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Understanding groundwater/surface-water interactions through hydropedological interpretation of soil distribution patterns

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Abstract. Understanding and quantifying groundwater/surface water interactions is important for effective water resource management. Characterisation of these interactions are however difficult due to heterogeneities in landscapes on difficulties in measuring hydrological processes at different scales. Although soils play an integral role in the hydrological functioning of landscape, very few groundwater/surface water interaction studies consider soils as key components of hydrologic variation. In this study, 21 catchments in South Africa with available stream attributes such as baseflow index (BFI) and an index of streamflow variability (CVB) were identified. The soils of the catchments were interpreted and grouped into four classes based on their dominant hydrological response namely: Recharge, Interflow, Responsive (shallow) and Responsive (wet). The dominant soil distribution patterns in the catchments were then determined. Significant positive correlation coefficients (r) exists between BFI and soil attributes such as depth (r = 0.72), clay content (r = 0.50) and percentage coverage by 'Recharge' soils (r = 0.78). The occurrence of 'Interflow' and shallow soils decreased BFI significantly (r = -0.79 and -0.66 respectively). CVB are however positively correlated to the area of 'Interflow' soils in the catchment (r = 0.73) and negatively to the area under 'Recharge' soils (r = -0.65). Soils dominant in the valley bottom suggest that there are considerable differences in groundwater/surface water interaction mechanisms. Based on the results three perceptual models were constructed: 1) vertical drainage through soils and recharge of groundwater in the upper slopes of the catchment are dominant, with return flow to the soil in lower lying positions, both the soil and groundwater contribute the stream) 2) vertical drainage through soils and recharge of groundwater dominant in upper and lower lying positions, no return flow to soils, only groundwater contribute to stream and 3) lateral flow at soil bedrock is dominant throughout catchment, limited recharge, stream fed through lateral flow from soils with limited groundwater contribution.

1 Introduction

Characterising groundwater/surface water interactions forms an integral part of water resource management. Quantifying the exchange processes and flow rates between groundwater and surface water is important, not only for pollution protection and control, but also in management of water-use (Kalbus et al., 2006). Groundwater policies should account for the impact of aquifer drawdown on surface water depletion (Sophocleous, 2002). In the South African context, the National Water Act of 1998 requires that a 'reserve' should be established before new water use licenses are granted. This reserve includes a volume of water sufficient to supply basic human needs of dependents on the water resource as well as sustaining ecological needs. The reserve is therefore the minimum volume of water which should be available for humans and the environment during and after any land-use change which affects water resources. Establishing the reserve requires accurate understanding of hydrological processes and quantification of the contribution of different water sources to streams (DWAF, 1999). Although groundwater/surface water interactions have been the subject of much research in the recent past, the mechanisms involved are not yet fully understood (Levy and Xu, 2012). Progress is hindered by the difficulty in holistically measuring hydrological processes at different scales, heterogeneity of different hydrological landscapes and scientific separation of sub-disciplines within hydrological sciences (e.g. geohydrology and surface hydrology).

Several techniques exists to study groundwater surface water interactions. These techniques are discussed comprehensively by Kalbus et al. (2006) and include: direct measurements of water flux with seepage meters; heat tracer methods which are based on the inherent difference in temperature between groundwater and surface water; methods based the application of Darcy's law, such as piezometer nests for calculating hydraulic gradients and slug or permeameter tests to estimate the hydraulic conductivity and lastly mass balance approaches such as hydrograph separation and measuring increments in streamflow. Almost every process of interest in the hydrological cycle (for example evapotranspiration, infiltration and groundwater flow) is difficult to observe and measure, because these processes are dynamic in nature with strong temporal variation (Sivapalan 2003). Soil properties are in the short term not dynamic in nature and their spatial variation is not random (Webster, 2000).

Since soils are a first order control in partitioning of hydrological flowpaths, controlling residence times and storage of water, they play a major role in groundwater/surface water interactions (Park et al., 2001; Soulsby et al., 2006). Soils facilitates infiltration, thereby controlling stormflow generation and acts as water storage for evapotranspiration. Soil is also responsible for redistributing water in the critical zone; laterally downslope towards drainage channels, and vertically to below the root zone, into fractured rocks and eventually recharge into the groundwater zone (Schulze, 1995; Sivapalan, 2003). Hydrologists agree that the spatial variation of soil properties significantly influences hydrological processes but they often lack the skill to gather and interpret soil information (Chirico et al., 2007; Lilly et al., 1998).

The relationship between soil and hydrology is however interactive; soil has the ability to transmit, store and react with water but, on the other hand, water is a primary agent in soil genesis, resulting in the formation of soil properties containing unique signatures of the way they formed. The correct interpretation of spatially varying soil properties associated with the interactive relationship between soil and hydrology (hydropedology) can serve as indicators of the dominant hydrological processes (Ticehurst et al., 2007; Van Tol et al., 2010; Van Tol et al., 2013).

Ebrahim and Villholth (2016) studied the shallow groundwater availability in 21 perennial and relatively undisturbed catchments with long term streamflow records in South Africa. As part of their study they explored relationships between catchment attributes such as area, river length and average slope, and attributes indicative of groundwater/surface water interactions. The only soil attribute mentioned in Ebrahim and Villholth (2016) was the average sand content. In this paper it is argued that soils and their spatial distribution might be used to improve the characterization of groundwater/surface water interaction. The objectives of the paper was 1) to explore relationships between soils and their spatial distribution and catchment attributes indicative of groundwater/surface water interactions and 2) to conceptualize groundwater/surface water interactions in the selected study areas based on the dominant soils and their spatial distribution.

