

CORRELATING SOIL HYDROLOGY WITH SOIL MORPHOLOGY

C.W. van Huyssteen, M. Hensley and P.A.L. le Roux

Department of Soil, Crop and Climate Sciences,
University of the Free State, Bloemfontein 9300, South Africa

ABSTRACT

There is a close relationship between the water regime of a soil profile and its morphology, mainly because water plays a primary role in soil genesis. The hydrological characteristics of soil can either be determined quantitatively by regular measurements, or qualitatively by inference from the soil properties (e.g. colour, exchangeable bases, occurrence of mottles and concretions). Defining the relationship between soil profile morphology and soil water regime is generally difficult due to the lack of sufficient quantitative and qualitative soil water data. This is not the case in the Weatherley catchment, close to Maclear, where an experiment was laid out to monitor and model total catchment hydrology.

Neutron water meter data, measured weekly since January 1997 provides preliminary data for interpreting soil hydrology. This data can be used to draw comparisons between different diagnostic soil horizons of different soils. The neocutanic B and yellow-brown apedal B horizons are saturated for relatively short periods (0 – 40 days per year); E and soft plinthic B horizons for slightly longer periods (24 – 80 days per year); while G horizons and “unspecified material with signs of wetness” are almost continuously saturated (250 – 360 days per year).

These relationships has potential to improve the understanding and definition of hydrological response units, necessary for the modelling of catchment water yield, especially base flow.

1 INTRODUCTION

Procedures for establishing the potential water yield of catchments are important, and become increasingly so as the demand for water increases. Expansion of knowledge in this regard is therefore desirable. This led to the establishment of an intensively measured catchment at Weatherley, in the north eastern Eastern Cape Province. Various WRC funded, and other projects are conducted in this catchment (Lorentz, 2001; Lorentz, Goba & Pretorius, 2001 and Van Huyssteen, Hensley & Le Roux, 2002). The relationship between soil water regime and soil profile morphology has, however, up to now received little attention (Van Huyssteen, *et al.*, 2003).

Because water plays a dominant role in soil genesis, the amount of water that has been available during this process is reflected in the morphology of the profile. There is therefore a close relationship between the water regime of a soil profile and its morphology. The hydrological characteristics of soil can either be determined quantitatively by regular measurements, or qualitatively by inference from the soil properties (colour, exchangeable bases, occurrence of mottles, concretions, etc). Soil colour and the occurrence of mottles are the most important soil property used to predict the water regime of soils. Major soil classification systems of the world (Soil Survey Staff, 1975 and FAO, 1998) utilise soil colour as distinguishing criteria. The definitions for colour defined horizons in South Africa (Soil Classification Working Group, 1991) were also compiled to differentiate between horizons with differing hydrological characteristics. The hypothesis is that red apedal B horizons are freely drained, yellow-brown apedal B horizons are well drained, and E horizons are poorly drained (Le Roux *et al.*, 1999). This conforms with the hypothesis that duration of water saturation determines the quantity and type of iron oxide minerals present and hence the soil colour (Schwertmann, 1993).

In a paper titled "Hydrology and Soil Science" Amerman (1973) concludes that hydrologists need an improved understanding of the hydrology of soils, and that they are looking to soil scientists for assistance. Schwertmann and Kämpf wrote in 1985 that "Studies in which soil temperature and soil moisture regimes are measured and directly related to the pedogenic Fe oxides would thus be very desirable." Improved understanding of the relationship between the water regimes of soil profiles and their morphology will lead to better classification of these soils. This will lead to improved

definitions of hydrological response units (Flugel, 1993), and ecotopes (MacVicar, et al., 1974). This will contribute to improved pedotransfer and therefore better performance of models such as ACRU (Schulze, 1995) and SWAMP (Bennie, Strydom & Vrey, 1998). Although the relationship between soil properties and soil water regime has up to now received relatively little attention in South Africa, valuable contributions have been made by Donkin & Fey (1991), Van Huyssteen (1995) and Le Roux (1996). It is impossible to quantify the soil hydrology of all catchments to the same extent as is the case in Weatherley. Interpretation of the Weatherley catchment data will therefore improve technology transfer in this regard and will enhance the feasibility of extrapolating results to other catchments.

