Groundwater Recharge Estimates in Mine Site Using Integrated Hydrological Model: Review and Critique

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Abstract

Recharge estimation is a fundamental input for water resources management. There are several methods for recharge estimation although they are normally subjected to large uncertainties. Empirical models which are often used in hydrological studies for recharge estimate, however, do not always provide reliable results. For that reason, integrated hydrological models have become a preferred approach of estimating recharge due to the inclusion of major processes of the hydrologic cycle pertaining to surface water and groundwater that are not fully captured in empirical models. In this study, the groundwater recharge was a difficult parameter to estimate because of the complexity of the site's hydrogeological system below a variable peatland and the area's complex snowmelt pattern. The objective of this study was to estimate the temporal and spatial distribution of recharge with MIKE SHE for the study area in order to use it as an input for a complex three-dimensional groundwater model in FEFLOW.

MIKE SHE is a physics-based, deterministic, integrated hydrological framework for hydrological modelling that solves the partial differential equations describing mass flow and momentum transfer. In this study, the MIKE SHE model run incorporated the processes of evapotranspiration, precipitation, snowmelt, overland flow, unsaturated zone, and groundwater flow to simulate recharge. The model was calibrated based on site data for overland flow, hydraulic` heads, and snowpack.

This paper presents a summary of the conceptual model for the study site and the various stages of the MIKE SHE model construction, calibration, and analysis of results such as recharge variability in space and time. More importantly, this study highlights some of the challenges associated with the application of the integrated hydrological modelling approach to complex hydrogeological systems and presents some critiques made during the development of the recharge model. It further suggests recommendations for improvement in recharge estimates for future integrated hydrological models.

Introduction

Recharge estimation is a fundamental input for water resources management. There are many methods for recharge estimation although they are all subject to uncertainties (Islam et al., 2016). For instance, empirical models are often used for the estimation of recharge but do not always provide reliable estimates. For that reason, integrated hydrological models, which help simulate the major processes of the hydrologic cycle including surface water and groundwater, are sometimes used to estimate recharge distribution with less uncertainty. But do integrated hydrological models always provide reliable estimates of recharge?

This paper reviews and outlines some drawbacks associated with using some integrated hydrological models to estimate recharge to a groundwater system in a mine site.

In this study, groundwater recharge was difficult to estimate due to the complexity of the site's hydrogeological system and the complex snowmelt patterns in a spatially variable peatland, hence the use of an integrated hydrological model. The objective of this study was to estimate the temporal and spatial distribution of recharge with MIKE SHE and the result used as an input for a three-dimensional groundwater FEFLOW model to simulate the development of an underground mine and its impacts. The recharge pattern from MIKE SHE was also compared to typical recharge patterns for soils from the Snowmelt Model.

Methodology

The integrated hydrological modelling approach used to estimate groundwater recharge in the study area involved the characterization of the site's geology/hydrogeology, the use of climate data, land use data, overland flow data, unsaturated zone data, and saturated zone data. The utilization of these data in the model was then followed by model calibration.

Study area

The confidential nature of the project does not permit a detailed description of the study site. Hydrogeological information of the site is therefore presented in general terms. The site receives a total precipitation of about 530 mm with more than 50% accumulating as snow. This snow accumulation on the site's extensive but spatially variable peatland makes characterizing recharge during snowmelt challenging. Recharge is further complicated by the site's complex hydrogeology which comprises a shallow and a deep groundwater system. The shallow groundwater system is in the high hydraulic conductivity quaternary deposits of glacial, fluvial and aeolian clastic sediments while the bedrock which forms the deep system is weathered and fractured at the upper part but unfractured at the base. The bedrock material consists of mafic and ultramafic rocks, quartzite, mica schist and gabbro. Figure 1 below shows the map of the study area.

