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ABSTRACT: The hydrological response of catchments is determined by the combined hydropedological response of hillslopes. In the Ntabelanga area, 56% of the households use pit latrines and untreated drinking groundwater supplies. Soil morphological properties and their spatial distribution were used to conceptualize hillslope hydropedological behaviour to determine the fate of *Escherichia coli* and faecal coliform from 4 pit latrines. Four hillslopes below the pit latrines (MT1, MT2, MT3, and MT4) occur above first-order tributaries to the Tsitsa River, South Africa, were studied. The studied sites are adjacent to the proposed footprint of a planned multi-purpose storage dam, Ntabelanga. Apedal soils, without morphological evidence of saturation, dominated the upper slopes of MT1 and the lower slopes of MT2, thus promoting vertical drainage. Hydromorphic properties were observed at the soil/bedrock interface in the lower parts of MT1 and the entire slope of MT4. This signifies slowly permeable bedrock and the occurrence of lateral flow. High clay contents and strong structured soils were dominant in MT3, indicating slow internal drainage with a large adsorption capacity. The conceptual models derived from morphological properties were verified using soil physical and organic pollutant measurements. In general, hydraulic conductivity values support the interpretations made from soil morphological measurements. Faecal coliforms and *E coli* bacteria counts were mostly <1 CFU/g soil in MT1, MT2, and MT4; hillslope migrations were detected in MT3 posing pollution risks.

KEYWORDS: *E coli*, faecal coliforms, hillslope hydrology, pit latrines, soil morphology

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Introduction

Socio-economic conditions, environmental awareness, sociological attitude and everything that happen in a catchment area are reflected in the quality of the water that flows through it.[1] In a catchment or area of interest, each soil type is expected to have a unique influence on the hydrology[2] which can also directly regulate soil water flows determining concentrations of faecal bacteria within the environment.[3,4] Hydrologists concur that the spatial variation of soil properties significantly influence hydrological processes, which may denote the responsiveness of components in solution and adsorbed/attached on the soil colloids.[3] Soil properties in a relatively short period of time are not dynamic in nature and their spatial variation is not random[5]; soil can, over a long period of time, imprint a signature on concentration distributions of pollutes and water behaviour in a hillslope. Accurate knowledge of the processes that control the subsurface transport of water and faecal material is therefore needed to assess contamination potential.[6] Previous studies[3,6,7] have suggested that coarser-textured soils and higher flow rates are associated with less deposition of colloidal and nano-scale particles on soil surfaces which gradually decrease in concentrations with soil depth. On the contrary, finer-textured soils and lower flow rates tended to produce greater colloidal deposition and nonmonotonic deposition profiles that exhibit a peak in retained concentration. The attachment process happens through exchanges with grain surfaces by strong primary minimum interactions. The deposition profiles occur in movement of faecal particles, both in water-saturated porous media and near-surface fluid domains.[6,7]

The interaction between topography, soils, climate, and vegetation results in environmental patterns that contain valuable information on the way they function.[7] The spatial distribution of soil properties exhibits a common form of organization and symmetry, including vertical horizonation typical of soils and lateral topographic-related distribution of soils in a hillslope.[2] This concept of the association of soil properties with topography and hydrological processes is also captured in the terms pedosequence or hydrosequence in relation to hillslopes.[8] The correct interpretation of spatially varying soil properties associated with the interactive relationship between soil and hydrology can serve as indicators of the dominant hydrological processes[9] and improve the understanding of hillslope hydrology.[10] The hillslope is therefore a key building block for understanding and simulating hydrological processes.[11] The hydrological response of catchments is determined by the combined hydropedological response of hillslopes in the particular catchment.[7,10] Over the past decade, studies on hillslopes catchment classification systems have received great attention,[12] motivated due to rising challenges in land-use changes on hydrology and environmental pollution problems. The use of conceptual and simulation models is a cost- and time-effective approach for a preliminary assessment of groundwater vulnerability to contamination and assists in land-use planning, resource management, and the design of monitoring programs.[13,14]

In developing countries, many households use pit latrines because of their low cost and easy availability.[4,3] Pit latrines generally lack a physical barrier, such as concrete between stored excreta and soil and/or groundwater.[15] Improved pit latrines are the most basic and inexpensive form of improved sanitation.[6] Examples of improved sanitation systems include water-based toilets that flush into sewers, septic systems, or pit latrines and ventilated improved pit latrines.[4,16] The Global Water Supply and Sanitation Assessment 2000 Report showed that access to improved sanitation lags behind access to water supply throughout much of the world and in particular within developing countries.[15]

It has long been acknowledged that the subsurface can be very effective at purifying water.[3,8,17] As water moves through the soil, natural processes (ie, soil pathogenic filtration ability) in the subsurface reduce the concentration of many contaminants including harmful microorganisms.[3] In the context of developing countries, water from protected supplies is frequently derived from groundwater via protected springs, protected dug wells, tube wells, and boreholes.[18] Although groundwater is generally of better quality than surface water, it can become contaminated and there is special concern that on-site sanitation systems may in certain circumstances contribute to contamination of drinking water supplies.[6] According to United Nations,[17] the use of groundwater, which typically receives no subsequent treatment to improve quality for drinking water supplies, is increasing dramatically. Many people in developing countries rely on untreated groundwater supplies for their drinking water.[3]

In cases where groundwater is being extracted for use, an understanding of the area of recharge, rates of flow, and flow direction is important in minimizing and/or controlling groundwater pollution.[6] The degree to which reduction in contaminants associated with on-site sanitation occurs and therefore the vulnerability of groundwater to pollution is dependent on the nature of the subsurface and depth to water table.[6,7,19] Some hydrogeological and hydropedological environments are naturally more susceptible to contamination than others.[3] When drastic changes to the hydrological cycle occur, such as changes in groundwater-surface water interactions associated with dam construction (as in this study), it poses risks to groundwater contamination. The geology and soil type govern the change in water quality as the water moves through the unsaturated and saturated zones.[17] It is therefore important to understand how hydropedological factors control water and contaminant movement and behaviour to assess the risk posed to groundwater and human health.[3,6]

In this study, we hypothesized that hydropedological interpretations of soil properties can serve as cost-effective indication of organic pollutant migration. The purpose was then first to conceptualize the hydropedological behaviour of selected hillslopes based on soil properties and their spatial distribution to understand the migration of potential *E coli* and faecal coliform pollutes from pit latrines. Second, the correctness of the conceptual models was verified using selected soil physical measurements as well as measurements of the organic pollutants below the pit latrines.