2 Materials and methods

The 21 catchments studied by Ebrahim and Villholth (2016) were re-examined in this paper Table 1 and Figure 1a - d. Hydrologic attributes of the catchments were determined from long term measured streamflow records by Ebrahim and Villholth (2016). In this paper only the following three attributes were used; the drainage time scale (K), Baseflow Index (BFI) and a measure of hydrological variability (CVB). The drainage timescale can be calculated by (Brutsaert, 2008):

$$K = \frac{0.1n}{D_d^2 T_e} \tag{1}$$

Where n is the drainable porosity; D_d is the drainage density and T_e is the effective hydraulic transmissivity which is equivalent to the product of the hydraulic conductivity and the aquifer depth. The baseflow index (BFI) for each catchment was determined following the approach of Hughes and Hannart (2003). The CVB is an overall representation of the variation in streamflow (Hughes and Hannart (2003):

$$CVB = \frac{CV\ index}{BFI} \qquad (2)$$

The CV index is the long-term coefficient of variation in both the wet and dry season streamflow. For more details on how the relevant attributes were determined, please see Ebrahim and Villholth (2016). Annual rainfall for each catchment were obtained from Lynch and Schulze (2007).

Soil information was obtained from the Land Type database of South Africa (Land Type Survey Staff, 1972 – 2006). A land type is an area, demarcateable at a scale of 1:250 000, with relative homogenous soil forming factors i.e. climate, parent material, time and topography resulting in fairly homogenous soil distribution patterns. The soil classification employed in the Land Type database made use of two levels namely 'soil forms' as upper level and 'soil series' as a more specific level (MacVicar et al., 1977). A soil form is comprise of a specific vertical sequence of diagnostic horizons. In this study, only the soil forms were considered.

Each land type is divided into terrain morphological units (TMU's) namely crest (TMU1), scarp (TMU2), backslope (TMU3), footslope (TMU4) and valley bottom (TMU5). Not all TMU's are present in all land types. Each land type is accompanied by an inventory in which the area of the land type, the dominant TMU's and the area covered by each TMU and the average slope length, shape and angle of each terrain unit are presented. Soil forms, an estimated area covered by different soil forms, depth to restricting layer as well as estimated clay content are also available for each TMU. The 21 catchments are covered by 177 different land types with 38 different soil forms (Figure 1).

Each soil form recorded in the land type inventory is defined by a unique vertical sequence of diagnostic horizons. A horizon is a unit with relatively homogenous morphological properties e.g. structure, colour and redoximorphic features. These morphological properties were interpreted and related to their hydrological significance. The 38 soil forms were then regrouped into five hydrological classes based on their expected hydrological response as indicated by the soil morphology (following the classification of van Tol et al., 2013). These classes were:

- Recharge soils: These are soils without any morphological evidence of saturation. Vertical flow into, through and out of the profile is dominant. These soils are either shallow on fractured rock or deep and freely drained. Recharge of groundwater and fractured rock aquifers are expected to be the dominant flowpaths.
- Interflow soils: There are distinguished between two types of soils where sub-surface lateral flow is dominant. In duplex soils the textural discontinuity between A and B horizons promote ponding of drainable water on the A/B horizon interface. Soils overlying impermeable bedrock are often associated with redoximorphic properties indicating that ponding of water on the soil/bedrock interface do occur. Depending on the slope, lateral drainage on this interface is the dominant flowpath.
- Responsive (shallow): Typically shallow soils overlying impermeable bedrock with limited storage capacity of water. These soils tend to generate overlandflow and contribute to peak or quickflow of streams.
- Responsive (wet): These soils contain morphological evidence of long periods of saturation (gleysation), typical of wetland soils. Overlandflow is the dominant flowpath and is generated due to saturation excess.

In order to obtain an average hydrological soil class distribution for each catchment it was first necessary to determine the percentage of a catchment covered by specific land types. Secondly the relative coverage of different TMU's in specific land types were determined. The coverage by different hydrological soil classes on each TMU was then manually calculated for each land type. The percentage coverage of a specific land type in a catchment together with the relative coverage of different TMU's in a land type was then used to obtain an average weighting factor for each land type. This weighting factor was multiplied with the coverage of hydrological soil classes on each TMU and summed to obtain an average hydrological soil class distribution sequence for each of the 21 catchments. The average clay content and soil depth for each catchment were obtained with the same method. In addition, the dominant and sub-dominant soil forms in the valley bottom (TMU5) were recorded.

The total coverage of different hydrological soil classes per catchment; the coverage on different TMU's, average soil depth and average clay contents were statistically compared with the hydrological parameters (K, BFI and CVB) and selected additional catchment attributes. Addinsoft XLStat v. 17 was used for all statistical analysis.

3 Results

Average soil depth in the catchments ranged between 376 and 744 mm (Table 2). The shallower soils were generally found in the southern catchments (Figure 1c) and associated with soils of quartzitic sandstone of the Table Mountain Group (Land Type Survey Staff 1972 – 2006). The influence of the parent material is also visible in the low average clay contents of these soils, ranging between 6 and 10.2% for the 10 catchments in Figure 1c. The average clay content of the remaining 11 catchments ranged between 11.9 and 35.6%. The low clay contents of stations A4H008 and B1H004 were associated with sandstone parent material of the Ecca Group. Higher clay contents, especially those of the catchments in eastern part of South Africa (Figure 1d), were associated with dolerite and parent material rich in mudstone and shales.

'Recharge' soils dominated upper slopes (TMU1-3) in most of the catchments. In the southern catchments (Figure 1c), 'Interflow' soils and 'Responsive (shallow)' soils were however the dominant hydrological soil types. TMU5 positions occupy small areas of the catchments, the percentage covered by 'Responsive (wet)' soils were however considerably greater in the catchments in the eastern part of the country (Figure 1d), when compared to that of the southern (Figure 1c) and northern parts (Figure 1b).