This paper discusses initial results aiming to correlate soil hydrology with soil morphology. This relationship can be a valuable tool in characterising hydrological response units, necessary for the modelling of catchment base flow.

2 MATERIALS AND METHODS

Defining the relationship between soil profile morphology and soil water regime is generally difficult due to the lack of sufficient quantitative and qualitative soil water data. This is not the case at Weatherley, situated approximately 4 km from Maclear on the road to Ugie. The catchment is roughly 150 ha in extent and ranges from 1 260 m to 1 340 m above mean sea level.

The geology of the study area consists mainly of sandstone, shale and mudstone of the Molteno Formation as well as mudstone and sandstone of the Elliot Formation. Two dolerite dykes bisect the catchment, both of them running roughly in a north-south direction.

Vegetation is dominated by *Themeda triandra* and *Tristachya leucothrix* grasses. The vegetation can thus be classified as sour grassveld.

Long term average rainfall in the vicinity of the catchment is 750 mm per year. Average summer temperatures range between 10 and 25 °C, while the winter

temperatures range between 4 and 18 °C. Severe frost occurs in winter, while snow can occur on higher altitudes (Roberts, et al. 1996).

Soil water contents, measured weekly from 20 January 1997 until 19 December 2002, using a neutron water meter, are used in this discussion. Volumetric soil water contents and degree of water saturation (Hillel, 1980) was calculated from the neutron water measurements. The soil was deemed to be saturated, if degree of saturation was higher than 0.7 of porosity. This fraction was chosen as a first approximation and will be refined in future. Average duration of saturation above 0.7 of porosity ($AD_{s>0.7}$) was calculated as the time weighted annual average over the six year period that a horizon was saturated above 0.7 of porosity.

A profile pit was dug at each of the monitoring sites and soil properties were described and classified (Soil Classification Working Group, 1991). Soil samples were taken per diagnostic horizon, but in no more than 200 mm intervals. Soil samples were analysed for the properties related to soil hydrology, viz. pH, exchangeable cations, cation exchange capacity, iron (Fe), manganese (Mn), aluminium (Al), organic carbon and particle size distribution. Bulk density for selected horizons was measured using the core method.

3 RESULTS AND DISCUSSION

Data for the following four profiles Longlands, Pinedene, Tukulu, Longlands (Table 1), as defined by the Soil Classification Working Group (1991), will be discussed here. They occur as a toposequence in the given order over a distance of about 250 m on the eastern side of the catchment. The first profile is just below the crest formed by a rock outcrop of the Elliott formation, and the last profile is just above a shelf formed by Molteno sandstone which underlies the Elliott sandstone.

Table 1 Diagnostic horizon sequence for the soils used in this discussion.

Soil form	First horizon	Second horizon	Third horizon
Longlands	orthic A	E	soft plinthic B
Pinedene	orthic A	yellow brown apedal B	unspecified material with signs of wetness
Tukulu	orthic A	neocutanic B	unspecified material with signs of wetness

P201 (Longlands 2000)

The horizons are of similar loamy sand texture. The redoximorphic morphology intensifies with depth. The soil colour is paler and mottling increase from few in the A to many in the E and common in the soft plinthic B horizon.

Occurrence and duration of saturation increase with depth in this profile (Figure 1). Two saturation events occurred in the A horizon (0-430 mm) during the six year measuring period. In 2000 it was saturated once for 29 days and once in 2001 for 7 days. The incidence of saturation corresponds to above average rain in 2000 and 2001.

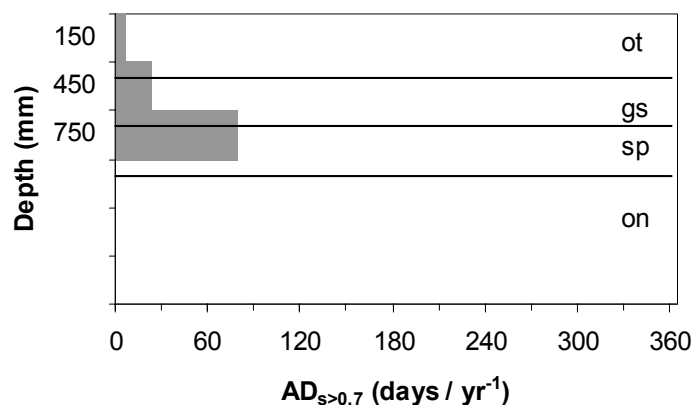


Figure 1 Average duration of saturation above 0.7 of porosity ($AD_{s>0.7}$), in the orthic A (ot), E (gs), soft plinthic B (sp) and unspecified material with signs of wetness (on), for P201 (Longlands)

