A Flexible Approach To Modelling Seepage From Coal Mine Waste Rock

Scott Jackson[1], Steve Momeyer[1], Justin Stockwell[1], Nicolas Francoeur[2]

50-60%

Abstract

A flexible model was assembled to represent the two dominant flow types within a large unsaturated end-dumped coal mine spoil. The proportion of total spoil basal discharge comprised of preferential flow through large macropores, and pressure waves driven by large infiltration events was proportional to spoil thickness, while the matrix flow component dominates the basal seepage hydrograph for large spoils. The proportion of total spoil discharge comprised of these flow regimes changed as spoiling progresses. Spoil wet-up is well represented by the modelling approach, as is seasonal variability in constituent concentrations, and the nitrate decay signature following spoil wet up.

Keywords: Waste rock water balance, water quality modelling, coal, nitrate

Introduction

The West Line Creek (WLC) catchment (10 km2; median elevation is 2,076 masl) is located within the Line Creek Operations mine site, operated by Teck Resources Ltd. in the Elk Valley coal block in eastern British Columbia, Canada. Spoiling of mine waste rock within the WLC catchment began in 1981 and ceased in 2014, with a total of 214 Mm3 of waste rock deposited via end-dumping methods. Total spoil area is approximately 27% of total catchment area, with an average thickness of 85 m. Mean annual precipitation (MAP) is 630 mm, with 50%-60% of this falling as snow. Potential evapotranspiration (PET) is approximately 300 mm/year, with the actual evapotranspiration (AET) from the spoil surface approximately half of PET. This results in a natural catchment yield of 300 mm/yr (48% MAP), and a spoil yield of 495 mm/year – approximately 79% of MAP. Shallow groundwater bypass of the LC_WLC gauge is a factor, accounting for approximately 33% of the spoil basal seepage, and 54% of the natural catchment flow. Key constituents of interest (CIs) are SO4, Se and N-NO$_3$. At the LC_WLC monitoring station, Peak concentrations for SO$_4$ are relatively stable at ~1,400 mg/L, while Se peaked approximately 35 years after spoiling began at 650 µg/L and have dropped slightly to 600 µg/L. N$^-$NO$_3$ concentrations peaked at 50 mg/L 25 years after spoiling began and have been decreasing since approximately 2006 (36 years after spoiling began), to 20 mg/L currently (fig. 1).

Coal mine waste rock (spoil) facilities like that in WLC present unique modelling challenges due to their heterogenous and poorly sorted grain size distributions, high precipitation inputs, and large size. In addition, managing constituent loadings presents challenges with respect to receiving environment water quality, and requires a flexible, accurate and rapid modelling approach to evaluate the need for, and effectiveness of, mitigation measures from initial spoiling, through operations and into closure.

A regional survey of drainages containing large coal spoils indicated that most displayed slopes near zero on log-log plots of concentration vs. discharge, indicating that CI export from spoils is limited by transport capacity (discharge) rather than availability (Wellen *et al.* 2018). These relationships imply that as the proportion of waste rock coverage in a catchment increases, the export of weathered solutes is less limited by material availability and more limited by transport capacity. This relationship was not found to be correlated with waste rock position within the watershed (i.e., headwater or outlet). Instead, the available evidence indicates that most solute loads are mobilized via vertical percolation of meteoric water through the spoil, with the transit of non-contact run-on through the base of the spoil picking up minimal additional loads.

Log:log plots of concentration and discharge for SO_4, N^-NO_3, and Se at LC_WLC indicate that the WLC spoil behaves chemostatically, in that CI load release is proportional (positively correlated) to flow (fig. 2). This supports the conceptual model that solutes are readily mobilized from the spoil at rates that are proportional to spoil size (thickness, footprint, and volume) and flow through the spoil. Note that this finding diverges from the common assumptions used in water quality models that either the loading rate per mass waste rock is constant, and therefore concentrations decrease as flows increase, or that concentrations are fixed at constant values per month, allowing loads to increase with increasing discharge according to an average hydrograph, but not allowing replication of outlier high-magnitude discharge events (e.g., autumn rain on snow events) that can drive significant loading to the receiving environment.