A wide range of soil forms occur in the valley bottom of the catchments (Table 2 and Figure 2). In the following discussion the South African soil form is followed by the most appropriate group of the World Reference Base of Soil Resources (IUSS Working Group WRB, 2014). Katspruit soils (Gleysols) dominate the majority of the TMU5 positions of the eastern catchments. These soils are associated with long periods of saturation, reduction and gleyzation. They are typical examples of 'Responsive (wet)' soils. In Kroonstad soils (Stagnosols), some evidence of lateral flow such as removal of colloidal material and colouring agents is evident above the gleyed sub-soil horizon. Longlands (albic-Plinthosols) soils are marked by plinthite formation due a fluctuating water table. This soil form is an 'Interflow' soil; lateral flow is likely to occur on the soil/bedrock interface as well as the A/B horizon interface. Oakleaf (Cambisols) and Dundee (Fluvisols) dominating in some of the catchments are indicative of alluvial deposits in the valley bottom. These soil forms are typically comprised of coarse material and were interpreted to be 'Recharge' soils. Valsrivier (Luvisols) soils shows a marked increase in clay in the subsoil without any evidence of saturation. Lastly the Hutton (Ferrasols) are freely drained soils with no morphological evidence of saturation in the profile, typical of 'Recharge' soils.

Good positive correlations exist between BFI and K, average soil depth, clay contents and the percentage covered by ‘Recharge’ soils (Table 3 and Figure 2). Strong negative correlations were observed between BFI and CVB and percentage covered by ‘Responsive (shallow)’ and ‘Interflow’ soils. The strong correlation between BFI and K is further accentuated by similar correlations between K and other attributes as BFI (Table 3). CVB was inversely correlated with BFI, K, soil depth, clay content and the percentage of the area under ‘Recharge’ soils and ‘Responsive (wet)’ soils and positively correlated to the percentage of ‘Interflow’ and ‘Responsive (shallow)’ soils. Interestingly there were no significant correlations between the catchment area (Figure 2a) nor the mean annual rainfall (Figure 2b) and any of the streamflow attributes.

4 Discussion

The strong positive correlation between BFI and K, fittingly suggest that high K values (slow recession response) will result in higher baseflow (Ebrahim and Villholth, 2016). The inverse correlation between BFI and CVB is explained by equation 2, but further suggest that catchments with higher variation in streamflow are typically associated with lower baseflow. The lack of any significant correlation between catchment area (Figure 2a) and rainfall (Figure 2b) was also reported by McGuire et al., (2005) and indicate that internal catchment properties impact catchment functioning greatly.

A positive correlation between soil depth and both BFI and K indicates that deeper soils promote recharge and baseflow (Figure 2c). In high rainfall areas, the storage capacity of shallow soils can be exceeded shortly after the start of rain events and thereby promote the generation of overland flow due to saturation excess (Van Tol et al., 2010). Similar results were reported by Asano et al. (2002) and Uchida et al. (2006), both studies occupied with paired catchments in Japan. The difference in soil depth between the catchments was a dominant factor influencing bedrock flow and residence times of water as well as variations in stream flow. Deeper soils produced more, and more constant baseflow.

The correlation between the average particle size distribution and BFI was also reported by Ebrahim and Villholth (2016). They however compare the sand content, obtained from a global soil dataset, with the BFI and obtained a significant correlation of -0.68. Santhi et al. (2008), in contrast, found good positive correlations between the sand content and baseflow and recharge in several catchments in the US. This discrepancy highlights the important contribution of hydropedology to the holistic understanding of the hydrological functioning of soils, hillslopes and catchments. Although the positive relationship between the sand content and hydraulic conductivity are well documented, this small scale physical relationships are not always applicable at landscape scale. Based on Table 2 and 3, the catchments dominated by sandy soils are also those with the highest percentage of ‘Interflow’ soils, especially in the upperslopes (TMU1-3). The sandy surface material promote infiltration but the sandstone bedrock acts as an aquitard and promotes lateral flow at the soil/bedrock interface.

The very high negative correlation (-0.82) between BFI and the percentage of ‘Interflow’ soils on the TMU1-3 positions suggests that lateral flow in these catchments restricts deep percolation to the fractured rock or regional aquifer and baseflow (Figure 2e). In addition, lateral flows in the relatively shallow soils avail water for root uptake and evapotranspiration. The total volume of water available to streamflow are thereby reduced. The positive correlation between CVB and ‘Interflow’ soils suggest that lateral flows are typically event driven with a high degree of temporal variation. This is opposed to the inverse correlation between the percentages of the area under ‘Recharge’ soils and CVB. More recharge of fractured rock aquifers and bedrock flowpaths to the stream imply more stable baseflow (seasonal driven) with lower temporal variation.