Materials and Methods

Site description

The Mzimvubu River is the largest undeveloped river in South Africa, despite having a high seasonal water flow regime, good environmental status, potentials for agro-forestry, tourism, and irrigation of arable lands.[18,19] For this reason, the South African Government selected this river basin to construct a large infrastructural project called the Mzimvubu Water Project (MWP) near Mthatha in the Eastern Cape.[20] The footprint of the project spreads over OR Tambo, Alfred Nzo, and Joe Gqabi districts. The MWP will involve the construction of 2 dams, the 490 million m^3 Ntabelanga Dam, to be built on the Tsitsa River, a tributary of the Mzimvubu River and a smaller dam, Laleni, will also be built for generation of hydroelectricity, approximately 20 km downstream of the Ntabelanga dam. In the Ntabelanga area, 56% of the households still rely on pit latrines[21] and 32.4% use groundwater in particular river sources as well as 4.4% which depend on dam or stagnant sources.[22] The census data further categorize on sanitation access that 27.2% have pit latrines with ventilation, whereas 42.4% use pit latrines without ventilation.[20]

Four pit latrines were selected for this study (MT1, MT2, MT3, and MT4), located in the proximity of tributaries draining directly into the Tsitsa River. Two of the identified latrines were in the Ngqoko village (dam inlet) and the remaining 2 sites were located in the Sinqungweni village, near the proposed dam wall (Figure 1). These pit latrines were selected because of the easy accessibility as they were located adjacent to the only available road in the Ntabelanga valley. The sites are also located close to first-order tributaries to the Tsitsa River. The elevation (m.a.s.l) metres above sea level for the study sites and the actual distance between the sampling points are presented in Figure 2, starting from the pit latrine (marked MT-P) with the downslope soil classification and sampling locations (MT1-1, etc).

The area has a semi-arid climate which is characterized with an average annual rainfall of 700 mm, prominently received during the summer season (October to March). The substratum geology dominating in the area is mudstone and sandstones of the Beaufort Groups with frequent dolerite intrusions. Most of the vegetation types which inhabit the landscapes are grasslands and *Acacia thornveld* species which are also associated with riparian/wetland habitat units.[19]

Sampling and analysis

Soils on each of the selected hillslope which transects with the pit latrines (MT1, MT2, MT3, and MT4) were described, classified, and sampled. A hand auger was used to sample 3

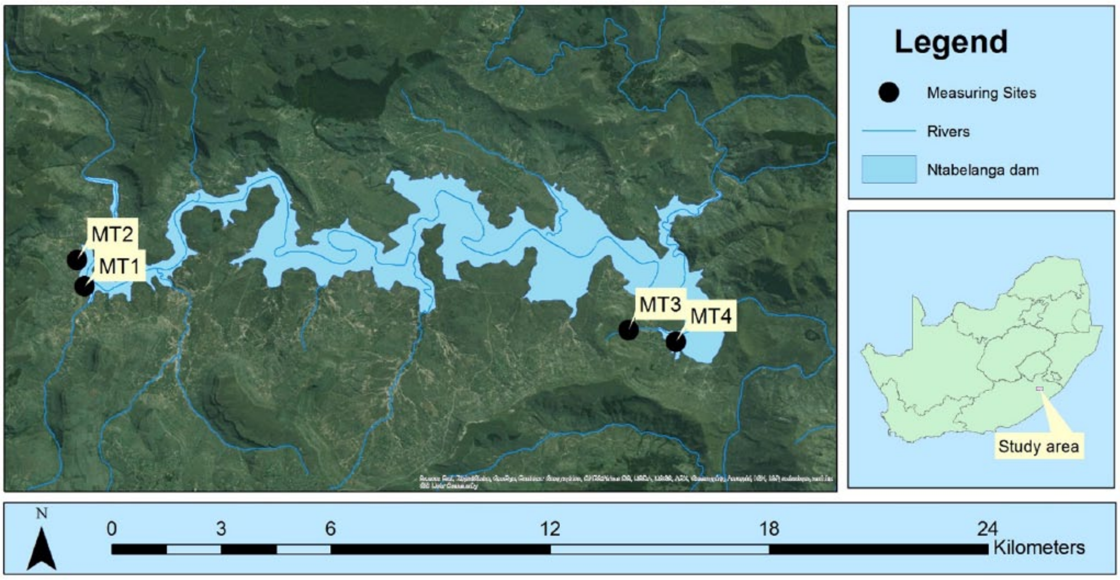

Figure 1. Map of the study area and selected sites.