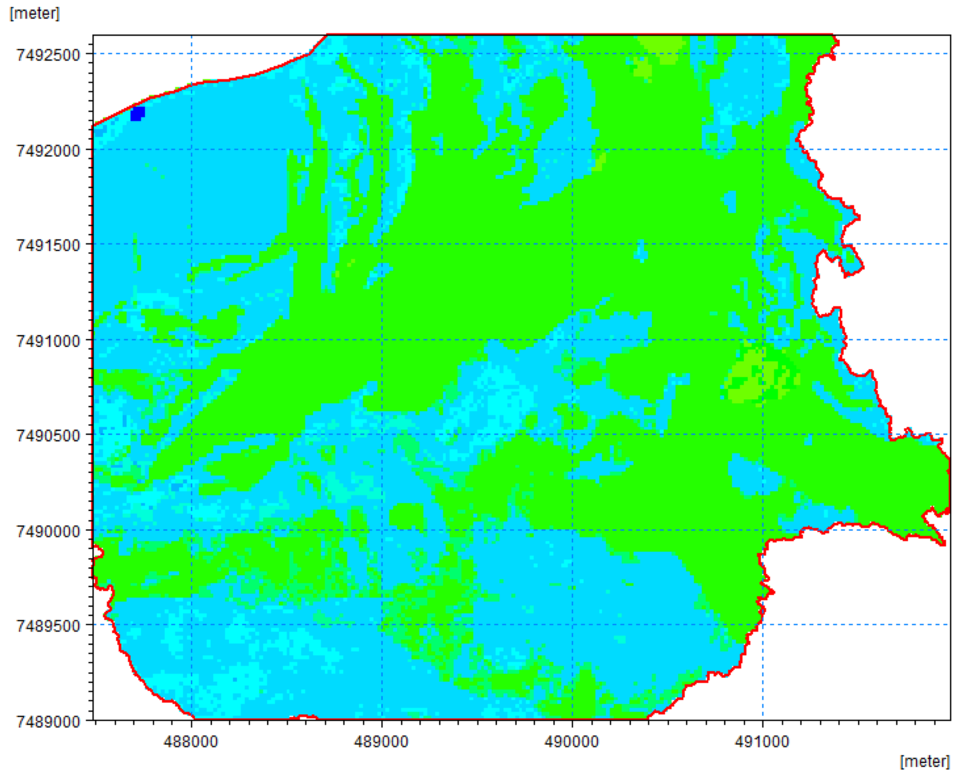

Figure 1: Map of the study area

Structure of the integrated hydrological model as applied to the study area

MIKE SHE is a physics-based, advanced, and flexible framework for hydrological modelling that solves the partial differential equations describing mass flow and momentum transfer (Graham and Butts 2005) Figure 2 below summarizes the structure of the MIKE SHE model in terms of how the various hydrological components are utilized in the estimation of recharge.