The morphological properties of the soil forms in the valley bottom positions reveal the nature of groundwater/surface water interactions. Streambanks of catchments with high BFI and K values and low CVB values are mostly covered by soils expressing morphological properties associated with long periods of saturation (Figure 2f). This is supported by the significant positive correlation between the coverage of ‘Responsive (wet)’ soils on the valley bottom and the K value as well as the inverse correlation between CVB and the coverage of ‘Responsive (wet’ soils on the TMU5 position. Although the relationship between Katspruit (Ka) soils and BFI and CVB can be explained with conventional pedogenesis, it is slightly more difficult to explain the dominant occurrence of some of the other soils and their associated BFI and CVB values in Figure 2f. For example, Oakleaf (Oa) and Hutton (Hu) soils are good examples of freely drained oxidized soils with no indication of any saturation within the soil profile, yet both Oa and Hu soils in Figure 2f are linked with high BFI and low CVB values. Logically, it appears that infiltrated water did not return to the soil in these catchments i.e. a bedrock flowpath fed the stream directly. It should be noted that the observation depth for the soil descriptions was limited to 1.2 m (MacVicar et al., 1977), and drainage to the stream might occur in deeper soil layers. The prominence of the ‘Interflow’ soil i.e. Longlands (Lo), in the valley bottom of the catchments with relatively low BFI and high CVB are indicative the lateral flows fed the stream directly. Lateral drainage was therefore not restricted to the upperslopes. Although subsurface lateral flow in the soil might contribute to baseflow, especially in headwater catchments (Levy and Xhu, 2012; Sophocleous, 2002), several researchers reported that lateral flows (interflow) can contribute to quick flows (Harr, 1977; Mosley, 1979; Retter et al., 2006; Roets et al., 2008). It appears that in these catchments, the sandy soils combined with slowly permeable bedrock results in the generation of quickflow rather than baseflow.

4.1 Perceptual hydropedological response models

Conceptually there are three distinct groundwater/surface water interaction mechanisms at play in the various catchments (Figure 3). In the first case (Figure 3a), vertical drainage is dominant on the TMU1-3 positions promoting recharge of the groundwater (Figure 3a-1). Lateral drainage occurs within the aquifer towards the stream (Figure 3a-2) and returnflow to the soil occur in the TMU4-5 positions resulting in saturation of the soil profile (Figure 3a-3). The stream is fed through both the soil (Figure 3a-4) and the groundwater (Figure 3a-5). This conceptual perceptual model is similar to the class 4 hillslope '*recharge to wetland*' as described by van Tol et al. (2013). Catchments exhibiting this type of behaviour are A4H008, B1H004, U2H006, U2H007, U2H013 and U7H007.

In the second case, recharge is also dominant (Figure 3b), however the presence of freely drained soils in the TMU5 position indicate that there are no significant returnflow to the soil in the lower lying positions. This hydrological behaviour is similar to class 3 hillslopes '*recharge to groundwater, not connected*' as described by van Tol et al. (2013), where groundwater contribute to streamflow without contact with the soil. Catchments B4H005, B7H004, B8H010, C8H005 and V6H004 are represented by the perceptual model.

The third perceptual model is similar to class 6 hillslopes '*quick interflow*' in the hillslope classification of van Tol et al. (2013). Lateral flow at the soil/bedrock and A/B horizon interface dominates the hydrological response (Figure 3c-1). Small quantities of recharge might occur through cracks and fissures in the bedrock, but this is not the dominant behaviour (Figure 3c-2). Streams are predominantly fed through lateral flows in the soils (Figure 3c-3). These lateral flows are event driven with relatively short residence times resulting in relatively high levels of variation in flows. Groundwater does contribute to streamflow (Figure 3c-4) but in smaller quantities than in the first two models (Figure 3a & b). Most of the studied catchments in the southern part (Figure 1c) falls within this category i.e. K2H002, K3H003, K3H005, K4H001, K4H002, K6H001, K8H001 and K8H002.

5 Conclusion

Understanding groundwater/surface water interactions is important for water resource management. In this study hydropedological interpretation of regional soil information explained a considerable amount of variation in stream attributes associated with groundwater/surface water interactions in 21 catchments. The soil information used gave a general description of soil distribution patterns in the selected catchments, but was limited in terms of observation depth. Yet, correlation coefficients obtained between BFI and hydrological soil types were encouragingly high. Hydropedological interpretation of soils can therefore contribute greatly to the understanding of the hydrological behaviour of landscapes. The soils and their associated properties occurring in the valley bottom positions also explained the mechanisms of groundwater/surface water interactions to some extent. Site visits with proper soil descriptions of the entire profile are likely to improve the understanding of these interactions. The three perceptual models of groundwater/surface water interaction and hydrological behaviour illustrated that dominant hydrological controls can be identified even though catchments differ vastly in terms of location, area and climate.

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Table 1: Catchment attributes applicable to this study (Ebrahim and Villholth, 2016)

Catchment	Station No	Area (km²)	Latitude	Longitude	Data available	Rainfall* (mm a^{-1})	K (day)	BFI	CVB index
B81D	B8H010	473	-23.893	30.358	1960 - present	619	53.1	0.37	8.1
A42D	A4H008	496	-24.217	27.973	1964 - present	596	84	0.48	3.6
B73A	B7H004	135	-24.556	31.032	1950 - present	702	85.3	0.41	4.4
B42F	B4H005	191	-25.036	30.219	1960 - present	696	119	0.54	2.5
B11K	B1H004	377	-25.674	29.173	1959 - present	640	168	0.61	2.7
C81F	C8H005	697	-28.376	28.860	1963 - present	681	64.6	0.32	5.8
V60B	V6H004	662	-28.405	30.013	1954 - present	808	65	0.28	8.7
U20D	U2H006	339	-29.382	30.278	1954 - 2013	955	82.7	0.43	3.7
U20B	U2H007	355	-29.442	30.149	1954 - present	992	111	0.47	3.3
U20A	U2H013	297	-29.513	30.094	1960 - present	960	107	0.42	3.7
U70A	U7H007	114	-29.862	30.244	1964 - present	1148	120	0.51	2.8
K60A	K6H001	26	-33.804	23.135	1961 - present	727	39.5	0.28	16.1
K40C	K4H002	35	-33.881	22.838	1961 - present	759	33.5	0.2	11.8
K50A	K5H002	57	-33.891	23.029	1961 - present	879	67.8	0.39	5.7
K30D	K3H005	185	-33.945	22.614	1969 - present	754	54.5	0.34	8.5
K70B	K7H001	134	-33.956	23.639	1961 - present	971	62.8	0.32	6.3
K40B	K4H001	112	-33.980	22.799	1959 - 1993	736	84.5	0.38	6.5
K80C	K8H002	23	-33.981	24.050	1961 - present	1163	45.5	0.27	7.8
K80C	K8H001	78	-33.982	24.021	1961 - present	1158	27.5	0.2	9.4
K30A	K3H003	145	-34.007	22.350	1961 - present	660	33.3	0.18	17.7
K20A	K2H002	130	-34.029	22.222	1961 - present	578	34	0.18	19.5

*Obtained from Lynch and Schulze (2007).