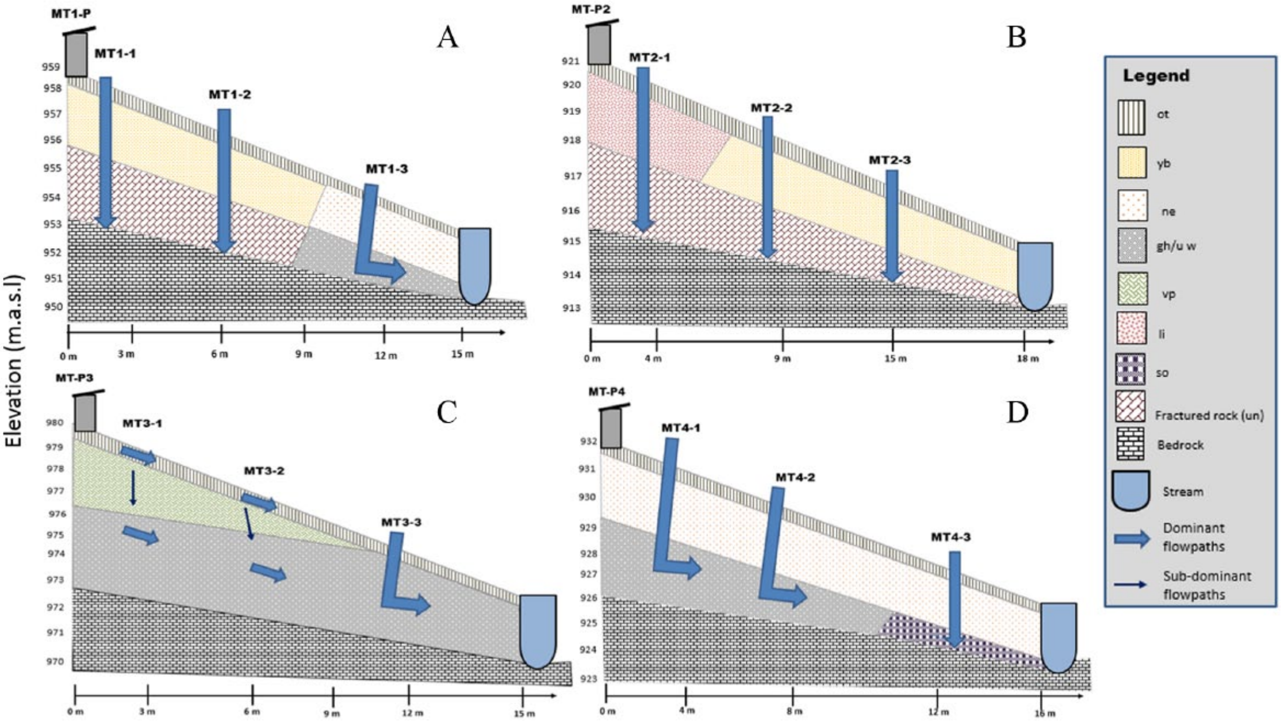

Figure 2. Conceptual models based on soil morphology of (A) MT1, (B) MT2, (C) MT3, and (D) MT4, respectively. ot, Orthic A horizon; yb, Yellow brown apedal B horizon; ne, Neocutanic B horizon; gh, G horizon; uw, unspecified with signs of wetness; vp, Pedocutanic B horizon; li, Lithocutanic B horizon; so, Saprolite.

observation points downslope of the latrine to the depth of the bedrock. The soils were classified in accordance to a taxonomic system for South Africa (SATS)[22] as well as the World Reference Base (WRB).[23] The hydropedological interpretation of the soil morphology followed the classification of soils on hillslopes in accordance with the technique by Van Tol et al.[9] In this technique, any soil features, including the diagnostic horizons and soil forms, are related to the hydrological response of the soils. The soils were then reclassified into hydropedological soil groups. These soil types are categorized as recharge, interflow (A/B), interflow (soil/bedrock), responsive (shallow), and responsive (saturated) soils.[2] The spatial distributions of various hydropedological soil groups were then related to the hydrological behaviour of the hillslope.

Undisturbed soil core samples were collected from each diagnostic horizon (roughly 30-cm intervals). The cores were used to measure selected hydraulic properties. The undisturbed cores have a diameter of 11 cm and height of 7.7 cm.

They were oven dried to determine the bulk density (g/cm^3) using the formula:

$$\frac{\text{Mass of dry soil sampled}\left(\text{g}\right)}{\text{Soil volume}\left(\text{cm}^3\right)}$$

The saturated hydraulic conductivity (K_s, mm/h) was measured in duplicate for each horizon using the modified falling-head conductivity method by Bouwer and Rice[24]:

$$K_s = \frac{L}{t} \times \frac{\left(h_0 + L\right)}{(h_1 + L)}$$

where L is the thickness of horizon (L), t is the time until constant infiltration rate was obtained (T); h_0 and h_1 are the head of water above surface before and at the start of test and after t respectively.

The soil textural classes (%) for the soil samples were determined by the Bouyoucos hydrometer method.[25] Textural analysis was determined for each varying diagnostic horizon in the profiles. Two replicate soil samples were collected in each horizon.

Pollutes analysis in soil samples was conducted for 2 main bacteria indicators; faecal coliforms and *E coli* bacteria. A total of 90 soil samples were collected from the various horizons in the hillslopes, during winter and summer seasons. The analysis for the faecal coliforms and *E coli* bacteria was done at the accredited laboratory, Bemlab in Somerset West, South Africa. The laboratory used the membrane filtration method[26] to identify the presence of both the *E coli* bacteria and faecal coliforms. The soil samples were extracted with Ringer's solution. For each soil sample, 100 mL of the extract was placed into a sterile honey jar. Thereafter, a single sachet of Colilert medium was added to the sample and the jar was then shaken gently until the media was dissolved. The sample was poured into a sub-divided Quanti-Tray, consisting of small and large wells and sealed in an IDEXX Quanti-Tray sealer. Each tray was incubated at 35°C ± 1°C for 18 hours. Results were then enumerated by placing each tray under a 6 W 365 nm UV light and counting the total number of small and large wells that fluoresces. *Escherichia coli* densities were taken as the number of positive wells which was presented as colony-forming units (CFU g/soil). The polymerase chain reaction (PCR) method[27] was used to further verify the detected *E coli* strands only.

Results

Soil morphology

Apedal soils of the Clovelly form (equivalent to Acrisols group, WRB[23]) are present at the upslope positions of MT1, ie, MT1-1 and MT1-2, as well as mid and lower slope positions of MT2, ie, MT2-2 and MT2-3, as shown in Table 1. A Glenrosa form (Leptosols, WRB), MT2-1 near the pit latrine, was identified, with a shallow profile. Saturation at the soil/bedrock interface was visible at MT1-3 and MT4, ie, MT4-1 and MT4-2 within the Tukulu soil form (Endo-Clayic Cambisols, WRB). High clay contents and strong structure are some of the dominant properties of the Sepane (similar to Gleyic Luvisols, WRB) and Katspruit soils (Gleysols, WRB) observed at MT3. Redox morphology indicates saturation at the soil bedrock interface in the Sepane soil, whereas the Katspruit soil is saturated for long periods of time, as presented in Table 1. Evidence of saturation such as bleaching in the soil matrix, grey mottles, and the rusty root channels were observed.

