenic oxides and morphology. *Soil Sci. Soc. Am. J.* **68** (1) 326–335. https://doi.org/10.2136/sssaj2004.0326

FITZPATRICK RW and SCHWERTMANN U (1982) Al-substituted goethite, an indicator of pedogenic and other weathering environments in South Africa. *Geoderma* **27** 335–347. https://doi.org/10.1016/0016-7061(82)90022-2

FITZPATRICK RW, TAYLOR RM, SCHWERTMANN U and CHILDS CW (1985) Occurrence and properties of lepidocrocite in some soils of New Zealand, South Africa and Australia. *Aust. J. Soil Res.* **23** 543–567. https://doi.org/10.1071/SR9850543

FITZPATRICK RW (1988) Iron compounds as indicators of pedogenic processes: examples from the southern hemisphere. In: Stucki JW, Goodman BA and Schwertmann U (eds.) *Iron in Soils and Clay Minerals*. NATO ASI Series, Vol 217. Springer, Dordrecht. https://doi.org/10.1007/978-94-009-4007-9_13

GÉNIN J-MR (2004) Fe(II-III) hydroxysalt green rusts; from corrosion to mineralogy and abiotic and biotic reactions by Mössbauer spectroscopy. *Hyperfine Interactions* **156/157** 471–485. https://doi.org/10.1023/B:HYPE.0000043268.31697.44

GREENLAND DJ and HAYES MH (1978) *The Chemistry of Soil Constituents*. John Wiley and Sons, London. 469 pp.

GRUNDLING P and GROBLER R (1995) Peatlands and mires of South Africa. In: *Stapfia 85, Zugleigh Kataloge der Oo. Landsmuseen Neue Serie* **35** 379–396.

GRUNDLING P, MAZUS H and BAARTMAN L (1998) Peat resources in northern KwaZulu-Natal wetlands: Maputaland. Department of Environmental Affairs and Tourism Report No. A25/13/2/7. Department of Environmental Affairs and Tourism, Pretoria.

GRUNDLING P, BAARTMAN L, MAZUS H and BLACKMORE A (2000) Peat resources of northern KwaZulu-Natal wetlands: Southern Maputaland and the North and South Coast. Report No. 2000-0132. Council for Geoscience, Pretoria.

HELGREN DM and BUTZER KW (1977) Paleosols of the Southern Cape Coast, South Africa: Implications for Laterite Definition, Genesis, and Age. *Geogr. Rev.* **67** (4) 430–445. https://doi.org/10.2307/213626

HILLEL D (1982) *Introduction to Soil Physics*. Academic Press, London. 364 pp. https://doi.org/10.1016/B978-0-08-091869-3.50005-6

IUSS WORKING GROUP WRB (2022) *World Reference Base for Soil Resources. International Soil Classification System For Naming Soils And Creating Legends For Soil Maps* (4th edn). International Union of Soil Sciences (IUSS), Vienna, Austria.

JOB N, MBONA N, DAYARAM A and KOTZE D (2018) Guidelines for mapping wetlands in South Africa. *SANBI Biodiversity Series* **28**. South African National Biodiversity Institute, Pretoria

JOOSTEN H and CLARKE D (1992) Wise use of mires and peatlands: Background and principles including framework for decision-making. International Mire Conservation Group and International Peat Society, The Netherlands.

KING M, VAUGHAN KL, CLAUSE K and MATTKE D (2019) Limitations to redoximorphic feature development in highly calcareous hydric soils. *Soil Sci. Soc. Am. J.* **83** (5) 1585–1594. https://doi.org/10.2136/sssaj2019.04.0108

KLEIN C and HURLBUT CS (1985) *Manual of Mineralogy* (20th edn). John Wiley and Sons, New York. 596 pp.

KOTZE DC and MARNEWECK GC (1999) Draft guidelines for delineating the boundaries of a wetland and the zones within a wetland in terms of the South African Water Act. As part of the development of a protocol for determining the Ecological Reserve for Wetlands in terms of the Water Act Resource Protection and Assessment Policy Implementation Process. Department of Water Affairs and Forestry, South Africa.

