The Application of Hydropedological Surveys to Quantify Near-Surface Impacts of Mining Waste

Johan van Tol[1], Simon Lorentz[2,3]

[1]Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein 9300, South Africa, vantoljj@ufs.ac.za

[2]Centre for Water Resource Research, University of KwaZulu-Natal, Pietermaritzburg 3200, South Africa [3]SRK Consulting (SA), Pietermaritzburg 3200, South Africa

Abstract

Near-surface and lateral flow discharge comprise an often neglected pathway for contaminant movement from mine wastes toward downslope water resources. Contaminant loads moving through near surface pathways can exceed contaminant loading via surface water or groundwater fluxes. Hydropedological surveys to identify and quantify these near-surface fluxes provide an effective method to evaluate the potential impacts via this pathway. This paper describes the methodology of hydropedological surveys and their application in two hard-rock mining sites. Conceptual hydrological response models were developed which assisted with the understanding of mechanisms, modelling and monitoring of contaminant migration from the sites.

Keywords: Hydropedology, source-pathway-receptor, soil morphology, waste impacts

Introduction

Improving water quality through reducing the impacts of pollution, restoring water-linked ecosystems and implementing Integrated Water Resource Management (IWRM) are some of the key targets of the UN Sustainable Development Goal number 6. Achieving these targets necessitates a holistic approach which requires accurate analysis and characterisation of hydrological processes, especially in the highly variable water regimes of semi-arid areas (Savenije & van der Zaag 2008; Lorentz et al. 2003). Typically such an approach will involve the identification, conceptualization and quantification of the hydrological flowpaths, connectivities and residence times of water at different spatio-temporal scales. Capturing these processes in hydrological models can assist with water quality and quantity estimations and inform decision makers on best management practices to reduce the impacts of land-use change on water resources.

Efforts to characterise and quantify of these hydrological processes to determine the impact of mining waste are however often confronted with questions such as: '*where should measurements be conducted*?' and '*what is the extrapolation value of point measurements*'. Valid questions, as most hydrological processes are difficult to observe, dynamic in nature with strong spatio-temporal variation (Park & Van de Giesen 2004; Ticehurst et al. 2007). Conversely, soil properties are not dynamic in nature and their spatial distribution is not random (Webster 2000) and since water is the primary agent in the formation of soil morphological properties, the interpretation of these can illuminate the hydrological processes in the soil. In addition, soils are largely responsible for portioning of hydrological flowpaths (overland flow, subsurface lateral flow or groundwater recharge) and therefore act as a first order control on hydrological processes (Soulsby et al. 2006).

This interactive relationship between soil and water is the foundation of the relatively new interdisciplinary research field; hydropedology. Hydropedology recognizes that soils both control hydrological behaviour but their characteristics can also be used to predict hydropedological behaviour at various different scales (Lin 2003). In the South African context hydropedological studies have made contributions to the efficiency of hydrological modelling (e.g. Le Roux et al.

2011) and model development, identification of contaminant migration pathways from pit latrines (Lorentz et al. 2015) and industrial spills. A hydropedological survey is also now an informal prerequisite for application of a Water Use Licence for open-cast mining. In this paper we present two case studies where hydropedological surveys were conducted to conceptualise and quantify the near surface hydrological pathways, fluxes and contaminant loads from two hard-rock mining sites.

Background to case studies

The two case study sites (Mine A and Mine B are located in the Limpopo Province of South Africa. The names of the mines and the exact location cannot be disclosed due to client confidentiality agreements. The annual rainfall are approximately 700 and 500 mm for A and B respectively. A is underlain by basic to intermediate rock types (dolerite, norite and dunite), whereas B is underlain by granitic parent material.

The first case (Mine A) deals with a risk assessment of liner options for managing the water balance of a Tailings Storage Facility (Mine B). In order to assess the pollution risk associated with the various options the hydraulic properties of the soils and the hydrological flowpaths within and downslope of the tailings footprint had to be characterised.

