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Predictive mine water balance modelling – does accurate mean reliable?

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Abstract

This work presents considerations that can be used by modellers, mining project proponents, and regulatory reviewers to confirm the reliability of predictive mine water balance models. While examples are from mountainous watersheds of British Columbia, Canada, the findings can be useful for watersheds elsewhere.

Predictive water balance models play a critical role in decision support systems for mine water management by: 1) supporting mine proponents in developing engineering designs with reduced costs and operational risks, and 2) informing the environmental effects assessment of proposed projects. Water resources modellers and reviewers (i.e., the proponents and regulatory agencies), put effort into confirming that the water balance models are sufficiently accurate, so that they can be used to fulfill the abovementioned objectives. Modelling accuracy is normally evaluated through the process of model calibration and validation with past and existing hydrometeorological data. Despite these efforts, accurately calibrated models are not necessarily reliable for prediction of future hydrologic conditions, particularly in mountainous watersheds with complex hydrometeorological processes (e.g., in British Columbia, Canada). This work presents some examples of common causes of unreliable water balance models.

Among these causes, one that can be easily overlooked by the modellers and reviewers, is an over-reliance on model accuracy (i.e., accurate calibration). Hydrometeorological data used for model calibration may be unreliable or not pertinent to future conditions. Unreliable data may range from unknown parameters (e.g., evaporation) to inaccurate measurements (e.g., inaccurately measured streamflow) or accurate measurements which are not representative of the entire watershed (e.g., point precipitation).

Even with hydrometeorological data that are accurately measured, the models developed based on such data may not be representative of the future hydrometeorological processes. For example, a model developed and calibrated for an undisturbed catchment, cannot be reliably used for modelling flow pathways from mine components that generate contact water via overland, toe seepage and groundwater recharge pathways.

Introduction

The authors have developed and peer-reviewed water balance models for several major mine projects, mostly in British Columbia (BC), and observed mining projects' increasing dependence on water balance models to provide reliable information for decision making in the evolving regulatory framework and variable financial markets.

Generally mining project proponents and regulatory reviewers have different expectations from water balance models. The proponents are most interested in information with major cost or operational implications. For example, whether a project will have a net water deficit (requiring water withdrawals) or surplus (requiring water treatment and discharge), or both (depending on wet or dry climate conditions). On the other hand, regulatory reviewers' main objective is to confirm whether project-affected flows and water quality will be within acceptable ranges. Given the inevitability of data uncertainty, a water balance model that reliably estimates a range of plausible flows addresses the objectives of both mining project proponents and regulatory reviewers better than a model that predicts an accurate set of values. However, preference of reliability over accuracy can be mis-communicated by the modellers, proponents, and regulators.

This work applies a commonly used modelling approach to three example watersheds with similar hydrologic regimes in BC to highlight potential reliability issues with model results in each case. The study conforms to the provincial recommendation of minimum of two years of monitored climate and flow data (BC MOE 2016) and the importance of reliable data collection and analysis (RISC 2018), and shows that in some cases two years of available data may not sufficiently demonstrate the natural variability of hydrologic regime. Hydrometric monitoring programs for mining projects are typically not established and maintained by qualified professionals. The collection of proper hydrologic data is critical to water balance modelling and understanding water management at a mine site. Many hydrology monitoring programs are underfunded, understaffed and staff available to run these programs are not adequately trained and the results are not properly quality reviewed. The ability of any model to be a useful tool for mine operators or regulatory decision maker is dependent upon the data used to develop and maintain it.

Finally, considerations and recommendations are provided for estimating contact water from mine components, which cannot be reliably simulated with models developed for undisturbed catchments, and for incorporating probabilistic approaches to characterize modelling uncertainty.

Runoff Modelling Approach

Due to modelling complexity, lack of available data, and time and budget limitations, the successful use of physically-based hydrologic models for mining projects have been (and realistically, in the near future, will be) limited in Canada. Instead, lumped conceptual models, which conceptually represent inflow, outflow and moisture content of a catchment, are commonly used in mining projects. Despite differences in details, most lumped conceptual models that are used for mine water balance models:

- include modules to convert input total precipitation data into rainfall and snowmelt
- compute evapotranspiration to estimate what portion of rainfall and snowmelt is available for runoff
- route a portion of available water overland, and store (and release) the remaining portion in (and from) a conceptualized soil water storage reservoir. Overland flow and water released from soil water storage comprise the total runoff from a catchment.