LAKER MC (2003) Advances in the South African Soil Classification System. In: Eswaran H, Rice T, Ahrens R and Stewart BA (eds.) *Soil Classification: A Global Desk Reference*. CRC Press, Boca Raton. https://doi.org/10.1016/B978-0-08-091869-3.50005-6

LAMBRECHTS JJN and MACVICAR CN (2004) Soil genesis and classification and soil resources databases. *S. Afr. J. Plant Soil* **21** (5) 288–300.

LAND TYPE SURVEY STAFF (1986a) Land Types of the map 2632 Mkuze. Soil and Irrigation Research Institute, Pretoria

LAND TYPE SURVEY STAFF (1986b) Land Types of the map 2830 Richards Bay. Soil and Irrigation Research Institute, Pretoria.

LAND TYPE SURVEY STAFF (1972–2002) Land types of South Africa: Digital map (1:250 000 scale) and soil inventory datasets. ARC-Institute for Soil, Climate and Water, Pretoria.

LE ROUX PAL and DU PREEZ CC (2006) Nature and distribution of South African plinthic soils: Conditions for occurrence of soft and hard plinthic soils. *S. Afr. J. Plant Soil* **23** (2) 120–125. https://doi.org/10.1080/02571862.2006.10634741

LE ROUX PAL and DU PREEZ CC (2008) Micromorphological evidence of redox activity in the soft plinthic B horizon of a soil of the Bainsvlei form in an arid bioclimate. *S. Afr. J. Plant Soil* **25** (2) 84–91. https://doi.org/10.1080/02571862.2008.10639900

LE ROUX PAL, VAN TOL JJ, KUENENE BT, HENSLEY M, LORENTZ SA, EVERSON CS, VAN HUYSSTEEN CW, KAPANGAZIWIRI E and RIDDELL E (2011) Hydropedological interpretations of the soils of selected catchments with the aim of improving the efficiency of hydrological models. WRC Report No. 1748/1/10. Water Research Commission, Pretoria.

LIN H (2012a) Hydropedology: addressing fundamentals and building bridges to understand complex pedologic and hydraulic interactions. In: Lin H (ed.) *Hydropedology: Synergistic Integration of Soil Science and Hydrology.* Elsevier, Oxford.

LIN H (2012b) Hydropedology: understanding soil architecture and its functional manifestation across scales. In: Lin H (ed.) *Hydropedology: Synergistic Integration of Soil Science and Hydrology.* Elsevier, Oxford. https://doi.org/10.1016/B978-0-12-386941-8.00002-2

LINDBO DL, STOLT MH and VEPRASKAS MJ (2010) Redoximorphic Features. In: Stoops G, Marcelino V and Mees F (eds) *Interpretation of Micromorphological Features of Soils and Regoliths.* Elsevier, Amsterdam. https://doi.org/10.1016/B978-0-444-53156-8.00008-8

LINDSAY WL (1979) *Chemical Equilibria in Soils.* John Wiley and Sons, Chichester. 449 pp.

LINDSAY WL (1988) Solubility and redox equilibria of iron compounds in soil. In: Stucki JW, Goodman BA and Schwertmann U (eds) *Iron in Soils and Clay Minerals.* NATO ASI Series, vol 217. Springer, Dordrecht. https://doi.org/10.1007/978-94-009-4007-9_3

LINDSAY WL (1995) Chemical reactions in soils that affect iron availability to plants. In: Abadia J (ed.) *Iron Nutrition in Soils and Plants.* Kluwer Academic Publishers, Dordrecht. https://doi.org/10.1007/978-94-011-0503-3_2

LINN DM and DORAN JW (1984) Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Sci. Soc. Am. J.* **48** 1267–1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x

LOEPPERT RH (1988) Chemistry of iron in calcareous systems. In: Stucki JW, Goodman BA and Schwertmann U (eds) *Iron in Soils and Clay Minerals.* NATO ASI Series, Vol 217. Springer, Dordrecht. https://doi.org/10.1007/978-94-009-4007-9_19

LOXTON RF (1962) The soils of the Republic of South Africa: A preliminary reclassification. *S. Afr. J. Sci.* **58** (2) 1–62.

