The need for improved representation of groundwater-surface water interaction and recharge in cold temperate – subarctic regions

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Abstract Groundwater models are commonly calibrated exclusively to groundwater level data and their predictive capability can be let-down by underdeveloped capabilities in recharge and would benefit from calibration to surface water flow – particularly in areas with seasonal frozen conditions and snowmelt.
Here, we present the Surface-Water-Accounting-Model (SWAcMOD). Designed to work in conjunction with existing groundwater modelling software, SWAcMOD gives the ability to produce detailed recharge, surface-water flows and evapotranspiration inputs for spatially distributed and transient groundwater models.
SWAcMOD enhances groundwater models' capabilities with respect to surface-water interaction with groundwater systems and through the combined approach, groundwater models can additionally be calibrated to gauged river flows further constraining mine water balances.

Key words recharge, surface water, water balance, modelling, MODFLOW

Introduction

Groundwater modelling software benefits from continued development and the two primary 'industry standard' toolsets; MODFLOW-USG, Panday (2013), and FeFlow are comprehensive packages for the representation of saturated zone mine hydrogeology. However, saturated zone models are typically calibrated exclusively to observed groundwater level data and their predictive capability are frequently let down by underdeveloped capabilities in recharge, coupled surface water flow simulation and unsaturated zone processes.

Groundwater models are expected to represent observed groundwater level fluctuation and additionally, in many areas, groundwater interaction with surface water systems and wetlands. The representation of groundwater level trends and seasonal fluctuation relies upon the appropriate magnitude and timing of recharge inputs to the groundwater model, which typically are highly variable spatially. Within groundwater modelling studies in the mining industry the use of basic estimates of recharge directly from rainfall records is not uncommon due to the uncertainty in the parameterisation of processes which delay, attenuate and partition rainfall between groundwater recharge, surface flow and actual evapotranspiration. These basic methods are particularly unsuitable in cold climates with soil-frost and snowpack generation-melt conditions resulting in the model's inability to represent observed responses and to compensate the recharge magnitude deficiencies through erroneous calibration of aquifer properties.

Representation of coupled groundwater and surface water flow systems is common in water resources modelling as regulation of abstraction is typically dependant on river flow thresholds or wetland saturation under the European Water Framework Directive. The program RRRR, Heathcote (2004) is a prime example of MODFLOW preprocessing software which enables more holistic water balance simulation. Good practice of mass conservative, routed and coupled surface systems from this sector can be developed into mining modelling more routinely.

Calculation of time-series recharge to groundwater and groundwater-surface water interaction is well documented and a plethora of 1D and basic 2D modelled examples exist in the literature. It is however challenging to scale the collective surface and subsurface processes applied in these studies to fully spatially distributed and time variant models and this is considered a major reason why overly simplified methodologies are commonly applied. Reasons for the limited number of mining studies with comprehensive handling of recharge and surface water interaction include:

1. The detailed datasets required to parameterise the key surface and subsurface processes have not been available.
2. Input file formats of the most commonly applied groundwater simulation packages (MODFLOW and FeFlow) are bespoke and require purpose built tools for their generation.
3. Difficult to produce and time consuming topological routing networks of surface water drainage need to be built into the model to provide mass conservative river flows.
4. Processes like the calculation of rapid runoff require daily, or sub-daily, transient calculation and the runtime for distributed simulations can be prohibitive.
5. There are several tools in existence however these are closed source or written in programming languages with a reducing user base which results in poor accessibility and limits the adaptation of the tool for the specific needs of new studies.

The Surface Water Accounting Model (SWAcMOD) program is presented herein. In an effort to overcome the above challenges to comprehensively represent the surface and near surface systems in mining groundwater models:

1. Newly available satellite datasets are presented to assist in the parameterisation of the model, alongside more conventional datasets.
2. The program directly produces the bespoke input files for the industry standard groundwater modelling tool MODFLOW, including the new Unstructured Mesh versions.
3. Topologically routed river networks can be simulated.
4. The modelling package is designed to take advantage of increasingly parallel computing architectures.
5. SWAcMOD is released under the GNU GPLv3 open source licence and written in the Python language to maximise accessibility.

Overview

SWAcMOD comprises a workflow of sequential processes derived from existing studies referenced in the literature. Processes can be optionally enabled or disabled depending on the needs of the site being modelled. The program is of modular design permitting additional processes to be added or adapted within the existing workflow.

The workflow constitutes a 1D model from ground surface down through the soil zone and unsaturated zones. The 1D model requires, as a minimum, rainfall and potential evapotranspiration (PE), with potentially additionally temperature and solar flux time series data alongside parameters controlling how water is partitioned through each process. Fig. 1 summarises the 1D workflow.