For consistent assessment of example cases in this study, all cases were modelled with the United States Geological Survey (USGS) monthly water balance model, a lumped conceptual runoff model also known as the Thornthwaite monthly water balance (McCabe and Markstrom 2007). The USGS model was selected for this study because its inputs are normally available in mining projects as part of their hydrometeorological data collection program. Inputs to the model are monthly precipitation, as well as monthly temperature and latitude of the location which are used for the computation of evapotranspiration. Three sets of parameters control conceptualized processes in the model:

- temperature parameters to segregate total precipitation into rain and snow, and to compute snowmelt rate
- overland flow coefficients to estimate the portion of precipitation that flows overland
- coefficients to establish a relationship between soil water storage and release

Example Studies

Three example studies were selected for this study. Two studies, East BC Mine Site and North BC Mine Site, represent watersheds that contained proposed mining projects. Climate and runoff data used for these cases in this study are publicly available via the BC Mine Information website (https://mines.nrs.gov.bc.ca/); however, project names have been removed to allow for an impartial assessment of the data collected for the project. The third example study, Upper Penticton Creek (UPC;) watersheds (Moore et al. 2021a and 2021b), is presented to assess the value of having long-term, research-level streamflow and climate data for runoff modelling purposes.

All three example study watersheds are in warm-dry-summer and cold-wet-winter climate conditions. These watersheds demonstrate a nival hydrologic regime with snowmelt-driven high flows during the spring freshet, which generally starts in April and peaks in May or June. After the spring freshet, streamflows decrease in summer and are supplied by groundwater discharge, occasional rainfall events, and water released from lakes and wetlands. Rain-driven streamflows in fall can punctuate the annual hydrograph and create a secondary (or in some cases even primary) annual peak flows. Annual low flows occur in winter when precipitation falls in the form of snow and streamflow is limited to groundwater discharge.

Table 1: Summary information of example study watersheds

	East BC Mine Site	North BC Mine Site	UPC Watersheds[1]
Catchment area (km^2)	50	50	5
Mean catchment elevation (m)	1,000	1,500	1,750
Concurrent climate and runoff data	36 months	39 months	32 years
Mean annual precipitation[2] (mm/year)	710	800	770
Mean annual runoff[2] (mm/year)	330	530	395

Notes:

[1] Values provided in the table are for each of the 240 Creek and 241 Creek watersheds

[2] mean annual observed value during the period of record

East BC Mine Site Watershed

This proposed mining project is in a watershed within the Rocky Mountain foothills, with an approximate catchment area of 50 km^2 and mean elevation of 1,000 metres above sea level (masl).

A hydrometric monitoring station was installed on, and collected continuous streamflow data from, the mouth of this watershed for three water years (i.e., October to September). Installation of the hydrometric station, as well as data collection and analysis, followed the provincial guidelines at the time (RISC 2009). A climate station, approximately located at an elevation similar to that of the mean elevation of the watershed, collected daily temperature and precipitation data during the same three years.

North BC Mine Site Watershed

This proposed mining project is in a watershed within the Omineca Mountains of BC, with an approximate catchment area of 50 km^2 and mean elevation of 1,500 masl.

Streamflow from the watershed was continuously monitored with a hydrometric monitoring station for three water years (i.e., October to September) and three additional months (i.e., October to December) after the end of the third water year. Streamflow data collection during this period was deemed consistent with the provincial guidelines at the time (RISC 2009). A climate station, approximately located at an elevation similar to that of the mean elevation of the watershed, collected daily temperature and precipitation data during the same period.

Upper Penticton Creek Study Watersheds

The UPC study has been monitoring climate and streamflow data from multiple catchments since mid-1980s (Moore et al. 2021a). The UPC watersheds are located in the southern interior of BC. For the purpose of this work, two watersheds from the UPC experiment were selected: an undisturbed control catchment (240 Creek) and a treatment catchment (241 Creek) which has been harvested since mid-1990s. Each watershed has an approximate catchment area of 5 km^2 and mean elevation of 1,750 masl.