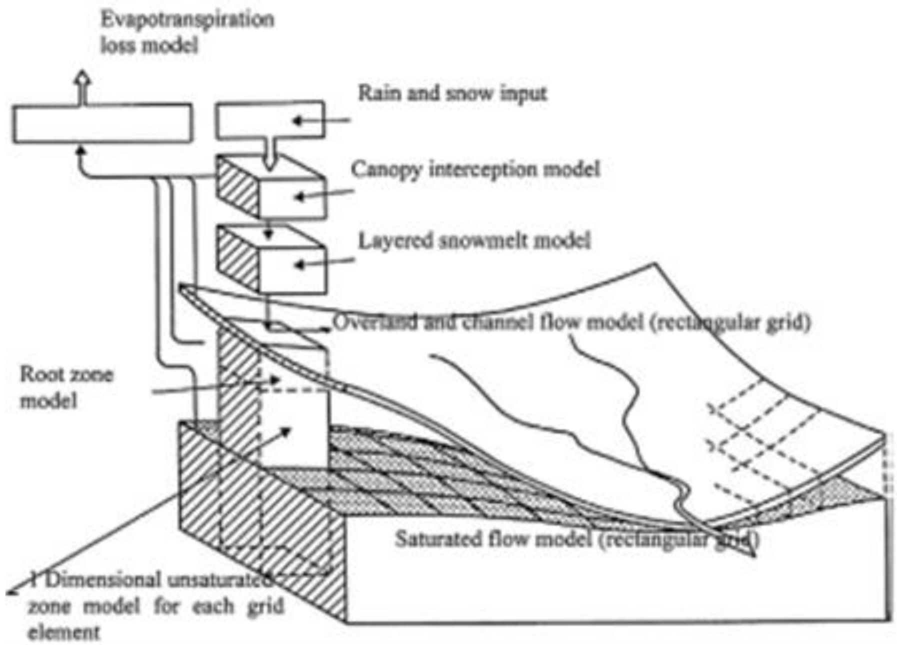

Figure 2: MIKE SHE model structure (Regard et al., 2010**)**

Data and Discussion

MIKE SHE Model Construction

The model domain (mine site) spanned across three sub-catchments. It was vertically discretized and represented the 15 m depth of the stratigraphical sequence corresponding to the Quaternary deposits. This 15 m thick alluvial deposits which sit atop a deep weathered and fractured bedrock was more significant than the deeper bedrock because that is the depth where recharge is more important in the model.

The executed MIKE SHE model included the process models of evapotranspiration, precipitation, snowmelt, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions (Graham and Butts 2005) to estimate recharge. MIKE SHE describes recharge as "Total recharge" which includes parameters like exchange between unsaturated and saturated zones, recharge from bypass or macropores, direct flow between saturated zone and overland, etc., (DHI MIKE 2017).

The model was calibrated based on field data from overland flow, hydraulic heads, and snowpack.

The input data for the model was based on data measured on site as well as from indirect measures.

Climate Data

Precipitation, air temperature, and reference evapotranspiration data were required as climate input data. The first two parameters were obtained from a meteorological weather station close to the study area and were applied to the model daily.

The reference evapotranspiration is the amount of water that is evapotranspirated from a given reference surface (typically of a well-watered grass or crop) (FAO 1998). This input was obtained from the satellite MODIS.