In the second case study (Mine B), the water flow and contaminant migration from tailings impoundments, stockpiles and waste rock dumps of a mine had to be assessed to recommend appropriate monitoring, remediation and management actions. Previous work on Mine B focussed mainly on the potential contribution of polluted groundwater to a stream approximately 300 m downslope of the site. Contaminant loads in the groundwater could however not account for the increase in observed loads in the stream below the site. It was therefore hypothesised that the stream might be polluted through near-surface flowpaths and migration of contaminants.

Methodology

Hydropedological surveys were conducted in accordance with the methodology provided by Le Roux et al. (2011), on both A and B in order to characterise the dominant hydrological behaviour of the sites.

Dominant hillslopes/transects on each of the sites were identified from terrain analysis to ensure that the heterogeneity of soil distribution patterns in the landscapes are captured. Two transects were identified for A and three for B. Soil profile pits (23 and 9 for A and B respectively) were opened along these transects up to the soil/bedrock interface. Additional observations were made using hand augers and in erosion gullies or hillslope seeps. Soils were then classified in accordance with the South African Soil Classification System (Soil Classification Working Group 1991). All morphological properties and all soil horizons (including saprolite i.e. weathering rock) were described in detail, with particular emphasis to those properties influencing, or impacted by, the water regime of soils. These include *inter alia*, colour and colour variation, mottling, aggregation accumulation of iron, manganese and carbonate precipitates and the degree of saprolite weathering. The classified soils and associated properties were then interpreted grouped into one of six hydrological soil types, briefly summarised in tab. 1.

The dominant hydrological response for each of the sites were then determined based on the following considerations i) the occurrence of various hydrological soil types (tab. 1) in a hillslope, ii) the sequence of various soil types along the hillslope (distribution pattern), iii) the fraction of slope covered by different hydrological soil types and lastly iv) the dominant mechanism whereby water will reach the stream (van Tol et al. 2013).

The dominant hydrological responses of the various slopes are graphically presented as Conceptual Hydrological Response Models (CHRM). The CHRM's were validated and improved using measured soil physical properties and water levels in piezometers as well as through isotope analysis.

Results

Mine A The hydropedological survey of Mine A showed that shallow recharge soils dominate crest and midslope positions of this landscape (fig. 1-1). Vertical flow through the soil and into permeable rock and saprolite dominates. Slowly permeable bedrock below the saprolite restricts deeper drainage and

Table 1 Hydrological soil types (adapted from Van Tol et al. 2013).

Soil type	Description
Recharge (deep)	Deep freely drained soils without any morphological indication of saturation. Vertical flow through and out of the profile into the underlying bedrock is the dominant flow direction.
Recharge (shallow)	Shallow soils overlying permeable fractured rock. Vertical flow and out of profile is dominant with limited contributions to evapotranspiration (ET).
Interflow (A/B)	Duplex soils where the textural discontinuity facilitates build-up of water in the topsoil. Duration of drainable water depends on rate of ET, position in the hillslope, and slope with discharge in a predominantly lateral direction.
Interflow (soil/bedrock)	Soils overlying relatively impermeable bedrock. Hydromorphic properties signify temporal build of water on the soil/bedrock interface and slow discharge in a predominantly lateral direction.
Responsive (shallow)	Shallow soils overlying relatively impermeable bedrock. Limited storage capacity results in the generation of overland flow after rain events.
Responsive (wet)	Soils with morphological evidence of long periods of saturation. These soils are close to saturation during rainy seasons and promote the generation of overland flow due to saturation excess.

promotes lateral flow in the permeable rock (fig. 1-2). Evidence for this is frequent lime precipitations occurring on localised outcrops of hard rock in the midslope positions (fig. 1-3) where dissolved calcium-enriched water returns to the surface.

The lower midslope is covered by recharge soils (fig. 1-4). The soils are relatively shallow (< 500 mm) and overlies chemically weathered saprolite with signs of water logging on slowly permeable bedrock (> 1000 mm). Soil properties in the lower midslope (such as the chemically weathered saprolite and redoximorphic features) indicate that slope is hydrological connected as lateral draining water from upslope contributes to the water regime of this position. Again lateral flow in the saprolite is (at the fractured/hard rock interface) is significantly contributing to soils in lower lying positions (fig. 1-5).