MA Y, LI X, GUO L and LIN H (2017) Hydropedology: Interactions between pedologic and hydrologic processes across spatiotemporal scales. *Earth-Sci. Rev.* **171** 181–195. https://doi.org/10.1016/j.earscirev.2017.05.014

MABUZA B and VAN HUYSSTEEN CW (2019) Effect of degree and duration of water saturation on iron, manganese and exchangeable cations in wetland soils of Maputaland, KwaZulu-Natal, South Africa. *S. Afr. J. Plant Soil* **36** (4) 279–287. https://doi.org/10.1080/02571862.2018.1562112

MACVICAR CN and LOXTON RF (1967) *Soils of the Langkloof.* Technical Communication No. 59. Department of Agricultural Technical Services. Pretoria.

MACVICAR CN, DE VILLIERS JM, LOXTON RF, VERSTER E, LAMBRECHTS JJN, MERRYWEATHER FR, LE ROUX J, VAN ROOYEN TH and HARMSE HJ VON M (1977) *Soil Classification. A Binomial System for South Africa.* Sci. Bull. 390. Dep. Agric. Tech. Serv., Repub. S. Afr., Pretoria.

MACVICAR CN, FITZPATRICK RW and SOBCZYK ME (1984) Highly weathered soils in the east coast hinterland of Southern Africa with thick, humus-rich A horizons. *J. Soil Sci.* **35** 103–115. https://doi.org/10.1111/j.1365-2389.1984.tb00265.x

MARKER ME, MCFARLANE MJ and WORMALD RJ (2002) A laterite profile near Albertinia, Southern Cape, South Africa: its significance in the evolution of the African Surface. *S. Afr. J. Geol.* **105** 67–74. https://doi.org/10.2113/1050067

MASEDO J and BRYANT RB (1989) Preferential microbial reduction of hematite over goethite in a Brazilian Oxisol. *Soil Sci. Soc. Am. J.* **53** 1114–1118. https://doi.org/10.2136/sssaj1989.03615995005300040022x

MCCREA AF, ANAND RR and GILKES RJ (1990) Mineralogical and physical properties of lateritic pallid zone materials developed from granite and dolerite. *Geoderma* **47** (1–2) 33–57. https://doi.org/10.1016/0016-7061(90)90046-C

MCFARLANE MJ (1976) *Laterite and Landscape.* Academic Press, London. 151 pp.

MCKNIGHT C (1997) The Sandton-Midrand soil catena, a legacy of polycyclic weathering and erosion. *In*: South African Institute of Engineering Geologists. *Geology for Engineering, Urban Planning and the Environment Proceedings*, 12–14 November 1997, Midrand.

MEEK BD and GRASS LB (1975) Redox potential in irrigated desert soils as an indicator of aeration status. *Soil Sci. Soc. Am. Proc.* **39** 870–875. https://doi.org/10.2136/sssaj1975.03615995003900050025x

MUDALY L (2015) The contribution of manganese oxides to redox buffering in selected soils of the South African Highveld. MSc thesis, University of Pretoria.

NATIONAL RESEARCH COUNCIL (1995) *Wetlands: Characteristics and Boundaries.* National Academy Press, Washington, DC.

PARTRIDGE TC and MAUD RR (1987) Geomorphic evolution of southern Africa since the Mesozoic. *S. Afr. J. Geol.* **90** (2) 179–208.

PARTRIDGE TC, BOTHA GA and HADDON IG (2006) Cenozoic deposits of the interior. In: Johnson MR, Anhaeusser CR and Thomas RJ (eds.) *The Geology of South Africa.* Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria. 585–604.