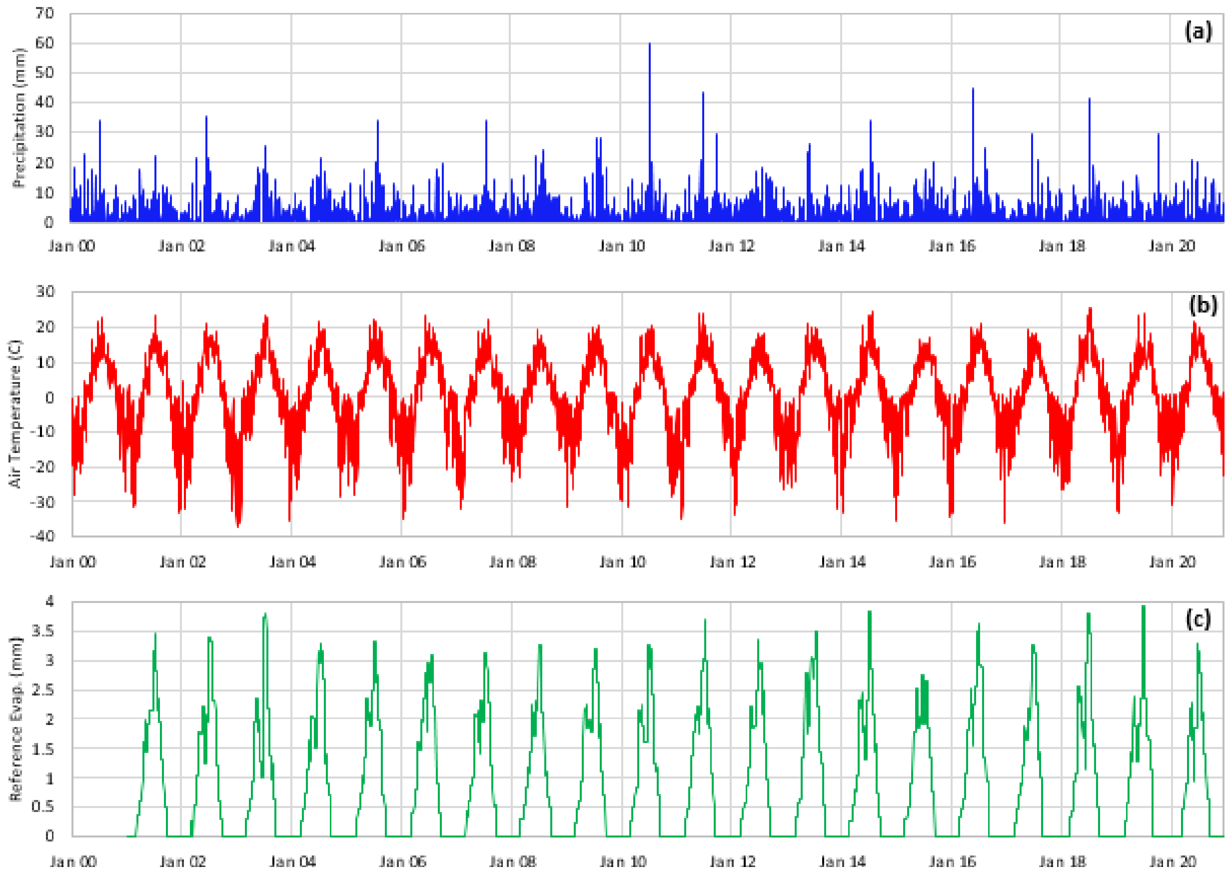

Figure 3: Climatic data input (a)precipitation (b)air temperature (c) reference evapotranspiration

Land Use

The study area has different land use areas such as transitional wood, inland marshes, peatbogs, coniferous forest, non-irrigated arable land, mineral, and industrial sites. Evapotranspiration parameters were required by MIKE SHE for each type of crop. The leaf area index (LAI) and root depth for each crop were therefore obtained from FAO's database (Fischer et al.,2008) and used to calculate the real evapotranspiration.

Overland Flow

The movement of water over the surface was also simulated by executing the overland flow module which required parameters such as Manning number (M), detention storage and initial water depth. Manning number is the reciprocal of Manning's roughness coefficient (n) and was assigned based on the land use. This parameter varies from around 10 to 100 and a higher value led to faster overland flow therefore this was a calibration parameter. The detention storage and initial water depth were assumed as zero due to low variability in topography.

Unsaturated Zone

As the objective of the model was recharge estimation, the model was built including the unsaturated zone module. Unsaturated soil parameters such as Van Genuchten parameters were taken from literature according to the type of soil due to the lack of field studies in the area to determine soil properties. In this study, soil parameters were set for gravel, sand, and till which are the dominant soil types for most recharge.

Saturated Zone

The saturated zone required parameters such as hydraulic conductivity and storativity which were taken from the FEFLOW groundwater model and were subjected to calibration. In the case of the groundwater simulation, boundary conditions such as no-flow and constant head were implemented.

Model Calibration and Validation

The model was calibrated against observed hydraulic heads measured in the sedimentary deposits, overland flow measured in the three sub-catchments within the model domain, and snow water equivalent calculated based on measured snowpack data.

The calibration determined some model parameters to reach a good match to the measured data.

The model calibration showed that the overland flow was sensitive to the Manning's number, therefore the recharge to the saturated zone was also sensitive to this parameter.

Since the recharge is influenced by processes such as snow accumulation and snowmelt, the parameters of threshold melting temperature and degree-day coefficient were set to 0°C and 2 mm/day/ °C, respectively. For this study, the snow water equivalent calibration did not require much effort in parameter adjusting.

In the case of the groundwater levels, these were calibrated by adjusting hydraulic conductivity and storativity by trial and error. It was noticed that the groundwater table influenced the recharge and evapotranspiration from the saturated zone. Figure 4 below shows the calibration of hydraulic heads in two monitoring wells out of tens of them. Simulated groundwater heads at these two wells did not match well against the observed heads. They were even worse in the other remaining wells.