The Water Survey of Canada has had continuous hydrometric monitoring stations on the 240 Creek (ID 08NM240) and 241 Creek (ID 08NM241) since 1984. Daily precipitation and temperature data is available since 1983 via the UPC data repository (Moore et al. 2021b).

Results

East BC Mine Site Watershed

First year of monthly precipitation, temperature and runoff data were used to calibrate the USGS model. Modelled runoff in the first year has an excellent match with observed runoff, with a Nash Sutcliffe Efficiency (NSE, Nash and Sutcliffe 1970) of 0.98 (Figure 1). Generally, an NSE of greater than 0.80 is considered a good match in hydrological modelling studies.

However, when the calibrated model was used with the second- and third-year of data, modelled runoff was unacceptably different from observed runoff, with negative NSE values (Figure 1), which are representative of conditions where the mean annual runoff would be a better predictor than the model.

This discrepancy in model performance is primarily due to unreliable (erroneous) precipitation data during the first year of climate data collection where the climate station had not been properly equipped with a wind shield and therefore substantially underestimated the precipitation totals. A model accurately calibrated to this one year of erroneous data would be greatly unreliable to predict runoff in the following years.

North BC Mine Site Watershed

The first- and second-year data, including reliable climate and streamflow data, were used to calibrate the USGS model. Modelled runoff in the first and second years had an excellent match with observed runoff, with NSEs of 0.94 and 0.98, respectively (Figure 2). However, when the model was run with the remaining 15 months of data (i.e., the third year and three additional months), the NSE decreased to 0.70; the model missed to capture the rainfall-induced high flow in the last month of November (Figure 2).

In this case, although two years of reliable data were used to accurately calibrate the model, the two-year period of modelling calibration happened to lack a distinct feature of nival hydrologic regimes in BC:

rain-induced high flows in fall. Therefore, the model was not trained to ~~(i.e., rain and snow conversion parameters were not set to)~~ simulate such high flows.