Soil physical measurements

The soils of MT1 and MT2 are relatively sandy and MT3 and MT4 had sandy clays. MT1 and MT2 had bulk densities averaging 1.57 g/cm^3. A slightly lower soil bulk density of 1.54 g/cm^3 was recorded in MT3 and MT4. The lowest bulk density (ie, MT3-3 and MT4 in the *ot* A surface diagnostic horizons) had a value of 1.37 g/cm^3, as shown in Table 2. In general, the soil profiles in MT1 and MT2 had higher hydraulic conductivities compared with MT3 and MT4. The only exception was observed under MT4-1 (Table 2) in the surface (*ot*) A horizon with the highest water conduction of 44.2 mm/h. Higher hydraulic conductivities within MT1 and MT2 profiles were only seen within a 60-cm soil depth. MT2-2 only conducted higher water flows below a depth of 80 cm in the soil profile. Hydraulic conductivity decreased with depth in all the sites.

Faecal coliforms and E coli bacteria

Soil samples across the hillslopes for faecal coliforms and *E coli* pollutants showed that most of the sites for both winter and summer seasons had counts which were <1 CFU g/soil.

The highest faecal coliform population detections above 4×10^4 CFU g/soil were observed in the lower slope of MT3-3 in winter. The prevalent rate of the bacteria increased far down from the source pit latrine within the *gh*/*uw* layer (signs of wetness). In the summer season, higher counts above 3.7×10^3 CFU g/soil were record in the upper slope of MT1-1. These counts were observed in the surface (*ot)* A diagnostic horizon.

Escherichia coli population counts in Table 2 recorded high values of 1.8×10^2 CFU g/soil concentration also under MT3-3. High counts above 1.2×10^2 CFU g/soil in the upper sample point close to the pit latrine (MT3-1) were noted in this winter season. As can be seen in Table 2, MT3-1 to MT3-3 was the only site which showed concentrations of *E coli* population in the winter season. In the summer season, *E coli* population detections had an average above 2×10^1 CFU g/soil. These counts were detected in MT1-3, MT2-3, MT3-1, and MT4-2. In the previous winter season, the sites had no *E coli* count detection. The only exclusion was noted in MT3-1. In MT3-1, *E coli* population counts were increasing towards the subsoil layers (2.0×10^1 at 17 cm to 3.0×10^1 CFU g/soil at 60 cm).

Table 1. Selected soil morphological properties and classification.

SITES	DEPTH (CM)	COLOUR		STRENGTH	STRUCTURE	MOTTLES					DH	SOIL FORMS	SOIL GROUPS
		DRY	WET			(%)	FREQUENCY	SIZE	COLOUR	ROOT CHANNELS		(SATS)	(WRB)
MT 1-1	0-30	10YR 5/3	10YR 4/6	Weak	Single grained	—	None	—	—	—	^{*1}*ot*	Clovelly	Acrisols
	30-60	10YR 5/6	7.5YR 5/6	Weak	Apedal	—	None	—	—	—	^{*2}*yb*		
	60-90	10YR 7/6	7.5YR 4/6	Weak	Crumb	—	None	—	—	—	^{*3}*un*		
	90-120	10YR 4/2	10YR 4/2	Medium	Crumb	—	None	—	—	—	^{*4}*un*		
MT1-2	0-30	10YR 5/6	10YR 4/4	Medium	Angular blocky	—	None	—	—	—	*ot*	Clovelly	Acrisols
	30-60	10YR 4/4	10YR 3/4	Weak	Apedal	—	None	—	—	—	*yb*		
	60-90	10YR 5/6	10YR 4/4	Weak	Moderate blocky	—	None	—	—	—	*un*		
	90-120	10YR 4/6	10YR 5/3	Medium	Moderate blocky	—	None	—	—	—	*un*		
MT1-3	0-30	10YR 4/3	10YR 3/2	Medium	SANBL	—	None	—	—	—	*ot*	Tukulu	Endo-Clayic Cambisols
	30-60	10YR 6/3	10YR 3/3	Medium	Angular blocky	5	Few	Small	Yellow, black	—	^{*2}*ne*		
	60-90	10YR 6/4	10YR 4/2	Medium	Crumb	10	Many	Medium	Grey	Bleached	^{*3}*uw*		
	90-110	10YR 8/2	7.5YR 4/6	Strong	Crumb	10	Many	Medium	Grey, yellow	Bleached	^{*4}*uw*		
MT 2-1	0-15	10YR 5/4	10YR 4/3	Medium	Single grained	—	None	—	—	—	*ot*	Glenrosa	Leptosols
	15+	10YR 5/3	10YR 4/2	—	—	—	None	—	—	—	^{*2}*li*		
MT2-2	0-30	10YR 4/6	10YR 3/4	Weak	Apedal	—	None	—	—	—	*ot*	Clovelly	Acrisols
	30-50	10YR 5/6	7.5YR 4/4	Weak	Apedal	—	None	—	—	—	*yb*		
MT2-3	0-30	10YR 4/4	10YR 3/3	Weak	Granular	—	None	—	—	—	*ot*	Clovelly	Acrisols
	30-60	10YR 5/6	10YR 4/6	Medium	Moderate blocky	—	None	—	—	—	*yb*		
	60-90	10YR 4/6	10YR 4/4	Weak	Moderate blocky	—	None	—	—	—	*un*		
	90-110	10YR 5/6	10YR 3/2	Weak	Crumb	—	None	—	—	—	*un*		
MT 3-1	0-17	10YR 5/3	10YR 3/2	Weak	SANBL	—	None	—	—	—	*ot*	Sepane	Gleyic Luvisols
	17-60	10YR 3/3	10YR 2/2	Strong	SANBL	—	None	—	—	—	^{*2}*vp*		
	60-79	7.5YR 3/2	7.5YR 3/1	Strong	SANBL	2	Few	Small	Brown and grey	Bleached	*uw*		
MT3-2	0-19	10YR 5/3	10YR 3/2	Medium	Granular	—	None	—	—	—	^{*1}*ot*	Sepane	Gleyic Luvisols

(Continued)

Table 1. (Continued)