On average, the E horizon (430-730 mm) saturates 1.7 times during the year, with each event lasting 14 days. It had $AD_{s>0.7}$ of 24 days per year. Saturation ranges from 0 days in 1997 (lowest annual rainfall) to 69 days in 2000, when the highest annual rainfall was recorded.

The soft plinthic B horizon (730-980 mm) saturates slightly more times (2.3) per year but has a much longer $AD_{s>0.7}$ of 80 days, ranging from 43 days in 1999 to 154 days in 2000. The longer $AD_{s>0.7}$ in the soft plinthic B is to be expected, given the underlying impervious saprolite.

Although no water measurements are available for the underlying saprolite, it is expected that the upper part of this horizon will be saturated for longer periods than the soft plinthic B horizon.

P202 (Pinedene 1100)

The profile has a medium sandy loam texture in the A and B horizons, with a fine sandy loam texture in the two C horizons. Matrix soil colour becomes paler (value increases) with depth. There are no mottles in the A, few faint Fe oxide mottles in the B, common faint Fe oxide mottles in the C1 and few prominent Fe mottles in the C2 horizons.

The first two layers of this profile is drier than the P201-Longlands. There is no saturation in the orthic A horizon and minimal (7 days) in the yellow-brown apedal B horizon. The deep subsoil is wetter than profile P201-Longlands and almost constant saturated (Figure 2). The increase in saturation corresponds with a increase in Munsell colour value and clay content.

No water saturation was recorded in the orthic A horizon of the Pinedene profile. The yellow-brown apedal B horizon (450 mm) had $AD_{s>0.7}$ of 7 days per year. This results from one incident in 2000 when the horizon had $AD_{s>0.7}$ of 32 days and one incident in 2001 when it had $AD_{s>0.7}$ of 7 days. Above average rainfall was recorded in both these years. No saturation was recorded at this depth during the other years. No saturation was recorded at this depth during the other years.

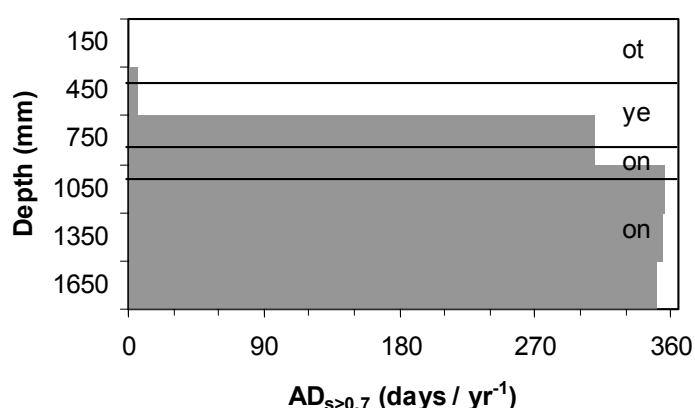


Figure 2 Average duration of saturation above 0.7 of porosity ($AD_{s>0.7}$), in the orthic A (ot), yellow-brown apedal B (ye) and unspecified material with signs of wetness (on), at P202 (Pinedene)

At 750 mm the unspecified material with signs of wetness had $AD_{s>0.7}$ of 309 days per year. Annual saturation varies from 196 days in 1999 to 348 days in 2002. Water saturation at this measuring depth was almost constant throughout the year. The frequency of saturation is therefore low (1.8). The higher than expected frequency is a result of four dry spells in 2000 and two in 2001. During the other years the horizon was unsaturated only once during the year.

At 1 050, 1 350 and 1 650 mm the unspecified material with signs of wetness was saturated almost constantly. Average duration of saturation is 350 days per year, with average frequency of saturation less than once per year.