Table 2 Dominant land types and associated distribution of hydrological soil types in the selected catchments

Station No	Land Types		Soil Depth	Clay	Total				Recharge		Interflow		Responsive (wet)		Responsive (shallow)		Soil Form
	#[1]	Dominant[2]			Re[3]	IntF[4]	Res_W[5]	Res_S[6]	TMU 1-3	TMU 4-5	TMU 1-3	TMU 4-5	TMU 4	TMU 5	TMU 1-3	TMU 4-5	TMU5
			mm	%													
A4H008*	7	Ad20(24.4);Ad21(10.8);Fa286(23.6);Fa287(35.7)	557.2	11.9	48.9	7.6	0.7	42.8	33.3	15.6	2.2	5.5	0.0	0.7	41.1	1.7	Ka
B1H004*	4	Bb11(17.8);Bb12(19.1);Bb13(48.0);Bb(15.1)	718.6	13.8	71.1	21.5	1.6	5.8	68.9	2.2	13.0	8.5	0.0	1.6	5.2	0.5	Ka
B4H005*	6	Ac1(10.0);Ac75(39.0);Fa327(14.7);Fa343(30.7)	539.6	29.1	69.3	2.6	0.5	27.5	51.3	18.0	2.3	0.3	0.0	0.5	26.9	0.7	Oa
B7H004*	10	Ab40(15.6);Ab41(33.3);Ab59(13.4);Fb181(21.1)	538.3	26.8	83.1	9.8	0.2	6.9	72.6	10.5	5.8	4.0	0.0	0.2	6.7	0.2	Hu
B8H010*	18	Ab95(16.4);Ea204(15.1);Fa348(18.4)	599.4	24.1	69.3	8.4	0.8	21.5	40.6	28.7	5.2	3.2	0.3	0.6	19.2	2.3	Hu
K2H002#	8	Db33(13.8);Gb2(24.4);Ib142(47.0)	438.9	9.6	14.9	42.6	4.1	38.3	12.8	2.1	38.6	4.0	0.3	0.0	37.5	0.8	Lo
K3H003#	5	Db33(13.2);Gb2(23.4);Ib141(10.6);Ib142(45.0)	424.5	7.7	11.6	41.9	2.8	43.7	9.6	2.0	36.1	5.8	0.3	0.0	42.6	1.1	Lo
K3H005#	5	Gb2(28.1);Ib141(12.8);Ib142(54.2)	401.2	7.5	15.7	31.7	0.6	52.0	13.7	2.0	28.9	2.8	0.0	0.0	50.7	1.3	Lo
K4H001#	6	Gb2(27.3);Ib141(12.4);Ib142(52.7)	512.8	7.3	16.6	31.6	0.6	51.2	14.5	2.1	28.7	2.9	0.0	0.0	49.9	1.3	Lo
K4H002#	2	Gb2(34.2);Ib142(65.8)	376.4	6.0	12.4	35.2	0.0	52.4	10.4	2.0	32.6	2.6	0.0	0.0	51.2	1.1	Lo
K5H002#	4	Gb2(28.1);Ib141(12.8);Ib142(54.1)	378.2	6.1	16.5	30.1	0.0	53.4	14.3	2.2	27.5	2.7	0.0	0.0	52.0	1.4	Oa
K6H001#	7	Ib140(12.0);Ib141(15.0);Ib142(63.3)	383.4	8.5	9.8	28.1	0.4	61.7	8.2	1.6	25.0	3.1	0.0	0.0	60.0	1.7	Lo
K7H001#	5	Ib56(72.7);Ib64(18.3)	400.1	7.4	2.5	36.0	0.1	61.4	2.3	0.2	31.9	4.1	0.0	0.1	60.8	0.6	Kd
K8H002#	6	Ib56(94.1)	485.7	10.2	0.6	36.0	0.1	63.4	0.6	0.0	31.6	4.4	0.0	0.1	62.9	0.5	Lo
K8H001#	6	Ib56(89.7)	487.3	10.1	2.1	34.5	0.1	63.4	2.1	0.0	30.1	4.4	0.0	0.1	62.9	0.5	Lo
C8H005Ŧ	10	Bb124(27.0);Ca111(20.0);Fa631(21.2);Ib365(22.2)	400.3	25.4	31.9	24.5	3.5	40.1	23.6	8.3	20.6	3.9	1.3	1.2	37.6	2.6	Du
U2H013Ŧ	24	Ac212(15.1);Ac215(15.5);Ac309(10.9)	646.2	32.0	69.3	6.8	5.7	18.2	68.3	1.0	6.7	0.1	0.0	5.7	18.2	0.0	Ka
U2H007Ŧ	20	Ac206(10.2);Ac209(12.2);Ac211(14.6);Ac212(10.8);	656.3	32.6	77.3	6.5	3.5	12.7	76.4	0.9	5.7	0.8	0.0	3.4	12.7	0.0	Ka
U2H006Ŧ	16	Ac189(13.1)Ac193(13.0);Ac206(13.0);Ac209(15.9)	716.6	35.6	78.1	6.5	2.3	13.1	77.5	0.6	6.5	0.0	0.0	2.3	13.1	0.0	Ka
U7H007Ŧ	10	Ac234(35.1);Ac239(18.3);Ac240(11.1);Ac241(11.5)	744.9	35.6	83.0	5.3	4.0	7.8	81.8	1.1	5.3	0.0	0.0	4.0	7.8	0.0	Ka
V6H004Ŧ	28	Bb129(10.3);Bb49(15.0);Bb70(15.3);Fa802(11.4)	514.2	31.3	39.9	29.0	2.5	28.5	34.9	5.0	25.9	3.1	0.6	1.7	28.3	0.2	Va