SITES	DEPTH (CM)	COLOUR		STRENGTH	STRUCTURE	MOTTLES					DH	SOIL FORMS	SOIL GROUPS
		DRY	WET			(%)	FREQUENCY	SIZE	COLOUR	ROOT CHANNELS		(SATS)	(WRB)
	19-61	10YR 4/2	10YR 3/2	Strong	SANBL	—	None	—	—	—	^{*2}*vp*		
	61-70	10YR 4/3	10YR 3/3	Strong	SANBL	3	Few	Small	Brown and grey	—	*uw*		
MT3-3	0-20	10YR 4/3	10YR 3/4	Strong	Crumb	—	None	—	—	—	*ot*	Katspruit	Gleysols
	20-80	10YR 5/6	10YR 4/2	Strong	Crumb	7	Many	Medium	Grey	Bleached	^{*2}*gh*		
	80+	10YR 6/1	7.5YR 4/1	Medium	Crumb	10	Many	Large	Grey and yellow	—	*un*		
MT 4-1	0-20	10YR 5/3	7.5YR 3/2	Medium	Granular	—	None	—	—	—	*ot*	Tukulu	Endo-Clayic Cambisols
	20-60	10YR 5/4	7.5YR 3/2	Weak	SANBL	5	Many	Medium	Yellow and red	Rusty and bleached	*ne*		
	60-85	10YR 5/3	10YR 5/4	Medium	Crumb	12	Many	Medium	Grey, yellow	Bleached	*uw*		
MT4-2	0-30	10YR 5/4	7.5YR 3/3	Medium	Granular	—	None	—	—	—	*ot*	Tukulu	Endo-Clayic Cambisols
	30-60	10YR 5/4	7.5YR 3/2	Weak	SANBL	5	Many	Medium	Yellow, red	Rusty and bleached	*ne*		
	60-85	10YR 5/3	10YR 5/4	Medium	Crumb	15	Many	Medium	Grey, yellow	Bleached	*uw*		
MT4-3	0-30	10YR 4/3	10YR 3/3	Medium	SANBL	3	Few	Small	Red, grey	—	*ot*	Tukulu	Endo-Clayic Cambisols
	30-60	10YR 4/4	10YR 3/4	Medium	SANBL	5	Many	Medium	Orange, brown	Bleached	*ne*		
	60-65	10YR 5/3	10YR 5/4	Medium	Crumb	11	Many	Medium	Grey, yellow	Bleached	*uw*		
	65+	10YR 4/4	10YR 3/4	—	—	—	—	—	—	—	*so*		

^{*1}*ot*, Orthic A horizon; ^{*2}*yb*, Yellow brown apedal B horizon; ^{*2}*ne*, Neocutanic B horizon; ^{*2}*li*, Lithocutanic B horizon; ^{*2}*vp*, Pedocutanic B horizon; ^{*2}*gh*, G-horizon; $^{*3/4}$*un*, unspecified; ^{*3}*uw*, Unspecified material with signs of wetness; ^{*1}*so*, Saprolite; SANBL, Sub-angular blocky.

Table 2. Selected soil physical properties and organic pollutants counts below selected pit latrine sites.

SITES	DEPTH (CM)	HORIZON	PARTICLE SIZE DISTRIBUTION, %			B*D*, G CM^{-3}	KS, MM H^{1}	FAECAL COLIFORMS, CFU/G		*ESCHERICHIA COLI*, CFU/G	
			CLAY	SILT	SAND			SUMMER	WINTER	SUMMER	WINTER
MT1-1	0-30	*ot*	13.3	7.9	78.2	1.47	23.1	3700	<1	10	<1
	30-60	*ye*	18.1	7.8	73.9	1.65	17.7	<1	70	<1	<1
	60-90	*un*	23.1	19.2	57.3	1.55	4.5	80	<1	<1	<1
	90-120	*un*	23.1	19.2	57.3	1.55	4.5	<1	<1	<1	<1
MT1-2	0-30	*ot*	7.9	16.2	75.0	1.40	25.5	<1	<1	<1	<1
	30-60	*ye*	18.1	7.8	73.9	1.65	17.7	<1	<1	<1	<1
	60-90	*un*	23.1	19.2	57.3	1.55	4.5	10	10	<1	<1
	90-120	*un*	23.1	19.2	57.3	1.55	4.5	<1	40	<1	<1
MT1-3	0-30	*ot*	16.9	20.7	63.0	1.44	12.8	100	110	<1	<1
	30-60	*ne*	23.4	19.5	56.6	1.53	1.2	<1	<1	<1	<1
	60-90	*uw*	22.9	19.0	58.0	1.58	3.04	60	<1	20	<1
	90-110	*uw*	23.1	19.2	57.3	1.58	3.04	<1	160	<1	<1
MT2-1	0-15	*ot*	13.4	8.8	77.2	1.57	24.77	220	<1	<1	<1
	15+	*li*	13.9	7.6	79.0	1.55	25.5	70		<1	
MT2-2	0-30	*ot*	13.3	8.2	78.0	1.53	28.8	150	30	<1	<1
	30-60	*ye*	13.8	8.4	77.1	1.54	29.33	710	<1	<1	<1
	60-85	*un*	12.0	8.3	79.3	1.53	29.33	<1	<1	<1	<1
MT2-3	0-30	*ot*	13.1	7.6	78.8	1.55	13.28	70	<1	40	<1
	30-60	*yb*	13.8	8.4	77.1	1.54	22.1	<1	<1	<1	<1
	60-90	*un*	12.0	8.3	79.3	1.59	2.01	<1	<1	<1	<1
	90-110	*un*	12.0	8.3	79.3	1.59	2.01	<1	<1	<1	<1
MT3-1	0-17	*ot*	23.3	14.6	62.4	1.57	14.29	<1	100	<1	10
	17-60	*vp*	23.3	17.8	58.8	1.54	1.8	60	1700	20	120
	60-79	*uw*	22.5	18.5	59.0	1.45	5.3	110	700	30	10
MT3-2	0-19	*ot*	23.3	14.6	62.4	1.57	11.73	1000	190	<1	10
	19-61	*vp*	23.3	17.8	58.8	1.54	1.8	<1	400	<1	<1
	61-70	*uw*	22.5	18.5	59.0	1.45	5.3	<1	10 000	<1	<1
MT3-3	0-20	*ot*	23.3	14.6	62.4	1.57	16.29	30	120	<1	<1
	20-80	*gh*	28.6	14.3	56.0	1.45	5.4	<1	<1	<1	<1
	80+	*un*	22.5	18.5	59.0	1.45	5.4	200	42 000	<1	180
MT4-1	0-30	*ot*	21.3	18.5	59.7	1.37	44.2	<1	<1	<1	<1