P203 (Tukulu 2100)

The profile has a coarse sandy loam texture, except for the B horizon which has a medium sandy loam texture. Matrix soil colour becomes pale with depth. There is no mottles in the A horizon, but common coarse Fe oxide mottles in the B, many distinct Fe oxide mottles in the C1 and many prominent Fe oxide mottles in the C2 horizons.

The first two layers of this profile is similar to P202-Pinedene, drier than the P201-Longlands, however, the character of saturation in the deeper subsoil is quite unique. No saturation (Figure 3) is recorded in the orthic A horizon (150 mm) or in the upper neocutanic B (450 mm). At 750 mm, the lower part of the neocutanic B horizon had $AD_{s>0.7}$ of 38 days per year. This ranges from 0 days in 1997 to 95 days in 2002. Saturation took place in 2.2 events per year, lasting 17 days each per event. The unspecified material with signs of wetness (1 050 mm) had $AD_{s>0.7}$ of 180 days per year. The saturation also took place in 2.2 events per year, but lasted 83 days per event. At 1 350 and 1 650 mm the unspecified material with signs of wetness had $AD_{s>0.7}$ of 130 days per year.

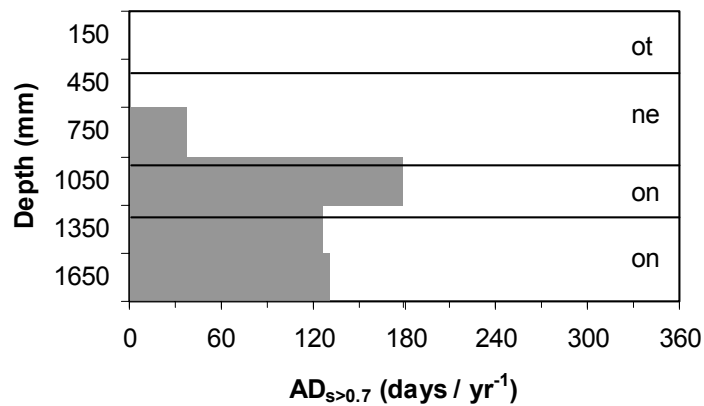


Figure 3 Average duration of saturation above 0.7 of porosity ($AD_{s>0.7}$), in the orthic A (ot), neocutanic B (ne) and unspecified material with signs of wetness (on), at P203 (Tukulu)

P204 (Longlands 2000)

The orthic A horizon has a loam medium sand texture, and the E and soft plinthic B has a fine sandy loam texture, and the G horizon which has a coarse sandy loam texture. Matrix soil colour becomes paler with depth. There are few prominent Fe oxide mottles in the A, many distinct Fe oxide mottles in the E, common prominent Fe oxide mottles in the B and many prominent Fe oxide mottles in the G horizon.

Similar to P201-Longlands the duration of water saturation increases very systematically with depth (Figure 4). The orthic A and E horizon (150 mm) had $AD_{s>0.7}$ of 84 days per year manifested in 1.5 events per year, each lasting 56 days per event. The soft plinthic B horizon (450 mm) had $AD_{s>0.7}$ of 133 days per year manifested in 2.2 events per year, lasting 61 days per event. The G horizon (750 mm) had $AD_{s>0.7}$ of 250 days per year with 2.5 events lasting 100 days per event. The lower G horizon (1 050 mm) is saturated almost constantly (361 days per year).

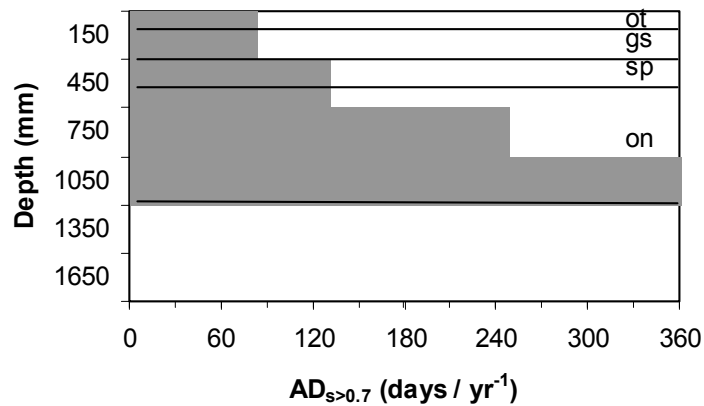


Figure 4 Average duration of saturation above 0.7 of porosity ($AD_{s>0.7}$), in the orthic A (ot), E (gs), soft plinthic B (sp) and unspecified material with signs of wetness (on), at P204 (Longlands)

Table 2 Average annual duration of saturation ($AD_{s>0.7}$), average event duration ($ED_{s>0.7}$) and average annual frequency of saturation events ($FE_{s>0.7}$) of above 0.7 of porosity for P201, P202, P203 and P204, over the six year period 1997 - 2002.