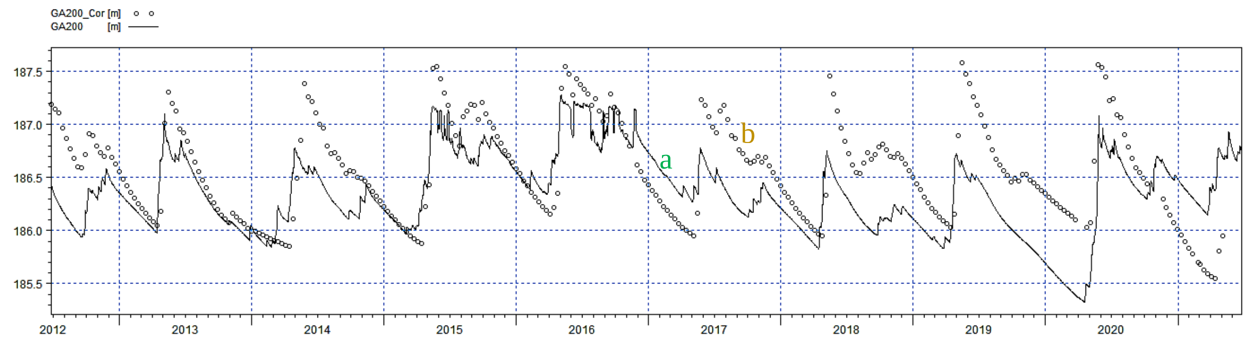

Figure 4: Calibration of the groundwater component (a) Groundwater table simulated by MIKE SHE and (b)Comparison of the modelled and observed hydraulic heads.

Results

After running the MIKE SHE model, an output of daily estimates of recharge to the saturated zone for each cell in the model domain was computed. Recharge varied significantly both spatially and temporally. Different recharge rates were expected due to the spatial heterogeneity of the study site in terms of geology and hydraulic properties of geological materials. Spatial variations were observed depending on the spatial distribution of geological materials while temporal variations were more dependent on the seasonal variations of precipitation and temperatures. The central part of the study site, which is covered with gravel, sand, and till had more recharge in comparison to its surrounding regions which had peat as the main soil cover (Figure 5). According to the MIKE SHE model convention, negative values represent recharge while positive values represent discharge from the saturated zone.