(Continued)

Table 2. (Continued)

SITES	DEPTH (CM)	HORIZON	PARTICLE SIZE DISTRIBUTION, %			BD, G CM^{-3}	KS, MM H^{1}	FAECAL COLIFORMS, CFU/G		*ESCHERICHIA COLI*, CFU/G	
			CLAY	SILT	SAND			SUMMER	WINTER	SUMMER	WINTER
	30-60	*ne*	17.9	20.6	61.5	1.58	10.48	<1	20	<1	<1
	60-90	*uw*	21.3	6.8	71.2	1.58	7.46	<1	<1	<1	<1
	90-110	*uw*	21.3	6.8	71.2	1.58	7.46	<1	<1	<1	<1
MT4-2	0-30	*ot*	21.3	18.5	59.7	1.37	16.4	180	9000	30	<1
	30-60	*ne*	17.9	20.6	61.5	1.58	10.48	40	40	10	<1
	60-85	*uw*	21.3	6.8	71.2	1.58	7.46	230	40	<1	<1
MT4-3	0-30	*ot*	21.3	18.5	59.7	1.37	16.4	290	<1	<1	<1
	30-60	*ne*	26.8	3.2	69.2	1.58	1.8	<1	<1	<1	<1

Discussion

Hillslope hydrology derived from soil morphology

Properties in each soil profile may show the amount and direction of water that can pass through over time.[28] Recharge soils have a higher ability to transmit water through soil profiles such as MT1-1 and MT1-2.[2] In the soil morphology models, a Clovelly soil form (Acrisols, WRB), typically promoted recharge of the groundwater aquifer. These soil profiles are considered to be freely drained. This is supported by bright yellow brown colours and the absence of any hydromorphic properties in the profile.[29] These properties agree with observations on yellow and red soils which also had high drainage potentials.[28,30] Hydrological movement of water through these profiles was more vertical flow. Transmission through lateral flow due to interflow (soil/bedrock) in MT1-3 was typical in the hillslope. The thickness of the arrows indicates the flow rates, whereas thicker arrows present faster flow rates than thinner arrows. Each arrow direction and thickness in the soil morphology models was inputted based on the individual hydropedological soil group properties identified within each soil profile. In the bottom hillslope transect, lateral flow drained most of the profile soil water into the adjacent stream.

Glenrosa soil forms (Leptosols, WRB) in MT2-1 are underlined with fragmented partially weathered rock. Responsive (shallow) soils usually emerge into permeable fractured bedrocks.[2,9] Higher potentials for vertical flow of water in the subsurface horizon in the profile are common. Fractured bedrocks overlain with partially weathered course materials[31] can easily facilitate water movement through the available soil macropores. Recharge soils in the morphological model with MT2-2 and MT2-3 caused vertical water flows throughout the site soilscapes.

Interflow (A/B) soils such as MT3-1 and MT3-2 are characterized with restricted water movement in the diagnostic subsurface B horizons.[9,23] Clay migrations/luviation promotes limited permeability of such profiles with Sepane form (Gleyic Luvisols, WRB). These duplex soils have a firmer clay grade in the subsoils than the overlying surface horizons.[2,23] Also, high Na contents in these soils cause clay dispersion. Separation of clay fractions can also reduce soil water movements.[29] Generally, vertical flow of water is minimal promoting more interflow.[2] The bottom section of the hillslope can develop saturation properties in time.[31] Katspruit soil form (Gleysols-WRB) in MT3-3 can result due to dominant lateral water flows. These responsive (saturated) soils are waterlogged with hydromorphological evidence.[2] Mostly such soils are close to saturation. Addition of rainfall enhances generation of overland flow due to saturation excess.[2] This can be observed on the soil surface as return flow. Even though hydromorphic properties show occurrence of anaerobic conditions due to saturation, sometimes the duration might not be known.[32] Using the dominant soil properties can reflect the duration period.[10] The matrix bleaching and grey mottles evidently show longer periods of saturation. Results observed on saturated profiles showed enhanced groundwater recharge.[33] These soils are also associated with increased baseflow towards the bottom of the hillslope transect.[2,29]

Deep interflow (soil/bedrock) soils such as MT4-1 to MT4-3 with a Tukulu soil form (Endo-Clayic Cambisols, WRB) signified restricted drainage at the soil-rock interface.[2] The rusty root channels provide an aeration route which oxidizes the reduced soils hence changing the ferric state ($Fe^{2}+$) back to the reddish ferrous state ($Fe^{3}+$).[34] It is well acknowledged that the soil bedrock interface and bedrock topography are important to subsurface stormflow in many hillslopes.[16,35]