Profile number	Depth (mm)	Diagnostic horizon	($AD_{s>0.7}$) (days/year)	($ED_{s>0.7}$) (days/event)	($FE_{s>0.7}$) (events/year)
P201 Longlands	150	ot	6	6	< 1.0
	450	gs	24	14	1.7
	750	sp	80	34	2.3
P202 Pinedene	150	ot	0	0	0.0
	450	ye	7	7	0.3
	750	ye/on	309	186	1.7
	1050	on	356	356	< 1.0
	1350	on	354	354	< 1.0
	1650	on	350	300	1.2
P203 Tukulu	150	ot	0	0	0.0
	450	ne	0	0	0.0
	750	ne	38	17	2.2
	1050	on	180	83	2.2
	1350	on	127	54	2.3
	1650	on	130	49	2.7
P204 Longlands	150	ot/gs	84	56	1.5
	450	sp/gh	133	61	2.2
	750	on	249	100	2.5
	1050	on	361	361	< 1.0

Profiles P201-Longlands and P204-Longlands form the end members of this catena. The distribution of $AD_{s>0.7}$ in these profiles are similarly systematic although the lower profile is wetter. In P201-Longlands $AD_{s>0.7}$ increase from one horizon to the next by 3,3 to 4 times and in P204 1,4 to 1,9 times. It is postulated that the underlying rock is impervious, restricting vertical drainage. This causes saturation in the overlying horizons. Water only drains laterally from these profiles. From P204-Longlands it exits and cascades over the sandstone shelf.

Water drains fast laterally from the E horizon, resulting in a short duration of reducing conditions, leading to removal of Fe (bleaching) and the formation of some Fe oxide mottles. Slower lateral drainage from the soft plinthic B horizon results in increased duration of saturation and reduction, leading to the increased localisation and accumulation of Fe and Mn oxides to form well defined Fe and Mn mottles as well as concretions.

The soil water regime of the P202-Pinedene is different. It is postulated that water drains fast laterally on top of the C horizons and slow in the C horizons due to the difference in clay content causing a prominent difference in $AD_{s>0.7}$ of the yellow-brown apedal B and the C horizons.

The soil water regime of profile P203-Tukulu (Figure 4) has the discrepancy of a wetter horizon (C1) overlying a drier subsoil horizon (C2). It is postulated that the high clay content in the C2 restricts vertical water movement due to a very slow hydraulic conductivity, causing saturation in the C1 horizon, periodically extending upwards into the neocutanic B horizon during wet spells. The low hydraulic conductivity of the C2 retard saturation of the horizon significantly. This phenomenon is reported to be prominent during major rain events of high intensity (Lorenz & Hickson, 2001). The result of periodic saturation in the C1 horizon is evidenced by the occurrence of many Fe oxide mottles.

4 CONCLUSIONS

There is a very good relationship between soil morphology and duration of water saturation. For example, E and soft plinthic B horizons had $AD_{s>0.7}$ of 24 – 80 days per year. It is indicative of good hydraulic conductivity in these horizons that leads to speedy removal of water. In contrast, the G and “unspecified material with signs of wetness” horizons had $AD_{s>0.7}$ close to 365 days per year. The long periods of saturation are correlated with a high clay content, mottling, and low chroma colours. The lack of mottling in neocutanic B and yellow-brown apedal B horizons are indicative of the low $AD_{s>0.7}$ of 0 - 38 days per year. Orthic A horizons can be very dry, or saturated, depending on the nature of the underlying horizons.

The relationship between soil morphology and soil water regime could be used by hydrologists to improve characterization of hydrological response units, aiding in the modelling of inter flow. This in turn should aid in better prediction of catchment water yield.