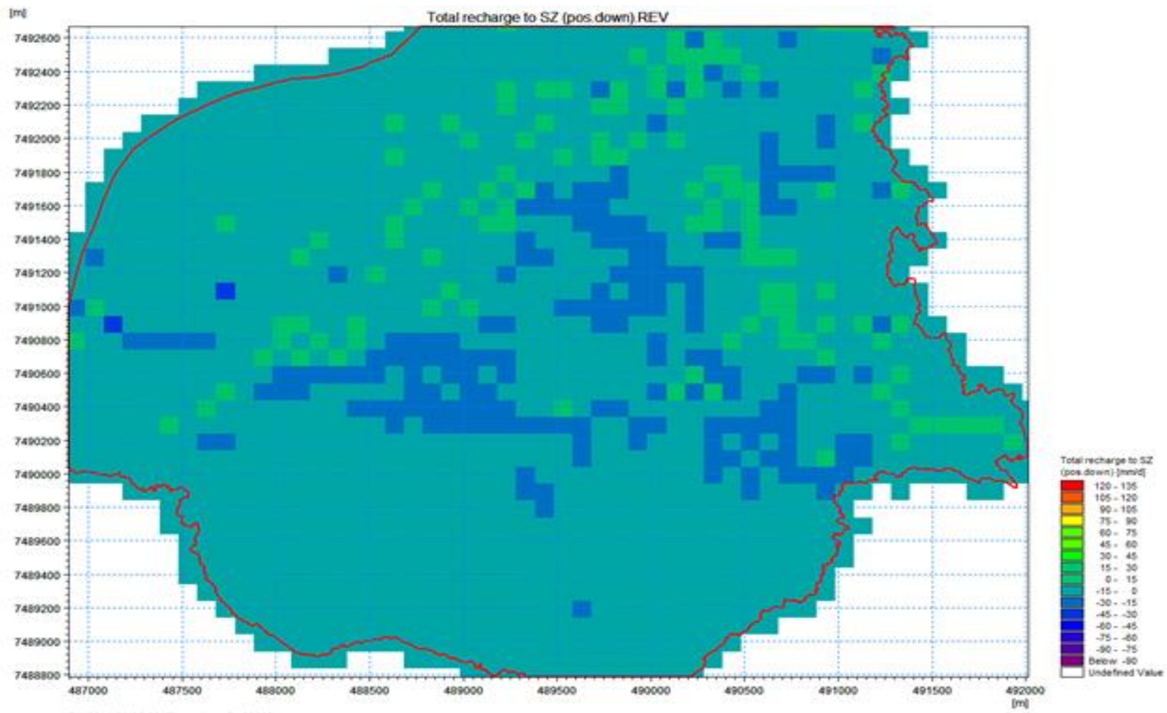

Figure 5: Spatial variation of recharge into the saturated zone

The estimated daily recharge in the various geological units of the model domain ranged from about 1 mm/d to about 40 mm/d (Figure 6). Average monthly values for recharge ranged from 0.1 mm/d to about 4.6 mm/d with the highest recharge estimates in the gravel formation and the lowest in the peat (Figure 7). Although recharge trends are captured in the results from MIKE SHE (Figure 6 and Figure 7), recharge estimates did not match so well with typical recharge patterns in till, gravel, and peat from the Snowmelt model (Figure 8).

Unlike typical recharge patterns for most soils which indicate zero during sub-zero temperatures, MIKE SHE rather showed a flip-flop trend in daily and monthly average recharge estimates with alternating positive and negative values. These rates are somewhat high in terms of magnitude. For example, a recharge rate of 40 mm/d is relatively high considering a maximum evapotranspiration rate of 3-4 mm/d from the surface only. At the same time, daily precipitation is only slightly higher than 40 mm/d.

The plots shown in Figure 6 and Figure 7 each represents recharge estimates from a single cell/pixel of the whole MIKE SHE output. The remaining pixels capture at each time different recharge estimates in the same flip-flop pattern. Although the developers of the software argue that negative values indicate recharge into the saturated zone and positive values represent discharge from the saturated zone, we think this is not a true representation of recharge on the study site. It was expected that only recharge estimates would be produced in the MIKE SHE model output since the various hydrological processes have already been included in the model. We identify the inability to deselect some of the components used in the computation of the "Total recharge" by the MIKE SHE model to sufficiently characterize the hydrological response of the study area's saturated zone as the cause of the negative and positive recharge estimates.

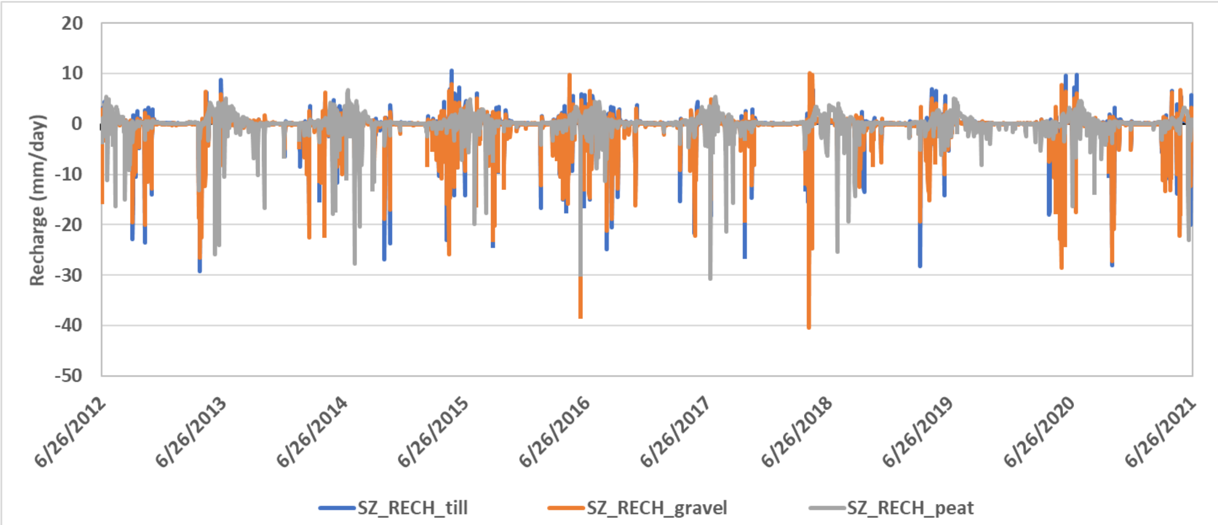

Figure 6: Daily recharge estimates for till, gravel, and peat from the MIKE SHE model