Represented processes include:

- Canopy / vegetation interception and evaporation.
- Temperature dependant precipitation as snowfall or rainfall.
- Snowpack development and melt.
- Partitioning of rainfall/melt water as rapid runoff.
- Soil Moisture Accounting and actual evapotranspiration (AE) calculation.
- Additional shallow ponding and impervious zone enhancements to the Soil Moisture Accounting.
- Urban water main or canal leakage.
- Interflow and combined near surface lateral flow processes.
- Attenuation of recharge as passes through the unsaturated zone.
- Surface flow time of concentration attenuation.
- Surface water abstractions and discharges.
- Bypass mechanisms of rejected recharge, macropore recharge and runoff recharge.

The 1D workflow is duplicated for each and every groundwater model cell, however the spatially variable parameters controlling each property can be spatially implemented either by zones of identically parameterised cells or via specification of unique values per cell. By this system the 2D parameterisation of the model can be readily setup. Fig. 2 is an example of zonal input of model properties in SWAcMOD at the scale of the MODFLOW-USG groundwater model mesh. Each of the hexagonal cells hosts a 1D workflow as presented in Fig. 1.

Of particular importance in cold climates recharge is the facility to represent most processes optionally using time variant parameterisation which permits frozen conditions and seasonal removal of connections to be imposed. This functionality is additionally used for Soil Moisture Accounting though the FAO 56 methodology permitting changing vegetation or crop rotation.

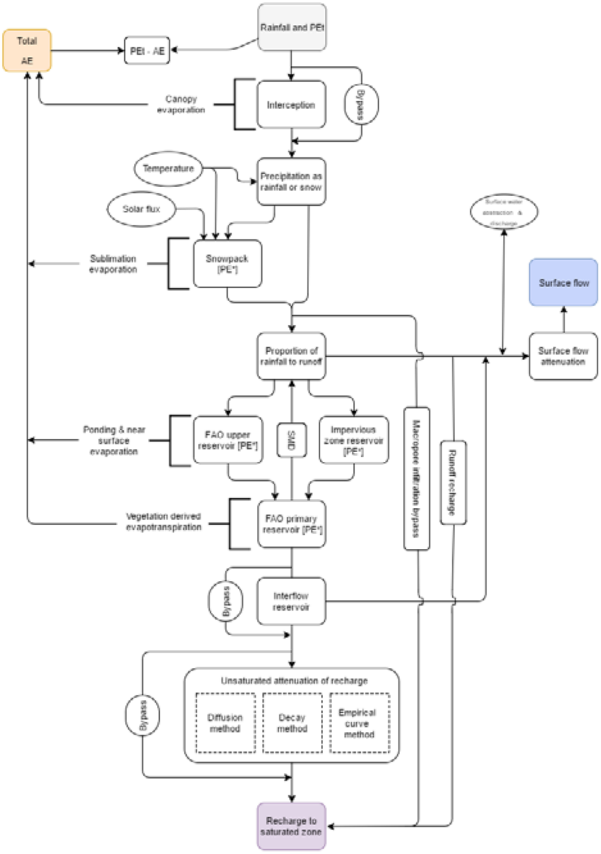

Figure 1 *SWAcMOD 1D process workflow.*

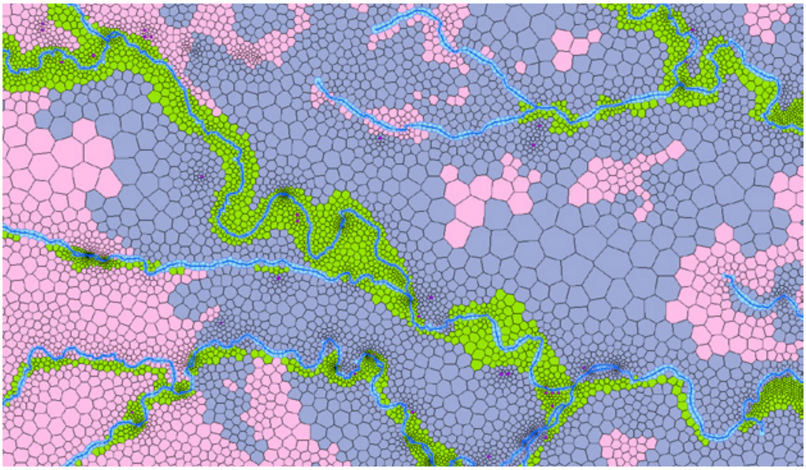

Figure 2 *Parameterisation by zones on a MODFLOW-USG mesh (as an alternative to unique values per cell)*

Fig. 3 is an example catchment summary for a model located in the centre of Finnish Lapland. Processes enabled in this model include snowfall-pack and melt, rapid runoff, Soil Moisture Deficit and AE accounting via an adapted form of the FAO56 methodology, Allen (1998), interflow, macropore bypass recharge (rapid recharge), secondary recharge from runoff (important for representation of observed increased melt recharge as approach surface water courses), surface water attenuation and groundwater recharge lag and attenuation. All processes down to the interflow store have time variant properties to permit soil freeze.