[1] Number of land types in each catchment; [2] Dominant land types in each catchment (>10% coverage); [3] Recharge soils; [4] Interflow soils; [5] Responsive (wet) soils; [6] Responsive (shallow) soils.

*Catchments are presented in Figure 1b; #Catchments are presented in Figure 1c; ŦCatchments are presented in Figure 1d.

5 Abbreviations of soil forms: Av – Avalon; Lo – Longlands; Ka – Katspruit; Oa – Oakleaf; Es – Estcourt; Hu – Hutton; R – Rock; Kd – Kroonstad; Du – Dundee; Va - Valsrivier

Table 3 Pearson correlation matrix coefficients between selected catchment and streamflow attributes and hydrological soil type distribution

Variables	BFI	K	CVB	Area	Rainfall	Depth	Clay	Recharge	Interflow	Res_W	Res_S	Recharge		Interflow		Res_W	Res_S	
								Total				TMU 1-3	TMU 4-5	TMU 1-3	TMU 4 -5	TMU 4-5	TMU 1-3	TMU 4-5
	index	days		km^2	$mm.y^{-1}$	mm	%	%	%	%	%	%	%	%	%	%	%	%
BFI (index)	**1.00**																	
K (days)	**0.94***	**1.00**																
CVB	**-0.84***	**-0.77***	**1.00**															
Area (km^2)	0.28	0.27	-0.28	**1.00**														
Rainfall ($mm.y^{-1}$)	-0.02	0.01	-0.30	-0.36	**1.00**													
Depth (mm)	**0.72***	**0.75***	**-0.61**	0.29	0.24	**1.00**												
Clay (%)	**0.50**	**0.52**	**-0.55**	**0.51**	0.21	**0.71***	**1.00**											
Recharge (%)	**0.78***	**0.75***	**-0.65**	0.43	-0.05	**0.84***	**0.84***	**1.00**										
Interflow (%)	**-0.79***	**-0.67**	**0.73***	-0.39	-0.04	**-0.74***	**-0.79***	**-0.91***	**1.00**									
Res_W[1] (%)	0.10	0.28	0.00	0.38	0.06	**0.43**	**0.56**	0.40	-0.24	**1.00**								
Res_S[2] (%)	**-0.66**	**-0.73***	**0.50**	-0.42	0.10	**-0.82***	**-0.80***	**-0.95***	**0.74**	**-0.53**	**1.00**							
Re[3] (TMU1-3) (%)	**0.76***	**0.79***	**-0.65**	0.35	0.08	**0.87***	**0.84***	**0.97***	**-0.85***	**0.47**	**-0.95***	**1.00**						
Re (TMU4-5) (%)	0.27	0.08	-0.19	**0.44**	**-0.52**	0.11	0.24	0.39	**-0.48**	-0.19	-0.26	0.17	**1.00**					
IntF[4] (TMU1-3) (%)	**-0.82***	**-0.70***	**0.74***	**-0.43**	0.02	**-0.76***	**-0.74***	**-0.92***	**0.99***	-0.21	**0.75***	**-0.85***	**-0.52**	**1.00**				
IntF (TMU4 -5) (%)	-0.18	-0.11	0.28	0.07	-0.40	-0.26	**-0.60**	-0.36	**0.50**	-0.31	0.24	-0.39	0.02	0.37	**1.00**			
Res_W (TMU4-5) (%)	0.42	**0.54**	**-0.45**	**0.46**	0.32	**0.66**	**0.78***	**0.63**	**-0.58**	**0.83***	**-0.64**	**0.70***	-0.12	**-0.54**	**-0.48**	**1.00**		
Res_S (TMU1-3) (%)	**-0.66**	**-0.72***	**0.49**	**-0.44**	0.13	**-0.82***	**-0.80***	**-0.95***	**0.74***	**-0.53**	**1.00***	**-0.95***	-0.28	**0.76***	0.23	**-0.64**	**1.00**	
Res_S (TMU4-5) (%)	-0.22	-0.39	0.28	0.27	**-0.58**	**-0.53**	-0.43	-0.35	0.21	-0.29	0.42	**-0.50**	**0.49**	0.18	0.32	-0.41	0.39	**1.00**