Deep interflow soils occur in the valley bottom positions (fig. 1-6). Lime precipitations in the biopores and matrix of soils in these positions is an indication that there is a significant contribution of water via the saprolite/rock flowpath (fig. 1-5) from higher lying positions. These morphological properties forms in the capillary zone of a seasonal fluctuating water table. This is supported by the presence of manganese accumulations in the biopores indicating low degrees of reduction and some degree of stagnation/slow flow and biological impact. The signature implies an inflow of water from upslope that slowly drain through the toeslope soil with a controlled release to the streams. Grey matrix colours in subsoils also indicate long periods of saturation. Throughout the site, infiltration through fissures in the hard rock is possible, but this is considered to be sub-dominant flowpaths.

Mine B Vertical flow through recharge soils and into saprolite and fractured rocks is the dominant flowpath in the crest positions of slopes in Mine B (fig. 2). Solid granitic layers will however promote the generation of

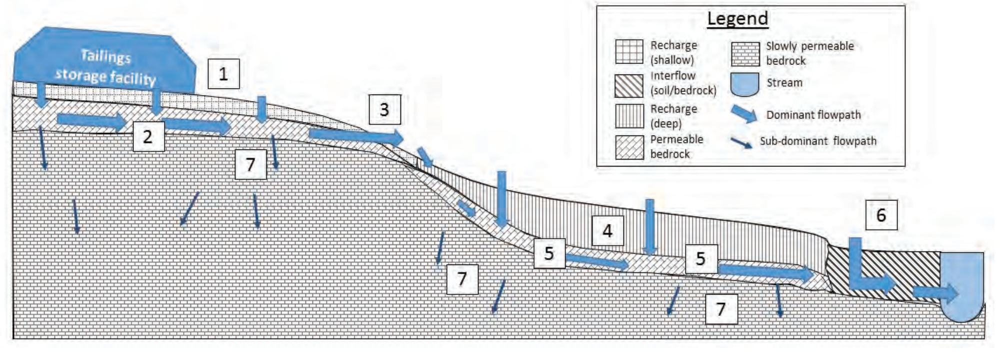

***Figure 1** Conceptual hydrological response model of hillslopes in Mine A.*

lateral flow within the saprolitic layer. With an increase in slope, the depth of the saprolite decrease, resulting in lateral flow at the soil/bedrock interface. At the lower midslope positions return flow to the surface is visible between fractured rock outcrops. This water re-infiltrates the soil and flows laterally at the soil bedrock interface resulting in long periods of saturation in the valley bottom positions.

The hydropedological study in combination with isotope analysis, numerical modelling and measured water quality indicators showed that, a relatively high percentage (> 70%) of mass loads are being transported through interflow to the river. Contaminants within the near-surface soils and preferential drainage paths are likely to be mobilised immediately following the first main rain event of the wet season, after which contaminants are then diluted with additional rain events ('typical' contaminant break-through curve). Cut-off trenches could therefore be successful implemented to intercept/treat contaminants.

Conclusions

The definition of the flow pathways based on the hydropedology studies, which included hydraulic characterisation of the materials, allowed for the estimation of water flux and solute load estimates from the vadose zone. Used in conjunction with hydrometric and isotope sampling, the hydropedology surveys were invaluable in characterising the fate of solutes in both sites.

Acknowledgements

The authors thank Digital Soils Africa for conducting the hydropedological surveys especially Prof. Pieter Le Roux and Dr. George van Zijl….

References

Le Roux PAL, Van Tol JJ, Kunene BT, Hensley M, Lorentz SA, Van Huyssteen CW, Hughes DA, Evison C, Van Rensburg LD, Kapangaziwiri E (2011) Hydropedological interpretation of the soils of selected catchments with the aim of improving efficiency of hydrological models: WRC Project K5/1748. Water Research Commission.

Lin H (2003) Hydropedology: bridging disciplines, scales and data. Vadose Zone J. 2, 1 – 11.