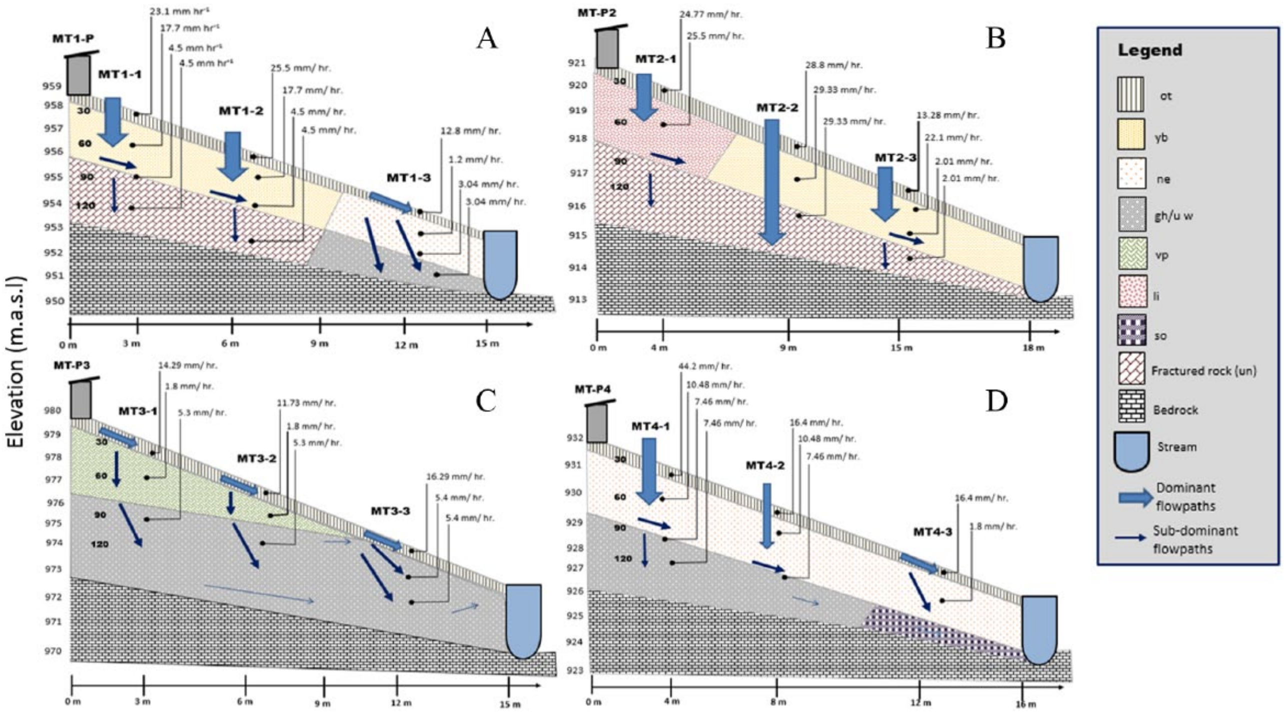

Figure 3. Conceptual models based on soil physical hydraulic response of (A) MT1, (B) MT2, (C) MT3, and (D) MT4, respectively. ot indicates Orthic A horizon; yb, Yellow brown apedal B horizon; ne, Neocutanic B horizon; gh, G horizon; uw, unspecified with signs of wetness; vp, Pedocutanic B horizon; li, Lithocutanic B horizon; so, Saprolite.

Vertical water flow within the surface layers in the morphology model can become lateral flow in the subsurface layers due to reduced soil-water transmission rates.[29]

Improvement to conceptual models using soil hydraulic parameters. Models in Figure 3 showed variations with the morphology conceptual models in Figure 2.

Models based on soil physical hydraulic response proved that the soil morphology model prediction can work under recharge soils (MT1 and MT2) when compared with interflow (A/B) and responsive (saturated) soils. Larger and few pores in sandy soils result in higher bulk densities (1.3-1.7 g/cm^3).[29] Subsoils tend to have compact soil structures due to fine silts and clays.[29,30] In the subsurface layers (MT1, MT2-1, MT2-3, and MT4), vertical conduct of water was lower than morphological interpretations alone. Although vertical flow might still be dominant, it is slower than the morphology models. Exceptions in MT2-2 might have been due to in situ material accumulations with high water transmission. High sand textures in these profiles reduce the blocking effect of clays between the A/B interception zones. Sandy textural distributions in MT1 and MT2 were agreeing with the main vertical water flows based on soil morphology models. Available macropores in sands conduct water flow evenly through the profiles. Finer-textured soils have both macro- and micropores. Such soils have a greater total porosity or sum of all pores than coarse-textured soils.[36] Water conduction can become variable under these profiles. The soil morphology models for MT3 and MT4 had lateral water flows caused by finer textures in the subsoil horizons. The preferential flow dynamics, velocity, and pathways differ between soils.[29]

A surface layer with a higher water conduction than the underline subsoil can result in occurrence of hydromorphic properties. Soil profiles similar to MT4-1 can develop saturation conditions within the subsoils due to lower soil hydraulic conductivities. These hydromorphic characteristics show that water movement is slow initially through such profiles. Hydraulic conductivity, however, is higher under saturated profiles as compared with unsaturated zones.[29,31] The bottom hillslope sections develop higher water conduction abilities due to saturation conditions. Most soil profiles tend to have high hydraulic conductivities in the surface layers. Root distributions and penetration increase the available channels for water movements. Most micro fauna also burrow in top soils because of residue accumulations.[29] In addition to the classical catenary model, the surface topography of these soils can also control hydrological regimes. But subsurface distribution patterns of soil and hydrology develop because of the underlying weathered materials.[30] Hydraulic conductivity of soils usually decrease in the subsoils. Hydraulic conduction of water can become subjected to the available subsoil material. Subsurface hydrological response mechanisms have been found to respond to threshold criteria rather than continuous fluxes. The lateral hillslope discharges are subject to control by bedrock topology rather than soil surface topography.[37] Changes in the flux of the water flow generally in the bottom parts of the hillslope can also be attributed to the process of deposition.[31] Fine clay fraction proportion increases on surface layers along streams.[38,39] Accumulation of fine textural classes and humus colloids can also promote retention of water in the surface horizons.[36] Reduction in the soil porosity can reduce water movement. Restrictions in water conduction can also be caused by clogging of pores as the organic colloids increase in the subsurface layers.[37] The low hydraulic conductivities might also have been brought about with the change in the flow directions. Odonkor and Ampofo[39] had similar findings, but on a saturated soil such as MT3-3, this effect was attributed to profile sealing over time. The finer materials clogging micropores can reduce infiltration and percolation promoting lateral water flows.