Methods

To accurately represent the flow driven chemistry signatures in the WLC drainage, a simple and flexible model was set up in the GoldSim environment. The modelling approach described herein strikes a balance between more complex physically based unsaturated zone flow models, and simple runoff coefficient-based flow models which are typically used in mine site water balance and water quality models. To achieve this, a two-reservoir water balance model was conceptualized as: 1) 'fast' flow representing flow via large interconnected macropores within the waste rock, and pressure wave flows resulting from large infiltration events (e.g.,

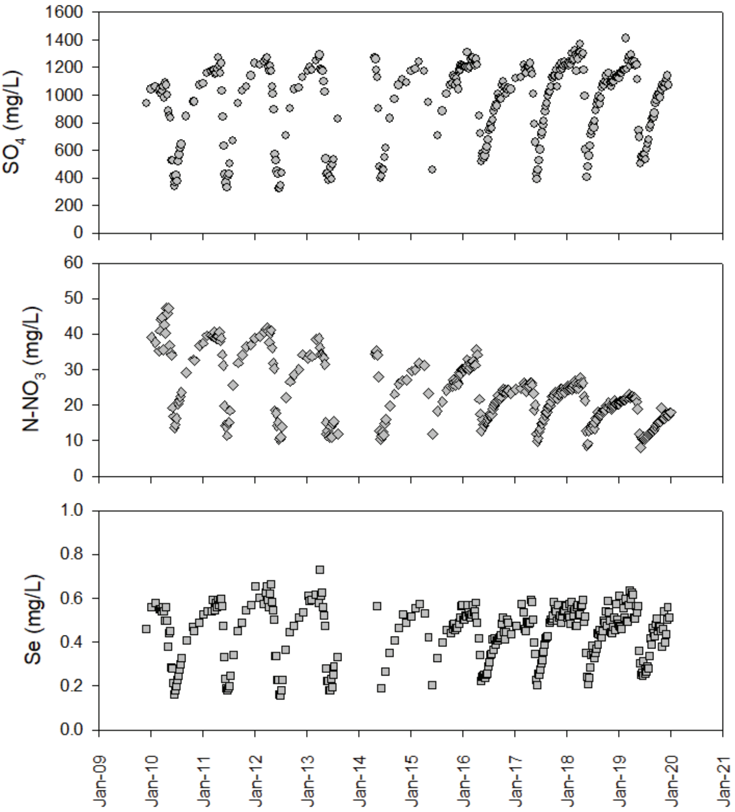

***Figure 1** Time-series of sulfate, nitrate, and selenium concentrations at the LC_WLC monitoring station.*

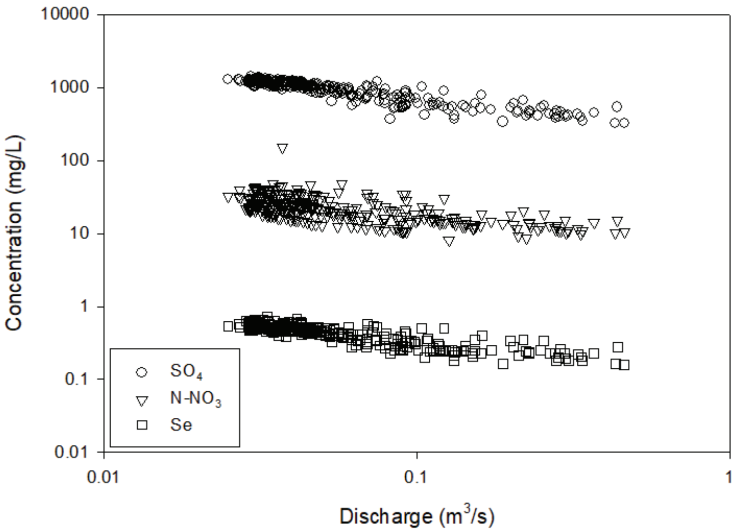

Figure 2 *Log:log plot of discharge vs. concentration for LC_WLC (2009-2019).*

Nichol *et al*. 2005; Neuner *et al*. 2013); and 2) 'slow' flow representing matrix flow through the smaller pore spaces, which typically lags large infiltration events (Blackmore *et al*. 2015; Barbour *et al*. 2016; Appels *et al*. 2018). Fast flow responses may result in large episodic loadings to downstream receiving environments, while slow flow responses comprise the majority of total annual loadings reporting from the spoil. These two processes act in tandem, and while some degree of hydraulic connection is expected to exist between the 'quick' and 'slow' flow pathways, for the purposes of this model they are assumed to be separate (fig. 3). This modeling approach is intended to provide greater flexibility in larger GoldSim mine site models, and direct integration (as opposed to standalone 1D or 2D unsaturated zone hydraulic models) allows for faster model turnarounds (in response to upset conditions, or to allow for multiple rapid sensitivities to be run to inform mine planning). Importantly, the use of a two-reservoir model allows the transition from new spoils dominated by preferential flow to mature spoils dominated by matrix flow to be accurately represented, without relying on hardcoded assumptions related to the timing of this transition (i.e., lag time between spoil placement, wet-up and resulting basal seepage response). Rather, transitions in basal seepage chemistry are a function of local climate, spoiling rate, spoil area, volume and thickness, and spoil moisture content.

The non-contact portion of WLC is located upgradient of the spoil and is characterized as high relief sub-alpine and alpine terrain, with extensive colluvial deposits. This area contributes substantial runoff that transits the base of the spoil rapidly through the coarse waste rock fractions that function as underdrains. Available evidence indicates

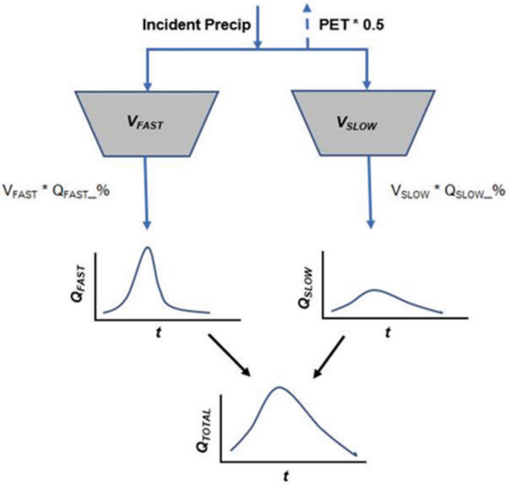

Figure 3 *Conceptual model of LCO-Dry Creek spoil hydrology.*

that these non-contact flows do not pick up substantial additional CI loads due to their limited transit times, and therefore low water:rock contact ratios. Runoff from the undisturbed areas in the WLC catchment was estimated using the GR4J model (Perrin et. al. 2003), and shallow groundwater bypass of the WLC hydrometric station was estimated to be 170 mm/yr on average (54% of total undisturbed catchment runoff, and 34% of total spoil seepage).

The R2 model incorporates the following assumptions:

- Spoil infiltration is allocated to the V_{FAST} (1%) and V_{SLOW} (99%) reservoirs according to a set fraction of the total amount and these proportions are held constant over the full model run. Note that for younger (i.e., thinner) spoils, as much as 20% of total infiltration is directed to the V_{FAST} reservoir.
- CI loads are partitioned between the two reservoirs equivalent to the infiltration proportions.
- Each reservoir has an upper volume limit set equal to the field capacity of the spoil, or the point above which water would drain freely from the spoil pore spaces. The difference between the field capacity and initial moisture content was assumed to represent the effective water retention capacity of the spoil and was relied on as a guideline which the modeled spoil water volumes could not exceed. This threshold also defines the equilibrium point between infiltration and basal seepage.
- Preferential flow pathways or pressure waves (V_{FAST} reservoir) are only expected to activate during high-magnitude infiltration events. The R2 model replicates this process by routing all infiltration to the V_{SLOW} reservoir if the infiltration amount is less than 10 mm/d.
- Seepage is released from the reservoirs by applying a negative exponential decay function to each reservoir volume, and the draindown rate (Q_{SLOW} = 0.0003) from the V_{SLOW} reservoir is two orders of magnitude lower than the draindown rate (Q_{FAST} = 0.06) from the VFAST reservoir. This parameterization was determined through model calibration to flows, concentrations and loads.
- As the spoil water content increases immediately following a large input of meteoric water (i.e., freshet), the total spoil water content approaches, but does not reach field capacity. Gravity drainage predominates, seepage rates are at annual maximums and are proportional to both the size of the spoil reservoir, and the magnitude of meteoric inputs. As spoil drainage progresses over the summer months and into the autumn, the seepage rate continues to drop, as a greater proportion of the water available for discharge is held by suction forces within the spoil matrix. This physical phenomenon is typical of unsaturated flow conditions and is represented in the spoil water balance model by allowing a set percentage of the available water to drain each timestep.
- As the seepage rates from the V_{FAST} reservoir are greater than the meteoric inputs in many months, the volume of available water within this reservoir decreases each month, and thus the seepage rate decreases in turn. Annually the water in the V_{FAST} reservoir drains completely.
- Because the seepage rate is much lower for the V_{SLOW} reservoir, the draindown rates are not sufficient to completely drain this reservoir on an annual basis, and thus the total reservoir volume increases over time as the spoil increases in size, until it reaches the equilibrium condition.
- The total basal seepage volumes and loads for each time-step are the sum of seepage from both the V_{FAST} and V_{SLOW} reservoirs.

Initially the V_{FAST} reservoir discharges the highest volumes on daily time-step (reflective of the flushing and pressure wave response), but as the spoil grows and wets up over time the discharge volumes from the V_{SLOW} reservoir dominate on an annual basis, consistent with other investigator's findings that matrix flow dominates the discharge signature of mature spoils.

Geochemical source terms for the WLC spoil were derived from WLC water quality data for SO4 and Se as a function of average spoil thickness, which is a surrogate for flow path length, and therefore water:rock contact ratios (tab. 1). The nitrate source term is applied for two distinct time periods; initial nitrate concentrations increase following a similar trend as selenium, and peak in 2006, about 7 years after a period of no spoiling (fig. 1). When the spoil appears to have wet up and reached equilibrium, nitrate concentrations decline, as seen in the monitoring data (fig. 1). This is a result of the finite source associated with blasting residue and rock type. The empirical relationship defining the nitrate source term in spoil discharge during wet-up is presented in tab. 1. While the spoil is wetting up, and nitrate concentrations in the spoil discharge are increasing, the finite nitrate source is modelled by accumulating a nitrate load in the spoil (matrix) reservoir with waste rock placement as:

Bulk Density * $N^{-}NO_3$ Loading Rate
* Spoiling Rate

Where, the bulk density is assumed as 1,500 kg/m^3 and the nitrate loading rate was set as 5 mg $N^{-}NO_3$ / kg of rock. The spoiling rate is in m3/day. The declining spoil nitrate concentrations are represented after spoil wet-up, by flushing the accumulated nitrate load from the spoil per the R2 model water balance. Spoil wet-up is defined by when the volumetric moisture content reaches long term average.

Results

The combined R2 and GR4J flow models were calibrated to measured flows at the LC_WLC hydrometric station over the 2012-2016 period and validated to the 2017–2020 period (fig. 5). Over the 2012–2020 period, measured average annual runoff was 184 mm, with modeled runoff slightly lower at 176 mm (not including groundwater bypass). The log-Nash-Sutcliffe Efficiency Index (which is more useful for assessing model predictive skill for the low-flow regime) was 0.93 and 0.90, and the RMSE values were 0.061 m^3/s and 0.016 m^3/s for the calibration and validation periods, respectively. Finally, calibration period R2 was 0.83, and 0.91 for the validation period. These values are indicative of a very well calibrated model, well exceeding the 'satisfactory' threshold suggested by Moriasi *et al*. 2015. Similarly, the progression of CI concentrations over the model run period, including the inter- and intra-annual variability, as well as the increases in all CIs up to the mid-2000's are accurately replicated by the model. Notably, the decay in nitrate concentrations is also well represented, following the peak in approximately 2006 (fig. 5).