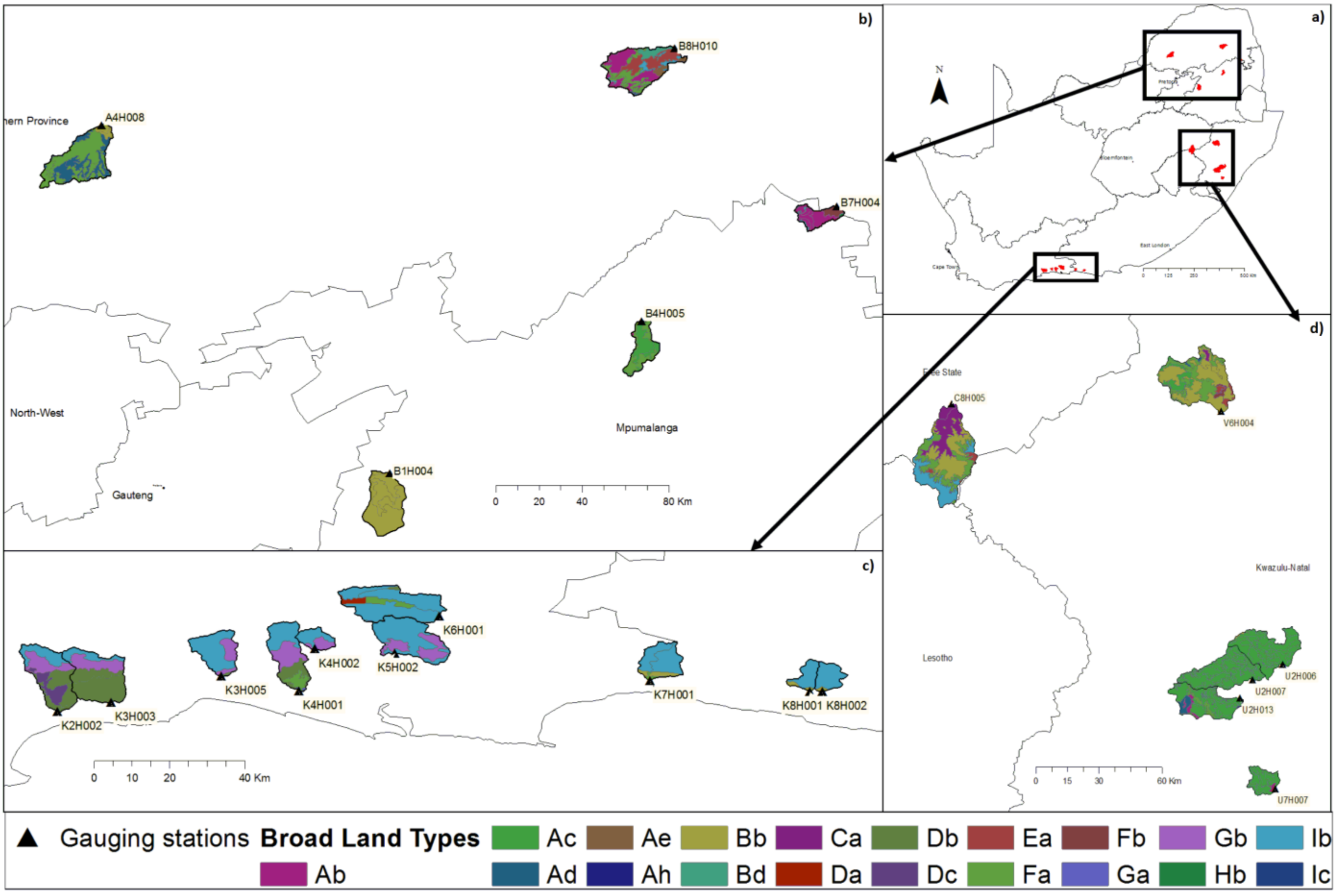

Figure 1: Selected catchments and broad land types of the catchments.