Distribution of faecal coliforms and E coli bacteria. Studies on soil faecal coliforms and *E coli*, national and international threshold detections, recommended that counts above 100 CFU g/soil can pose pollution threats to water resources.[40] Seasonal variation in the degree of attachment/detachment can be dependent on moisture and temperature regimes.[41] Generally, summer seasons tend to increase replication of faecal coliforms and *E coli*. Organic pollutes favour detachment and mobility across a hillslope due to increased moisture regimes. In winter seasons, high site accumulation is detected in the soil. This increases bacteria survival and reduce predation in the harsh seasonal periods.[42] The soil physical properties are also important in the behaviour of organic pollutes in a hillslope. Zhai et al[41] studied the subsurface flow of bacteria over a 32-day period and found out that faecal bacteria moved faster in coarser soil materials. This suggestion explained the higher retentions in MT3 more than MT1 and MT2 with courser soils. Zhai et al and Jamieson et al[41,42] reported greater survival rates of faecal bacteria in topsoil as compared with subsoil. Such findings were agreeing with MT1 and MT3-1 but at the same time contradicting with results detected in the subsoils of MT3-2 to MT3-3 and MT4. MT3-3 values equally pose groundwater contamination as they are way above the minimum recommended guideline ranges. Most of the sites where these counts were eminent, especially MT3 and MT4, were significantly detected in the rainy summer season as the soil profile water tables increased.

Such growth prevalence evidently demonstrates the conditions favourable for the bacteria to build up from the source pit latrines. In cases where the clay percentages increase especially within MT3 in particular and also MT4, release of materials into solution and water conduction is reduced due to the higher affinity of absorption associated with these soil particles.[3,6,36,41] The single soil property that appears to have the greatest impact on bacterial survival is moisture retention, which is linked to particle size distribution and organic matter content. Previous studies[42–44] observed that the survival of *E coli* in an organic soil over an 8-day period was 3-fold greater than in a sandy soil. Sjogren[45] compared the mortality of *E coli* O157:H7 in 2 different soil types and stated that fine soil particles could increase bacterial survival because of an increased ability also to retain moisture including nutrients availability. Responsive (saturated) soils contain a high subsurface clay percentage.[2] Responsive (saturated) and recharge soils tend to have higher population counts near the source pit latrines. Lateral flows associated with responsive (saturated) soils cause organic pollutants' mobility to increase towards the bottom hillslope sections.[41] Studies by Mubiru et al[44] on a dry loam soil showed that *E coli* cells were able to survive and proliferate once moisture was restored. The obtained data demonstrate that *E coli* and faecal coliform bacteria migration from the source pit latrine is also influenced more with the fluctuation changes occurring in the groundwater levels. As the soil water flow rate increases, the bacteria mobility directly surges. The threats on water resource pollutions can arise due to a constant supply of the bacteria through faecal matter from the source,[40,41,43] such as pit latrines.

Model implications. The main objective of this study was to conceptualize the hydropedological behaviour of hillslopes with pit latrines. The correctness of the models was verifiable when selected soil physical properties are inputted in each soil profile. We attempted to determine the soil flow directions and rates associated with each morphological soil group. Use of soil morphological models alone does give a good reference on soil-water behaviour mainly in recharge and interflow (soil/bedrock) soils. Limitations were noticeable in the subsurface layers of responsive (saturated and shallow) soils. The input of soil physical hydraulic response properties showed an overestimation on the soil-water movement based on soil morphology models in these profiles. The soil hydraulic knowledge generated from the models are related to *E coli* and faecal coliform bacteria concentrations in each soil group in the hillslopes. Soil leaching rates of organic pollutes depend on the soil group and soil-water transmission of the available profiles.[43,45] Migration of *E coli* and faecal coliform pollutes from pit latrines in the study was common during the rainy summer season in recharge, responsive (saturated), and interflow (A/B) soils. In the winter season with unfavourable bacteria growth conditions,[41,42] responsive (saturated) soils had higher bacteria concentrations. In cases where the detected organic pollutants remained greater than 100 CFU g/soil in the bottom section of the hillslope, pollution risks are higher to the catchment water resources. This approach can be viable and useful for possible mapping of ecological organic pollutants outbreaks, effectively way in advance. Implication of policy measures can be integrated early in the project planning phrase, especially within responsive (saturated) soils similar to MT3 and MT4. In the event that the proposed dam infrastructure (Ntabelanga dam) is constructed, recharge soils and interflow soils over time are likely to develop into the present responsive (saturated) soils.[23] Dam reservoirs can cause a permanent rise in the water table that may extend a considerable distance from the reservoir.[7,19] The risks of aquifer contamination are high in areas where pit latrines must be used, mostly where the water table is high or where there are very rapid groundwater flow rates.[6]

Conclusions

This study, on application of soil model information in the Ntabelanga catchment, concludes that soil morphology can provide a preliminary understanding of hillslope hydraulic responses. Hydropedological interpretations of soils in hillslope transects differ in their hydrological responses in each particular soil group. Recharge soil models for MT1 and MT2 are important in deep vertical groundwater restores. These soils have a limited direct soil-water contribution to streams. Models of responsive (saturated) and deep interflow soils in MT3 and MT4 promote lateral flows towards the bottom parts of the hillslopes recharging stream flows. The physical soil properties, ie, particle distribution, hydraulic conductivity, and bulk density results, supported the main vertical water flows under MT1 and MT2. These properties agreed with the combined vertical and lateral flows in MT3 and MT4 hillslope transects. Morphology alone without the physical soil properties (hydropedology) can in some soilscapes overconceptualize hydraulic response, especially movement of water down a soil profile, between different soil interface (A/B) horizons. The hydraulic conceptual models, however, agree on the detected concentrations of organic pollutes. The model soil groups, with the faecal coliforms and *E coli* bacteria counts, indicated higher migrations on responsive (saturated) soils in winter, ie, MT3 and recharge soils in summer, ie, MT1 and MT2. The soil model data can be useful to properly site the catchment pit latrines and avoid pollution of vulnerable soils as a footprint for the proposed Ntabelanga dam.

For further studies, it is important that focus be put on faecal contaminates behaviour across the hillslopes based on the hydropedological and chemical properties. Also, simulations of water flow fluxes using infinite mechanistic models such as Hydrus 2D. This can be generated to predict the catchment potential contaminate risk towards surface and groundwater resources.

Author Contributions

MM and JJvT conceived and designed the experiments, wrote the first draft of the manuscript: MM, contributed to the writing of the manuscript, and agree with manuscript results and conclusions, jointly developed the structure and arguments for the paper. JvT made critical revisions and approved final version. All authors reviewed and approved the final manuscript.

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