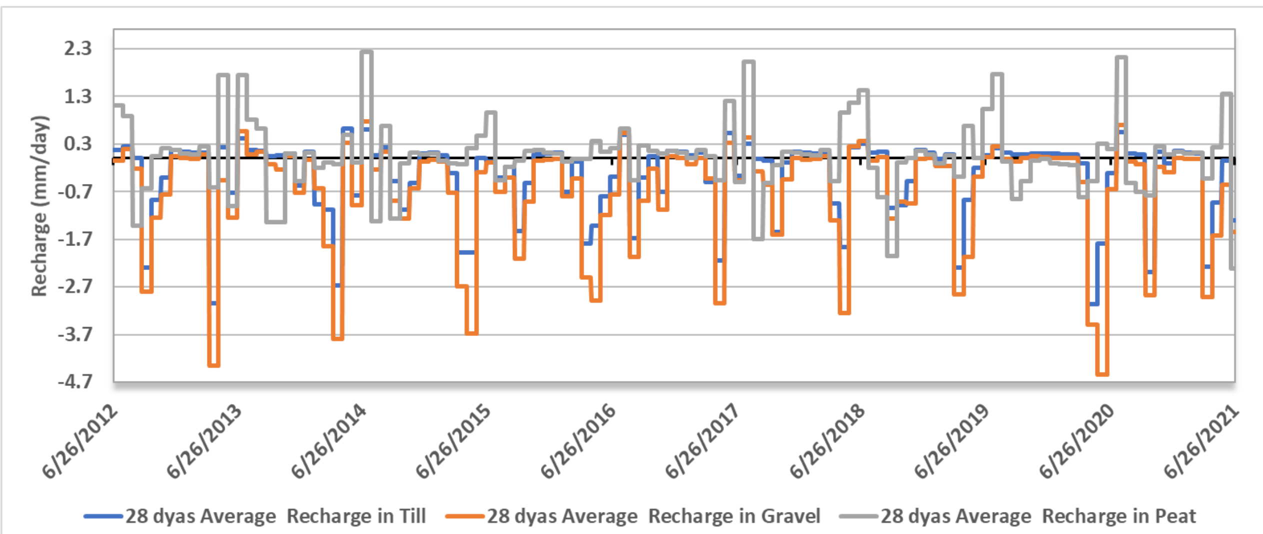

Figure 7: Monthly average recharge estimates for till, gravel, and peat from the MIKE SHE model