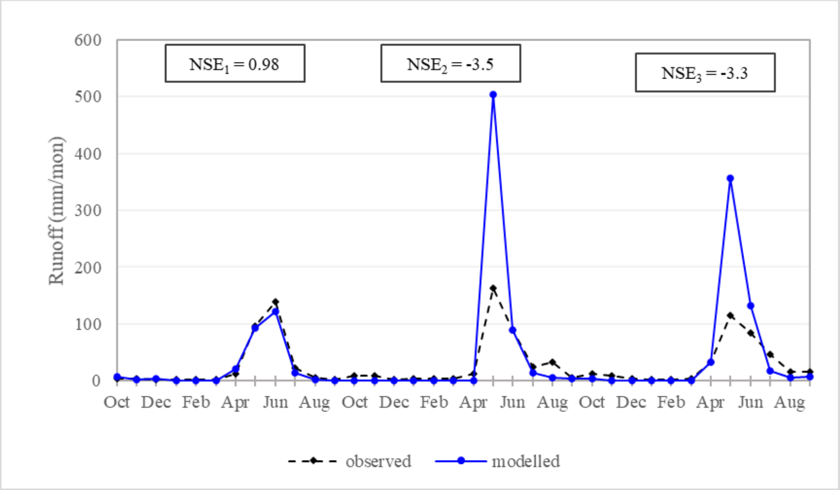

Figure 1: Observed and Modelled Monthly Runoff at East BC Mine Site Watershed

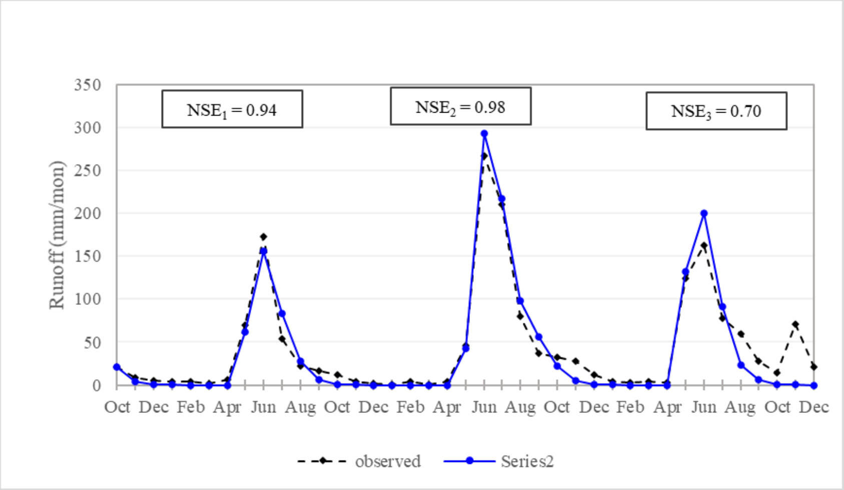

Figure 2: Observed and Modelled Monthly Runoff at North BC Mine Site Watershed

Upper Penticton Creek Study Watersheds

In this case, 32 years (1984-2015) of reliable climate and streamflow data were available. The USGS model was primarily trained (calibrated) with the first 15 years of data (1984-1999). There was an excellent match between modelled and observed runoff, with NSE of 1.0, for both the 240 Creek and 241 Creek watersheds. Due to the large number of years included in this analysis, as well as presence of two sets of observed runoff values for the 240 Creek and 241 Creek watersheds, the results are better visualized in a boxes-and - whiskers graph (Figure 3).

When the performance of this calibrated model was tested for the 2005-2014 period, modelled and observed runoff at the 240 Creek watershed (i.e., undisturbed control catchment) still showed a very good match, with an NSE of 0.90 (Figure 3). However, the 241 Creek watershed (i.e., the catchment with 50% harvested area) showed a weaker match between observed and modelled runoff, with an NSE of 0.81 (Figure 3). Spring freshet high flows (in May) at the 241 Creek watershed are higher than those of the 240 Creek watershed. This flashy high flow response is an expected outcome when a large portion of a catchment has been harvested. Additionally, the reduced vegetation yielded flashier overland runoff in May, the 241 Creek watershed likely has less soil water storage to be released in June than that of the 240 Creek watershed (Figure 3).

A notable observation was made for winter flows in 2005, which were substantially higher than the winter flows of all other years in both the 240 Creek and 241 Creek watershed. An example showing the 240 Creek flows in 2005, as well as the preceding and proceeding years, is provided in Figure 4. As seen in Figure 4, the model was unable to simulate this event of increased winter flow and confused it with a rain driven high flow in late fall. Although the main reason for higher-than-normal winter flows in 2005 is not known to the authors, it signifies the fact that the lumped conceptual model that was trained with the 1984-1999 did not properly conceptualize the physical process responsible for the higher-than-normal winter flows experienced in that year. Thus, even though the conceptual model performed well for the 1984-1999 period, during which time the processes responsible for flow generation can be assumed to be similar based on model performance, the model performed less well when processes different than those previously modelled occurred. Based on this, prediction of future runoff response under climate change, where flow generation processes are expected to change, will be less reliable. ~~that what responsible for such higher-than-normal winter flows, and is unlikely to reliably predict far future runoff responses of the catchment under climate change conditions.~~