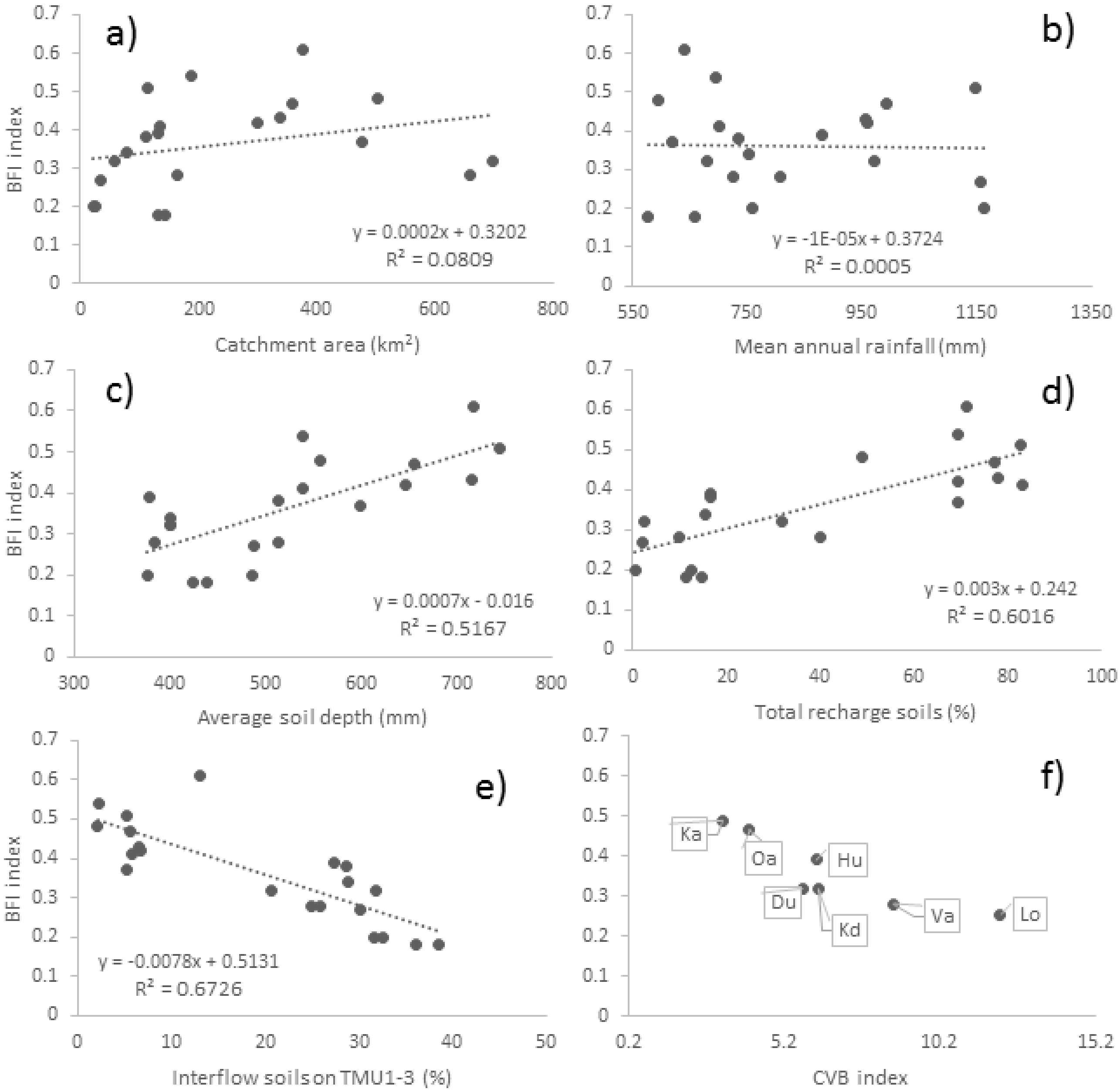

Figure 2: Relationship between BFI index and selected catchment attributes (a – e) and average BFI and CVB values associated with dominant soil forms on the TMU5 positions (f).

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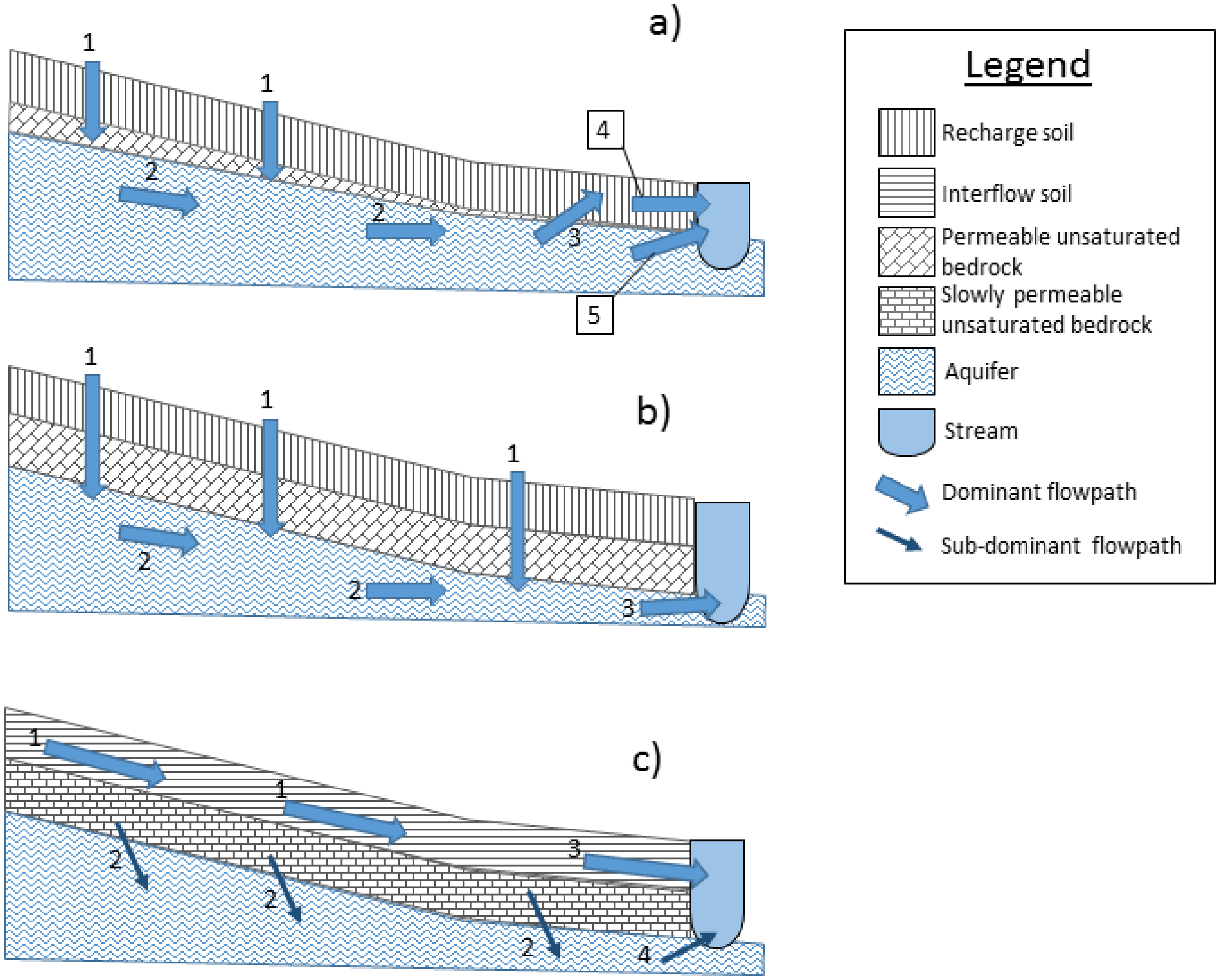

Figure 3: Perceptual models of dominant groundwater/surface water interactions.

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