PATRICK WH and JUGSUJINDA A (1992) Sequential reduction and oxidation of inorganic nitrogen, manganese, and iron in flooded soil. *Soil Sci. Soc. Am. J.* **56** 1071–1073. https://doi.org/10.2136/sssaj1992.03615995005600040011x

PATRICK WH and HENDERSON RE (1980) Reduction and reoxidation cycles of manganese and iron in flooded soil and in water solution. *Soil Sci. Soc. Am. J.* **45** 855–859. https://doi.org/10.2136/sssaj1981.03615995004500050006x

PEZESHKI SR and DELAUNE RD (2012) Soil oxidation-reduction in wetlands and its impact on plant functioning. *Biology* **1** 196–221. https://doi.org/10.3390/biology1020196

PONNAMPERUMA FN (1972) The chemistry of submerged soils. *Adv. Agron.* **24** 29–96. https://doi.org/10.1016/S0065-2113(08)60633-1

PRETORIUS L, VAN HUYSSTEEN C, BROWN L, GRUNDLING A and DOWNS C (2020) A characterization of wetland soils on the Maputaland Coastal Plain. *S. Afr. J. Plant Soil.* https://doi.org/10.1080/02571862.2020.1814433

RABENHORST MC and PARIKH S (2000) Propensity of soils to develop redoximorphic color changes. *Soil Sci. Soc. Am. J.* **64** (5) 1904–1910. https://doi.org/10.2136/sssaj2000.6451904x

REIMOLD WU (2006) Impact structures in South Africa. In: Johnson MR, Anhaeusser CR and Thomas RJ (eds.) *The Geology of South Africa.* Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria. 629–649.

ROBB LJ, BRANDL G, ANHAEUSSER CR and POUJOL M (2006) Archaean Granitoid Intrusions. In: Johnson MR, Anhaeusser CR and Thomas RJ (eds.) *The Geology of South Africa.* Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria. 57–94.

RSA (Republic of South Africa) (1998) National Water Act. Act No. 36 of 1998. *Government Gazette* **19182**. Government Printer, Cape Town.

RUBY C, ABDELMOULA M, NAILLE S, RENARD A, KHARE V, ONA-NGUEMA G, MORIN G and GÉNIN J-MR (2010) Oxidation modes and thermodynamics of Fe^{II-III} oxyhydroxycarbonate green rust: dissolution-precipitation versus *in situ* deprotonation. *Geochim. Cosmochim. Acta* **74** 953–966. https://doi.org/10.1016/j.gca.2009.10.030

SCHAETZL RJ and ANDERSON S (2005) *Soils: Genesis and Geomorphology*. Cambridge, New York. https://doi.org/10.1017/CBO9780511815560

SCHWAB AP and LINDSAY WL (1983) Effect of redox on the solubility and availability of iron. *Soil Sci. Soc. Am. J.* **47** 201–205. https://doi.org/10.2136/sssaj1983.03615995004700020005x

SCHWERTMANN U and FITZPATRICK RW (1977) Occurrence of lepidocrocite and its association with goethite in Natal soils. *Soil Sci. Soc. Am. J.* **41** 1013–1018. https://doi.org/10.2136/sssaj1977.03615995004100050042x

SCHWERTMANN U and TAYLOR RM (1989) Iron oxides. In: Dixon JB and Weed SB (eds.) *Minerals in Soil Environments*. Madison, Wisconsin.

SCHWERTMANN U and THALMANN H (1976) The influence of [FeII]{Si} and pH on the formation of lepidocrocite and ferrihydrite during oxidation of aqueous $FeCl_2$ solutions. *Clay Miner.* **11** (3) 189–200. https://doi.org/10.1180/claymin.1976.011.3.02

SOIL CLASSIFICATION WORKING GROUP (1991) Soil Classification – A taxonomic system for South Africa. *Memoirs on the Agricultural Natural Resources of South Africa.* No. 15. Soil and Irrigation Research Institute, Department of Agricultural Development, Pretoria.

SOIL CLASSIFICATION WORKING GROUP (2018) *Soil Classification: A Natural and Anthropogenic System for South Africa*. ARC-Institute for Soil, Climate and Water, Pretoria.

SOIL SURVEY STAFF (2010) *Keys to Soil Taxonomy* (11th edn). USDA-NRCS.