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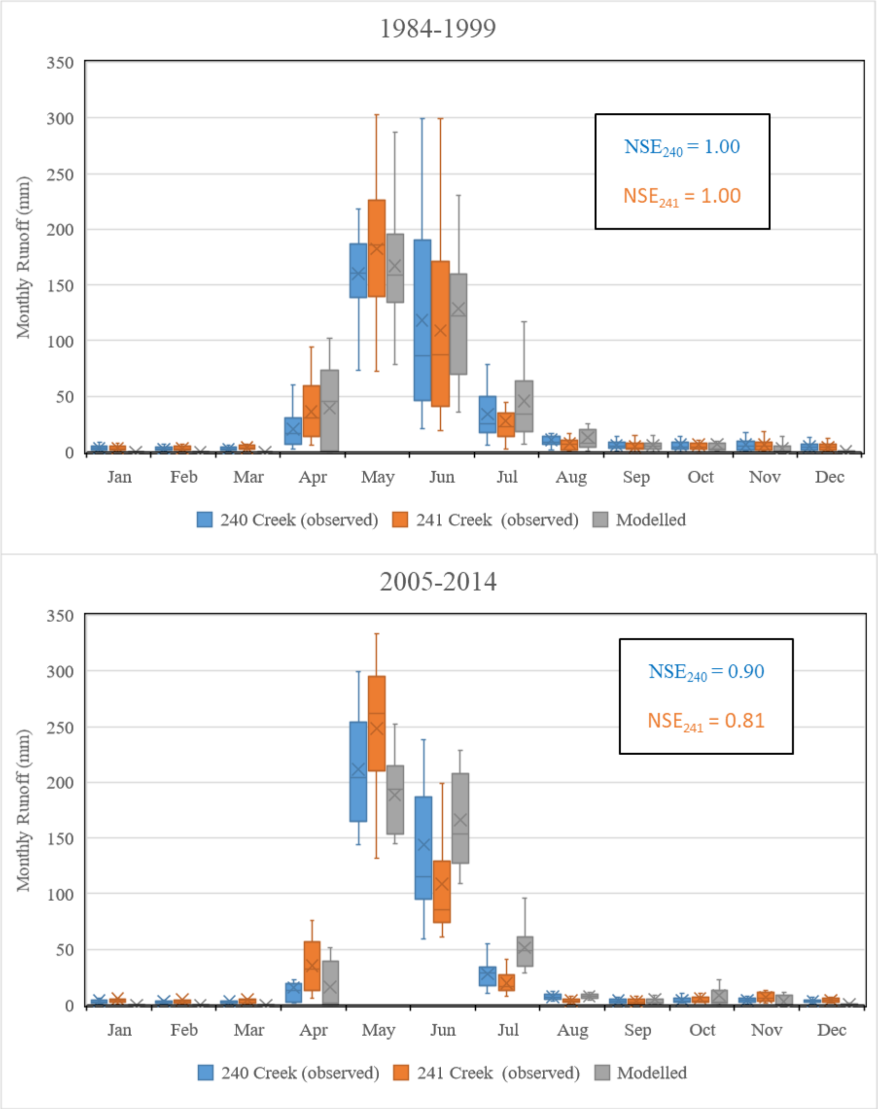

Figure 3: Visual Statistical Distribution of Observed and Modelled Monthly Runoff at Upper Penticton Creek Watersheds

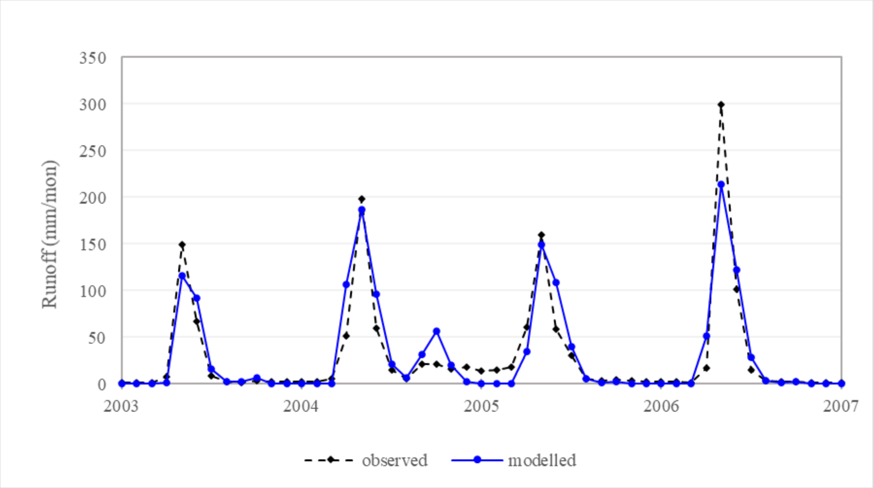

Figure 4: Observed and Modelled Monthly Runoff at 240 Creek Watershed, Demonstrating High Observed Winter Flows in 2005

Discussion – Runoff from Undisturbed Catchments vs. Contact Water from Mining Components

Combined saturated and unsaturated, physically-based models to simulate these flow pathways are not within the scope of this work. Nor are sufficient data required to reliably calibrate such models available in most mining projects. In the absence of such models, a set of conservative assumptions tailored for the purpose of the study should be made.