5 REFERENCES

- Amerman, C.R. 1973. Field soil water regime. **In:** R.R. Bruce, K.W. Flach, H.M. Taylor, M. Stelly, R.C. Dinauer and J.M. Hoch (Eds.). Hydrology and soil science. SSSA 9. Madison, WI.
- Bennie, A.T.P., M.G. Strydom and H.S. Vrey. 1998. Gebruik van rekenaar modelle vir landboukundige waterbestuur op ekotoopvlak. WNK Report No. TT 102/98. WNK, Pretoria.
- Donkin, M.J. and M.V. Fey. 1991. Factor analysis of familiar properties of some Natal soils with the potential for afforestation. *Geoderma*. 48:297-304.
- FAO, 1998. World Reference Base For Soil Resources. World Soil Resources Reports 84. FAO, Rome.
- Flugel, W.A. 1993. GIS-analysis to derive Hydrological Response Units (HRU's) for regional modelling using PRMS. **In:** Proc. International workshop on scale issues in hydrological / environmental modelling. Robertson, Australia.
- Hillel, D. 1980. Fundamentals of soil physics. Academic Press, New York.
- Le Roux, P.A.L. 1996. Die aard verspreiding en genese van geselekteerde redoksmorfe gronde in Suid-Afrika. Ph.D. tesis. University of the Orange Free State, Bloemfontein.
- Le Roux, P.A.L., F. Ellis, F.R. Merryweather, J.L. Schoeman, K. Snyman, P.W. Van Deventer and E. Verster. 1999. Guidelines for the mapping and interpretation of soils in South Africa. University of the Free State, Bloemfontein.
- Lorentz, S., 2001. Hydrological systems modelling research programme: Hydrological processes. WRC Report No. 637/1/01. WRC, Pretoria.
- Lorentz, S., Goba, P. & Pretorius, J., 2001. Hydrological processes research: Experiments and measurements of soil hydraulic characteristics. WRC Report No. 744/1/01. WRC, Pretoria.
- Lorentz, S & Hickson, R., 2001. Applying hillslope hydrology observations to catchment modeling in Molteno formations. Tenth South African Hydrology Symposium.
- MacVicar, C.N., D.M. Scotney, T.E. Skinner, H.S. Niehaus and J.H. Loubser. 1974. A classification of land (climate, terrain form, soil) primarily for rainfed agriculture. *S Afr J Agric Extension*. 3:22-4.

- Roberts, V.G., M. Hensley, A.L. Smith-Baillie and D.G. Patterson. 1996. Detailed soil survey of the Weatherly catchment. ISCW Report No. GW/A/96/33, ARC-ISCW, Pretoria.
- Schulze, R.E. 1995. Hydrology and agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modeling system. WRC Report No 63/2/84. WRC, Pretoria.
- Schwertmann, U. 1993. Relations between iron oxides, soil color and soil formation. p.51-69. **In:** J.M. Bigham and E.J. Coilkosz (Eds.). Soil color. SSSA Spec. Publ. 31. SSSA, Madison, Wisconsin.
- Schwertmann, U. and N. Kämpf. 1985. Properties of goethite and hematite in kaolinitic soils of Southern and Central Brazil. *Soil Sci.* 139:344-350.
- Soil Classification Working Group. 1991. Soil classification - A taxonomic system for South Africa. Mem. agric. nat. resour. S. Afr. No. 15.
- Soil Survey Staff, 1975. Soil Taxonomy - A basic system of soil classification for making and interpreting soil surveys. U.S. Govt. Printing Office, Washington.
- Van Huyssteen, C.W. 1995. The relationship between subsoil colour and degree of wetness in a suite of soils in the Grabouw district, Western Cape. M.Sc. thesis, University of Stellenbosch.
- Van Huyssteen, C.W., Hensley, M. & le Roux, P.A.L, Joseph, L.F. & du Preez, C.C., 2003. The relationship between soil water regime and soil profile morphology in the Weatherley catchment, an afforestation area in the North Eastern Cape. First progress report on WRC project No K5/1317. WRC, Pretoria.
- Van Huyssteen, C.W., Hensley, M. & le Roux, P.A.L.. 2002. Correlating soil hydrology with soil morphology for improved technology transfer. A report to the WRC on project No. K8/419. WRC, Pretoria.