STOLK A and VAN HUYSSTEEN CW (2019) Clay and iron oxide contents of prismacutanic B, G, soft plinthic B, and E horizons described during the land type survey of South Africa. *S. Afr. J. Plant Soil* **36** 165–172. https://doi.org/10.1080/02571862.2018.1544381

SWINKELS DAJ, ANTHONY KE, FREDERICKS PM and OSBORN PR (1984) Solid-state redox properties of manganese dioxide. *J. Electroanal. Chem. Interf. Electrochem.* **168** (1–2) 433–450. https://doi.org/10.1016/0368-1874(84)87114-2

TARDY Y (1992) Diversity and terminology of lateritic profiles. In: Martini IP and Chesworth W (eds.) *Weathering, Soils and Paleosols.* Developments in Earth Surface Processes 2. Elsevier, Amsterdam. https://doi.org/10.1016/B978-0-444-89198-3.50020-9

TROLARD F (2006) Fougerite: from field experiment to the homologation of the mineral. *Comptes Rendus Geosci.* **338** 1158–1166. https://doi.org/10.1016/j.crte.2006.08.003

TROLARD F and BOURRIÉ G (2008) Geochemistry of green rusts and fougerite: a reevaluation of Fe cycle in soils. *Adv. Agron.* **99** 227–288. https://doi.org/10.1016/S0065-2113(08)00405-7

TURNER DP, PATERSON DG and VAN DER WALT M (2023) Differences in clay percentages between A and E master horizons. Agricultural Research Council – Natural Resources and Engineering, Report No. GW/A/2023/03. Agricultural Research Council, Pretoria.

USDA-NRCS (2010) *Field Indicators of Hydric Soils in the United States*, Version 7.0. Vasilas LM, Hurt GW and Noble CV (eds). USDA, NRCS, in cooperation with the National Technical Committee for Hydric Soils.

VAN DER EYK JJ, MACVICAR CN and DE VILLIERS JM (1969) Soils of the Tugela Basin. A study in subtropical Africa. Natal Town and Regional Planning Reports Vol. 15. Natal Town and Regional Planning Commission, Pietermaritzburg.

VAN DER WAALS JH (2009) Generalised soil characteristics of the wetland zones of the Halfway House granites, Gauteng Province. Paper presented at: *Wetlands Indaba*, 27–30 October 2009, Langebaan

VAN DER WAALS JH and ROSSOUW PS (2010) Refining area specific wetland delineation criteria through the use of land type data. Paper presented at: *Wetlands Indaba*, 26–29 October 2010, Kimberley.

VAN DER WAALS JH and FAIRALL EP (2011) Pan African Parliament Development – The case for a wetland. Paper presented at: *National Wetlands Indaba*, 18–21 October 2011, Didima, KwaZulu-Natal.

VAN DER WAALS JH, ROSSOUW PS and FAIRALL EP (2012) Proposed hydric soil indicators for the soils of the Halfway House Granite Dome. Paper presented at: *Combined Congress (Soil Science Society of South Africa, South African Society of Crop Production, Southern African Weed Science Society)*, 16–19 January 2012, Potchefstroom.

VAN DER WAALS JH (2012) Proposed classification of organic matter enriched topsoil horizons in the South African Taxonomic System. Paper presented at: *National Wetlands Indaba*, 23–26 October 2012, Klein Kariba, Limpopo Province.

VAN DER WAALS JH (2013) Soil colour variation between topsoil and subsoil horizons in a plinthic catena on the Mpumalanga Highveld, South *Africa. S. Afr. J. Plant Soil* **30** (1) 47–51. https://doi.org/10.1080/02571862.2013.777132

VAN DER WAALS JH (2014) The development of a detailed wetland management guideline for the Halfway House Granite Dome. *International Association for Impact Assessment*, 27–29 August, 2014, Midrand.

VAN DER WAALS JH (2019) 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 3: Framework for regional soil contextualisation. WRC Report No. 2461/3/18. Water Research Commission, Pretoria.

VAN HUYSSTEEN CW and ELLIS F (1997) The relationship between subsoil colour and degree of wetness in a suite of soils in the Grabouw district, Western Cape I. Characterization of colour defined horizons. *S. Afr. J. Plant Soil* **14** (4) 149–153. https://doi.org/10.1080/02571862.1997.10635099

VAN HUYSSTEEN CW, ELLIS F and LAMBRECHTS JJN (1997) The relationship between subsoil colour and degree of wetness in a suite of soils in the Grabouw district, Western Cape II. Predicting duration of water saturation and evaluation of colour definitions for colour-defined horizons. *S. Afr. J. Plant Soil* **14** (4) 154–157. https://doi.org/10.1080/02571862.1997.10635100

VAN HUYSSTEEN CW, HENSLEY M, LE ROUX PAL, ZERE TB and DU PREEZ CC (2005) The relationship between soil water regime and soil profile morphology in the Weatherley catchment, an afforestation area in the north-eastern Eastern Cape. WRC Report No. K5/1317. Water Research Commission, Pretoria.