Results of the UPC watersheds model showed that a model calibrated to observed runoff from an undisturbed catchment was not reliable for modelling post-disturbance conditions. This illustrates that even when disturbance is as simple as ~~, even if the disturbance was limited to~~ vegetation harvesting, models calibrated to existing conditions do not perform well when conditions change. In the case of mine components (e.g., a waste rock dump), the hydrologic responses are conceptually different from those of undisturbed catchments. For example, the hydrologic response of a waste rock dump to precipitation includes a portion that flows overland, and a portion that infiltrates into the dump. From the infiltrated portion that flows through a combination of macropores and soil matrix, under a combination of unsaturated and saturated flow conditions, a fraction seeps from the toe of the dump and the remainder recharges to groundwater. These three pathways (i.e., overland flow, toe seepage, and groundwater recharge) cannot be reliably simulated with a lumped conceptual model calibrated with undisturbed catchment data.

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In the absence of reliable physically-based models, and given the shortfalls of using the undisturbed catchments model as explained above, a simplistic approach typically used for mine site catchments can be incorporated with sufficient, conservative assumptions. In this simplistic approach, coefficients are applied to the annual precipitation to estimate the annual overland flow, toe seepage, and groundwater recharge. The sum of these three coefficients would be equivalent of total runoff coefficient. Resultant annual values for overland flow, toes seepage, and groundwater recharge are then applied to presumed monthly distributions for each of these three pathways to estimate monthly values for each pathway. Assuming that the purpose of an example study is to model the effect of discharging contact water generated from a waste rock dump into a receiving environment waterbody, the following considerations should be taken into account with this simplistic approach:

- Higher coefficients (as explained above) would result in higher modelled contact water values which would be more conservative than lower modelled contact water values because they would overestimate the effects of contact water effluent discharge into the receiving environment. Observed annual precipitation and runoff values in the UPC watershed show an average annual runoff coefficient of 51% (Table 1; 395/770 =51%). For effluent water quality effects assessment, the overland flow, toe seepage, and groundwater recharge coefficient should be selected in a way that the sum of them is greater than 51%.
- Toe seepage and groundwater recharge flows pick up more geochemical loads than overland flow. Therefore, it is more conservative to assume more toe seepage and groundwater recharge, and less overland flow.
- Winter low flow conditions are generally the sensitive months of the receiving environment because they provide the least background flow for mixing with contact water effluent discharge. In such cases, less flashy (i.e., more uniform) hydrographs for contact water, which would assume that contact water store and release is more attenuated than a natural catchment, would be more conservative because they overestimate contact water effluent during winter low flow conditions.
- Abovementioned assumptions would not be conservative if the purpose of the study was, for example, designing the capacity of the contact water collection pond.

If the example study above were to be in the UPC watersheds, the following example assumptions would make a set of plausible contact water estimates:

- Overland flow, toe seepage, and groundwater recharge are 25%, 30%, and 20% of precipitation, respectively. They add up to 75% of precipitation, up from 51% for undisturbed catchments.

- Overland flow can reasonably be assumed to have the same monthly distribution as that of rain and snowmelt. Monthly distribution of toe seepage can be assumed to be the same as total runoff from undisturbed catchment, and groundwater recharge can conservatively be assumed to be uniform (which means higher contact water during winter low flow conditions).

Results of these assumptions for overland flow, toe seepage, and groundwater recharge, as well as the resultant total contact water, are shown Figure 5. The figure also shows runoff from undisturbed catchments which is less than the total contact water estimates in all months, especially during the winter low flow months.

These coefficients and monthly distributions are examples, based on experience of the authors with similar settings. Uncertainty in such assumptions would be better characterized if such fixed values were replaced with probabilistic values. Figure 6 shows an example where fixed values used to generate the hydrographs in Figure 5 were replaced with probabilistic values. This probabilistic (boxes and whiskers) graph provides more information than Figure 5 in terms of the plausible range of contact water generated in each month of the year. This probabilistic approach (i.e., presentation of a range of plausible outcomes) can support both mine planning and regulatory purposes based on the risk perspective of the reviewer.