Spoil yield is not stationary and net percolation to the spoil is greater than discharge from the spoil while the spoil is wetting up (fig. 6). Model results suggest approximately 36 years passed after spoiling began in 1980 before net percolation and spoil yield converged in 2007 (fig. 6). Note that the spoil dimensions have remained relatively stationary since about 2001. Nitrate concentrations reflect this transition from the spoil water balance 'wetting up,' to reaching equilibrium (net percolation = spoil discharge). The switch from an accumulating nitrate load to a declining one is governed by this transition in the water balance, after which the accumulated nitrate load in the spoil reservoir is released and allowed to flush from the spoil reservoir. The spoil is considered to reach this equilibrium once the moisture content reaches 11%.

Table 1 *West Line Creek spoil source terms.*

Parameter	Unit	Source Term	Notes
SO_4	mg/L	20.5 mg/L/m*T_{spoil}	
$D^{-}Se$	mg/L	0.0004*[SO_4] + 0.082	
$NO^{3-}N$	mg/kg	1,500*5*R_{spoil}	Applied during spoil wet-up

Notes:

1. [SO_4] is sulphate concentration (mg/L); [Se] is selenium concentration (mg/L)
2. T_{spoil} is average spoil thickness per unit area (m)
3. R_{spoil} is the spoiling rate in m^3/day

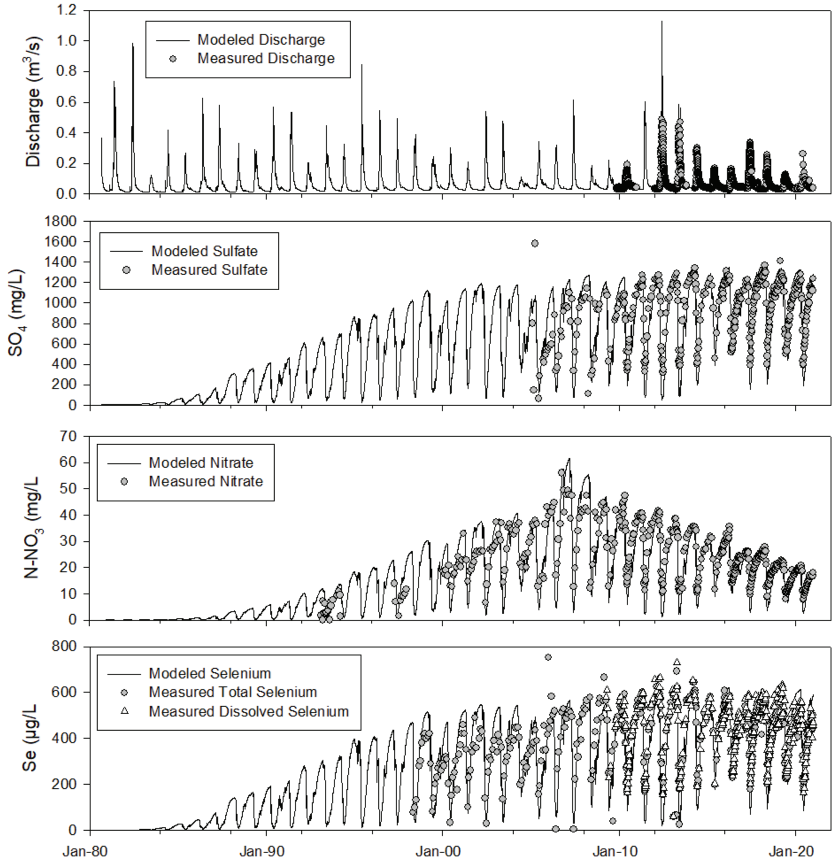

Figure 4 *Modelled (top to bottom) LC_WLC discharge, sulphate, nitrate, and selenium between 1980 and 2020 generated by spoil thickness-based approach.*