Lorentz SA, Hughes GO, Schulze RE (2003) Techniques for estimating groundwater recharge at different scales in Southern Africa. In: Xu, Y. and Beckman, H.E. (Eds) Groundwater Recharge Estimation in Southern Africa. UNESCO IHP

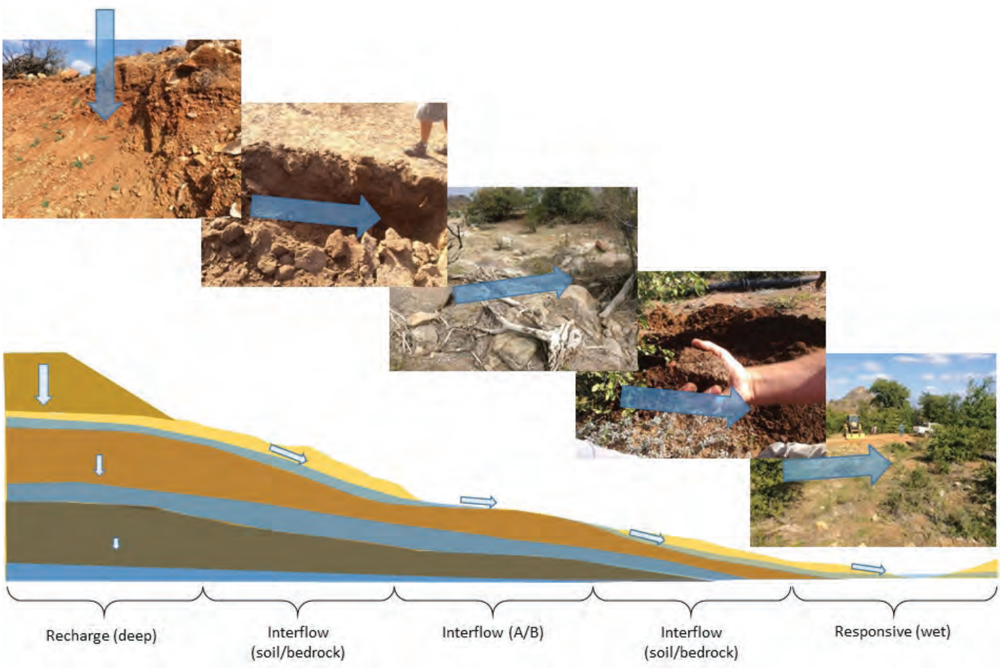

Figure 2 Soil distribution pattern and conceptual hydrological response model of hillslopes in Mine B.

Series No 64, UNESCO, Paris, France. ISBN 92-9220-000-3. Chapter 11, 149-164.

Lorentz SA, Wickham B, Still D (2015) Investigation into Pollution from On-Site Dry Sanitation Systems. Report No. 2115/1/15, Water Research Commission, Pretoria.

Park SJ, Van De Giesen N (2004) Soil-landscape delineation to define spatial sampling domains for hillslope hydrology. J. Hydrol. 295, 28 – 46.

Savenije HHG, van der Zaag P (2008) Integrated water resource management: Concepts and issues. Physics and Chemistry of the Earth, 33, 290 – 297.

Soulsby C, Tetzlff D, Rodgers P, Dunn S, Waldron S (2006) Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: An initial evaluation. J. Hydrol. 325, 197-221.

Soil Classification Working Group (1991) Soil classification: a taxonomic system for South Africa. Memoirs on the Agricultural Natural Resources of South Africa No. 15. SIRI, D.A.T.S., Pretoria.

Ticehurst JL, Cresswell HP, McKenzie NJ, Clover MR (2007) Interpreting soil and topographic properties to conceptualise hillslope hydrology. Geoderma 137, 279 – 292.

van Tol, JJ., Le Roux, PAL., Lorentz, SA. and Hensley, M. 2013. Hydropedological Classification of South African Hillslopes. Vadose Zone J. 12(4) – doi:10.2136/vzj2013.01.0007.

Webster R (2000) Is soil variation random? Geoderma 97:149–163. doi:10.1016/S0016-7061(00)00036-7