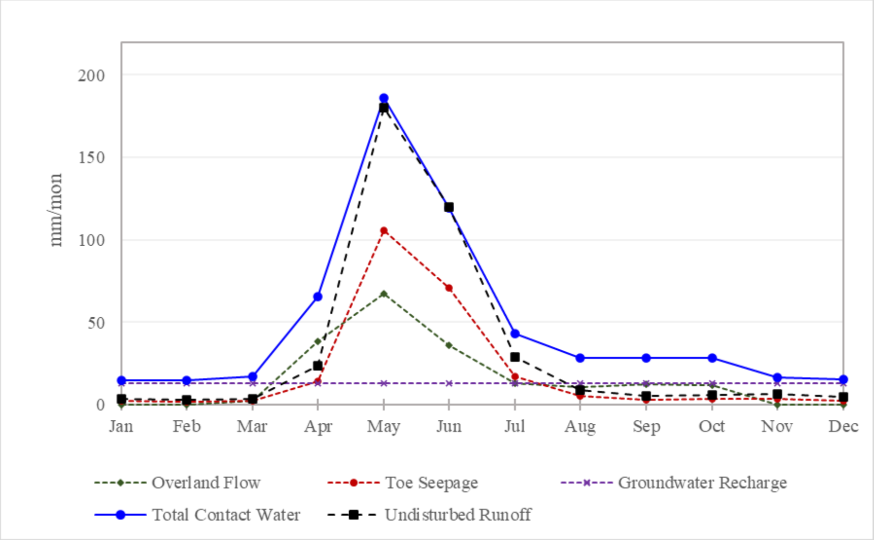

Figure 5: Example Comparison of Total Contact Water and Undisturbed Runoff with Data from the UPC Watersheds Model.

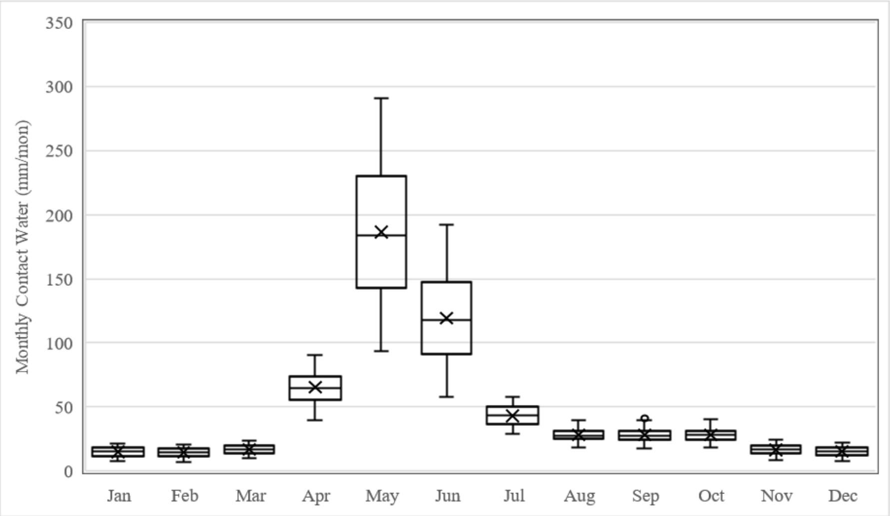

Figure 6: Example for Visual Statistical Distribution of Total Contact Water at Upper Penticton Creek Watersheds

Conclusions

Reliably monitored climate and flow data are the backbone of reliable modelling results. This study intentionally included one year of unreliable (erroneous) ~~climate~~ precipitation data in one of the three example studies to demonstrate the implications of such data to model results. Implementation of provincial and federal guidelines in installation of monitoring stations, as well as data collection and analysis, is the most important step of any water balance assessment, and if missed, cannot be compensated with modelling effort.

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In development and calibration of runoff models, instead of focusing on an accurate numerical match between the observed and modelled flows, emphasis must be put on confirming that the model reliably generates the known hydrologic responses in a study area. For example, the model must reasonably demonstrate the snowmelt-driven rising limb of the spring freshet, post-freshet recession limb, rain-driven punctuated flows in fall, and winter low flows, given the range of known temperature in the region.

Lumped conceptual models for runoff from undisturbed catchments do not reliably simulate contact water generated from mine components, which are conceptually different from those of undisturbed catchments. Physically-based models capable of simulating contact water from such mine components are data intensive, and even then may not provide reliable results. The data required to properly parameterize these models is typically not achievable given the budgets available to mining projects. In the absence of such models, conservative assumptions should be made for contact water generated from mine components.

It is important to bear in mind that a conservative assumption for one study (e.g., effects of contact water discharge into receiving environment) may not be conservative for another study (e.g., estimating the capacity of a contact water collection pond). Likewise, incorporating a probabilistic approach, rather than using fixed-valued assumptions, allows for a better characterization of modelling uncertainty.

Acknowledgements

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