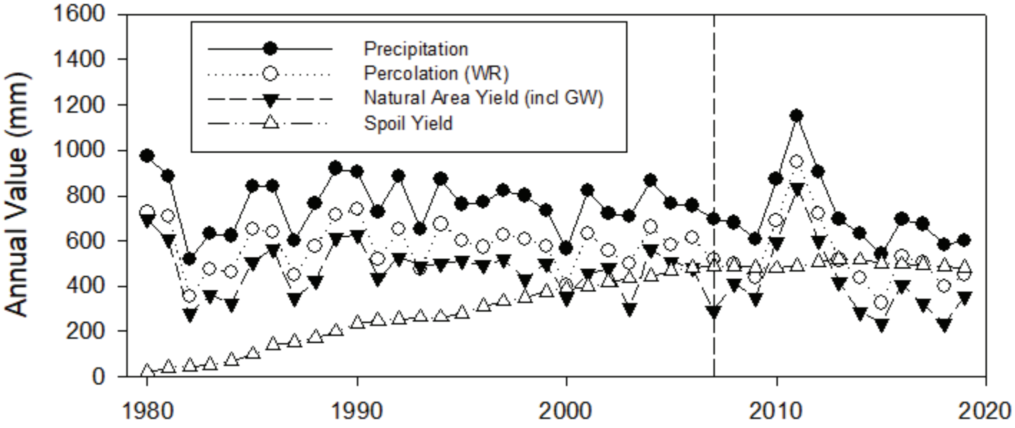

Figure 5 *Time series of annual water balance terms from integrated GR4J and R2 model for LC_WLC. Dashed line indicates 2007, when model indicates spoil was 'wetted up'.*

The empirically derived nitrate source term represents the observed nitrate decay by simple mass balance and flushing of the spoil reservoir. Flushing of the accumulated nitrate load from the spoil matrix produces modelled concentrations that are very well aligned with measured data and portray the long-term declining trend and seasonal range (fig. 5).

Conclusions

The model was applied to a mature waste rock facility and calibrated to observed streamflow and constituent concentrations and loadings in the receiving environment. Model results indicate that the proportion of total spoil seepage generated by the 'fast' flow pathway is proportional to spoil size/thickness, with basal discharge for large spoils comprised almost entirely of 'slow' matrix flow. Flows, CI concentrations and loadings are accurately replicated by the model, including the unique nitrate decay signature evident in the monitoring data, which is interpreted to be a function of a finite reservoir being flushed out according to the spoil water balance.

The modeling approach described here is intended to be incorporated into a large mine site water balance and water quality model. The relatively simple representation of the key processes governing the seepage and loading signatures of large coal spoils is computationally efficient, and digestible by a wide range of stakeholders. This modelling approach was applied successfully to several large coal mine spoils, with one representative example presented.

References

Appels WM, Ireson AM, Barbour SL (2018). Impact of bimodal textural heterogeneity and connectivity on flow and transport through unsaturated mine waste rock. Advances in Water Resources. 112: 254-265.

Barbour SL, Hendry JM, Carey SK (2016). High-resolution profiling of the stable isotopes of water in unsaturated coal waste rock. Journal of Hydrology. 534: 616-629.

Blackmore S, Smith L, Mayer KU, Beckie RD (2014). Comparison of unsaturated flow and solute transport through waste rock at two experimental scales using temporal moments and numerical modeling. J. Contam. Hydrol. 171: 49–65. http://dx.doi.org/10.1016/j.jconhyd.2014.10.009.

Moriasi DM, Gitau MW, Pai N, Daggupati P (2015). Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. Trans. ASABE. 58(6): 1763-1785. DOI 10.13031/trans.58.10715

Neuner ML, Smith DW, Blowes DC, Sego LJD, Smith L, Fretz N, Gupton M (2013). The Diavik waste rock project: Water flow through mine waste rock in a permafrost terrain. Applied Geochemistry. 36: 222-233.

Nichol C, Smith, L, Beckie R (2005). Field-scale experiments of unsaturated flow and solute transport in a heterogeneous porous medium. Water Resources Research, 41: doi:10.1029/2004WR003035.

Perrin C, Michel C, Andréassian V (2003) Improvement of a parsimonious model for streamflow simulation. J. Hydrol. 279: 275-289

Wellen CC, Shatilla NJ, Carey SK (2018). The influence of mining on hydrology and solute transport in the Elk Valley, British Columbia, Canada. Environmental Research Letters, 13: https://doi.org/10.1088/1748-9326/aaca9d.