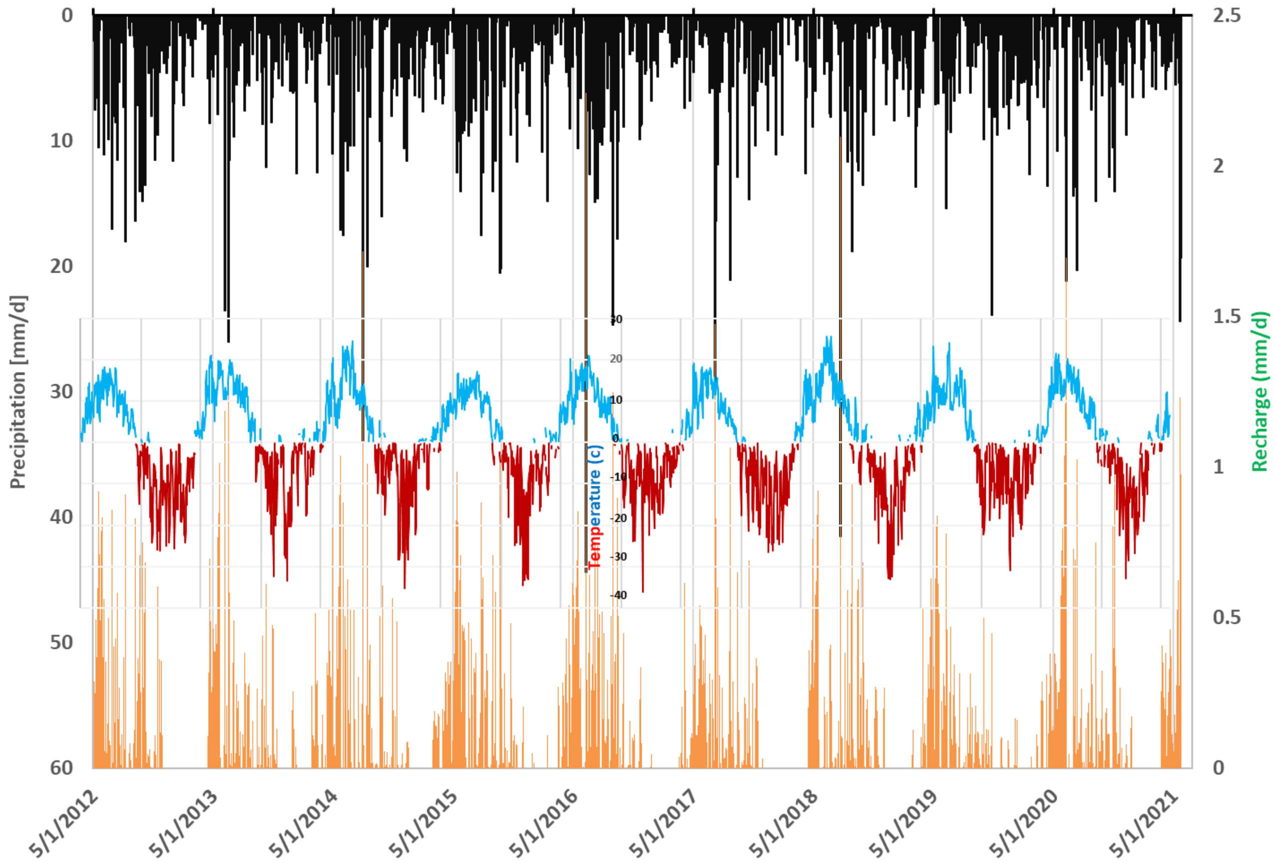

Figure 8: Temporal recharge pattern for geological materials (recharge on lower horizontal axis, temperature in the middle, and precipitation on the upper horizontal axis)

Conclusion

An estimation of the temporal and spatial distribution of recharge to the saturated zone to simulate the development of an underground mine and its impacts was performed with MIKE SHE; a physics-based, fully integrated alternative to the more traditional lumped, conceptual rainfall-runoff models. Results from the model served as an input for a three-dimensional groundwater FEFLOW model. While integrated hydrological models are known to estimate recharge with less uncertainty, results from MIKE SHE however did not match well with typical recharge patterns in till, gravel, and peat. MIKE SHE results showed a flip-flop trend in recharge estimates (alternating positive and negative values) and high daily rates which are contrary to the typical recharge patterns in geological materials which are often characterized by zero (no recharge) during sub-zero temperatures or some positive value (indicating recharge). This study therefore emphasizes that in as much as integrated hydrological models limit large uncertainties in recharge estimates by including components that cannot be assessed with other methods, they should be carefully evaluated before they are used in hydrological analyses. It is also recommended that the developers of the MIKE SHE model provide the flexibility for modellers to select or deselect the various components that are used to estimate recharge to closely characterize different site conditions.

References

DHI MIKE SHE. 2017. User Guide Volume 1. MIKE_SHE_printed_V1. book (mikepoweredbydhi.help)

FAO. 1998. Chapter 1 - Introduction to evapotranspiration. http://www.fao.org/3/X0490E/x0490e04.htm

Fischer, G., F. Nachtergaele, S. Prieler, H.T. van Velthuizen, L. Verelst, D. Wiberg. 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008). IIASA, Laxenburg, Austria and FAO, Rome, Italy.

Graham, D.N. and M. B. Butts. 2005. Flexible, integrated watershed modelling with MIKE SHE. In Watershed Models, Eds. V.P. Singh & D.K. Frevert Pages 245-272, CRC Press. ISBN: 0849336090

MODIS Web. https://modis.gsfc.nasa.gov/data/

Refsgaard, J.C., Storm, B., Clausen, T., 2010. Système Hydrologique Européen (SHE): Review and perspectives after 30 years development in distributed physically based hydrological modelling. Hydrol. Res. 41, 355–377

Saiful Islam, Ram Karan Singh, Roohul Abad Khan. 2016. Methods of Estimating Ground water Recharge. International Journal of Engineering Associates (ISSN: 2320-0804) # 6 / Volume 5 Issue 2