VAN HUYSSTEEN CW, LE ROUX PAL, HENSLEY M, and ZERE TB (2007) Duration of water saturation in selected soils of Weatherley, South Africa. *S. Afr. J. Plant Soil* **24** (3) 152–160. https://doi.org/10.1080/02571862.2007.10634799

VAN TOL JJ, LE ROUX PAL, HENSLEY M and LORENTZ SA (2010a) Soil as indicator of hillslope hydrological behaviour in the Weatherley Catchment, Eastern Cape, South Africa. *Water SA* **36** (5) 513–520. https://doi.org/10.4314/wsa.v36i5.61985

VAN TOL JJ, LE ROUX PAL and HENSLEY M (2010b) Soil indicators of hillslope hydrology in the Bedford catchments, South Africa. *S. Afr. J. Plant Soil* **27** (3) 242–251. https://doi.org/10.1080/02571862.2010.10639993

VAN TOL JJ, LE ROUX PAL, LORENTZ SA and HENSLEY M (2013a) Hydropedological classification of South African hillslopes. *Vadose Zone J.* **12** (4). https://doi.org/10.2136/vzj2013.01.0007

VAN TOL JJ, HENSLEY M and LE ROUX PAL (2013b) Pedological criteria for estimating the importance of subsurface lateral flow in E horizons in South Africa soils. *Water SA* **39** (1) 47–56. https://doi.org/10.4314/wsa.v39i1.7

VAN ZIJL G, TURNER D, PATERSON G, KOCH J, VAN TOL J, BARICHIEVY K, CLARKE C, DU PLESSIS M and VAN DEVENTER P (2020) The new soil classification system in South Africa, its history, important changes made and implications for users. *S. Afr. J. Plant Soil* **37** (5) 331–342. https://doi.org/10.1080/02571862.2020.1815244

VENEMAN PLM, SPOKAS LA and LINDBO DL (1998) Soil Moisture and Redoximorphic Features: A Historical Perspective. In: Rabenhorst MC, Bell JC and McDaniel PA (eds.) *Quantifying Soil Hydromorphology.* Book Series: SSSA Special Publications, Volume 54. https://doi.org/10.2136/sssaspecpub54.c1

VEPRASKAS MJ, RICHARDSON JL and TANDARICH JP (2006) Dynamics of redoximorphic feature formation under controlled ponding in a created riverine wetland. *Wetlands* **26** 486–496. https://doi.org/10.1672/0277-5212(2006)26[486:DORFFU]2.0.CO;2

VEPRASKAS MJ and LINDBO DL (2012) Redoximorphic features as related to soil hydrology and hydric soils. In: Lin H (ed.) Hydropedology: synergistic integration of soil science and hydrology. Academic Press (Elsevier), Oxford. https://doi.org/10.1016/B978-0-12-386941-8.00005-8

VERMAAK JJG (2000) Geotechnical and hydrogeological characterization of residual soils in the vadose zone. PhD thesis, University of Pretoria.

VODYANITSKII YN (2009) Mineralogy and geochemistry of manganese: A review of publications. *Eurasian Soil Sci.* **42** (10) 1170–1178. https://doi.org/10.1134/S1064229309100123

VODYANITSKII YN (2010) Iron hydroxides in soils: A review of publications. *Eurasian Soil Sci.* **43** 1244–1254. https://doi.org/10.1134/S1064229310110074

WEBER KA, ACHENBACH LA and COATES JD (2006) Microorganisms pumping iron: anaerobic microbial iron oxidation and reduction. *Nat. Rev. Microbiol.* **4** 752–764. https://doi.org/10.1038/nrmicro1490