Uncertain model properties have been constrained through calibration to river flow gauging prior to dam construction, measured snow thickness (green dots in Fig. 3), Sentinel Satellite derived snow cover spatial distributions over time and Sentinel Satellite derived AE inference. In addition, several properties, for example rapid runoff characteristics and vegetation rooting depths, have been estimated based on experience from past studies and reference material respectively.

The bottom three plots represent time series inputs for MODFLOW-USG and are the primary outputs for the model. These are the 'surface component of total river flow' (all excluding baseflow), 'Unutilised PE' (the input to control riparian evapotranspiration) and 'recharge to the saturated zone'. These three outputs are spatially distributed however this plot summarises the average daily time series values for this aggregated catchment area.

All units in Fig. 3 are millimetres, the temporal resolution is daily.

Solution to the problem of spatial parameterisation

The primary source of time series input data derives from meteorological stations providing high quality data at a specific locality. River flow gauging additionally provides good constraint on uncertain parameters at catchment scale. In particular, constraining the parameters and processes which influence the rate of recession from high flow events and, separately, the periods where rivers are dominantly groundwater baseflow derived can assist in the estimation of annual recharge magnitude. Beyond this however spatial parameterisation can be highly uncertain and a model's predictive capabilities are not improved through imposition of heterogeneity that cannot be backed up by observed data or conceptual relationships.

A major new source of data has become available in 2016 and 2017 to assist in the spatial parameterisation of surface processes. The Sentinel 2 satellites are part of the European Space Agency's Copernicus Programme and are primarily intended for application in the management of forestry and agriculture, assisting in prediction of crop yields. These data can additionally inform on areas of wet ground, snow cover, general landuse and vegetation efficiency to evapotranspire water. These multi-band data are freely available for all landmasses at a resolution of between 10 and 60m in x-y depending on the band combinations desired with new data for any given location becoming available every 5 days since March 2017 (ESA, 2017).

From recent application in Finnish Lapland it has been our experience that around 60% of the flybys are not adequate for use due to cloud cover. However, a single good dataset each month has been sufficient to observe the evolution of snowpack and melt, and the development of the otherwise highly uncertain vegetation evapotranspiration characteristics, both over space and time. Combined with conventional meteorological and monitoring datasets the uncertainty of processes controlling recharge to groundwater can be greatly reduced. Fig. s 4 through 9 denote Sentinel data for March (dominated by snow melt), August (peak period for vegetation evapotranspiration), and October (as the end of the warm season prior to freezing conditions). The purple and pink in the NDVI and Vegetation index data readily show water, snow and ice cover. The intensity index is an analogue for evapotranspiration.

Solution to the problem of time consuming file formatting and complex river topology

If the surface water processes are enabled, SWAcMOD assists in the generation of topologically sorted routing networks. The inputs to this process are topography and, optionally, user defined river locations.

The output of the overall process is formatted into MODFLOW-USG compliant ASCII files permitting MODFLOW to be run directly. The files currently generated include Recharge (RCH), Stream Flow Routing (SFR) and Evapotranspiration (EVT).

Solution to the problem of run-times and accessibility

Proprietary and closed source modelling packages are anticipated to be the primary barrier to accessibility and adaptability of similar programs, limiting use and applicability to unique study areas. A primary goal of the SWAcMOD program is to facilitate improved representation of water balances, recharge and groundwater – surface water interaction in groundwater modelling and, as such, the program is issued under the open source GNU GPLv3 licence.

The SWAcMod library is written in Python which is arguably one of the most readable and easy-to-use languages. Its built-in, high-level data types (e.g. dictionaries) and dynamic typing (i.e. no need to declare the types of arguments and variables) allow Python code to be on average 3-5 times shorter than analogous Java code, and 5-10 times shorter than C++ or FORTRAN code.

Python has been selected for this program as it is one of the most common programming languages, relatively easy to learn and has a growing user base, particularly in academia and amongst new graduates. Fortran is considered to be used for most scientific codes in the mining industry historically however its user base is declining, this language is rarely taught in universities.

The downside for Python is that it typically runs slower than programs written in low-level implementation languages like C++ or Java, and this is particularly limiting in scientific and numerical computing. In order to mitigate this drawback, we have implemented the

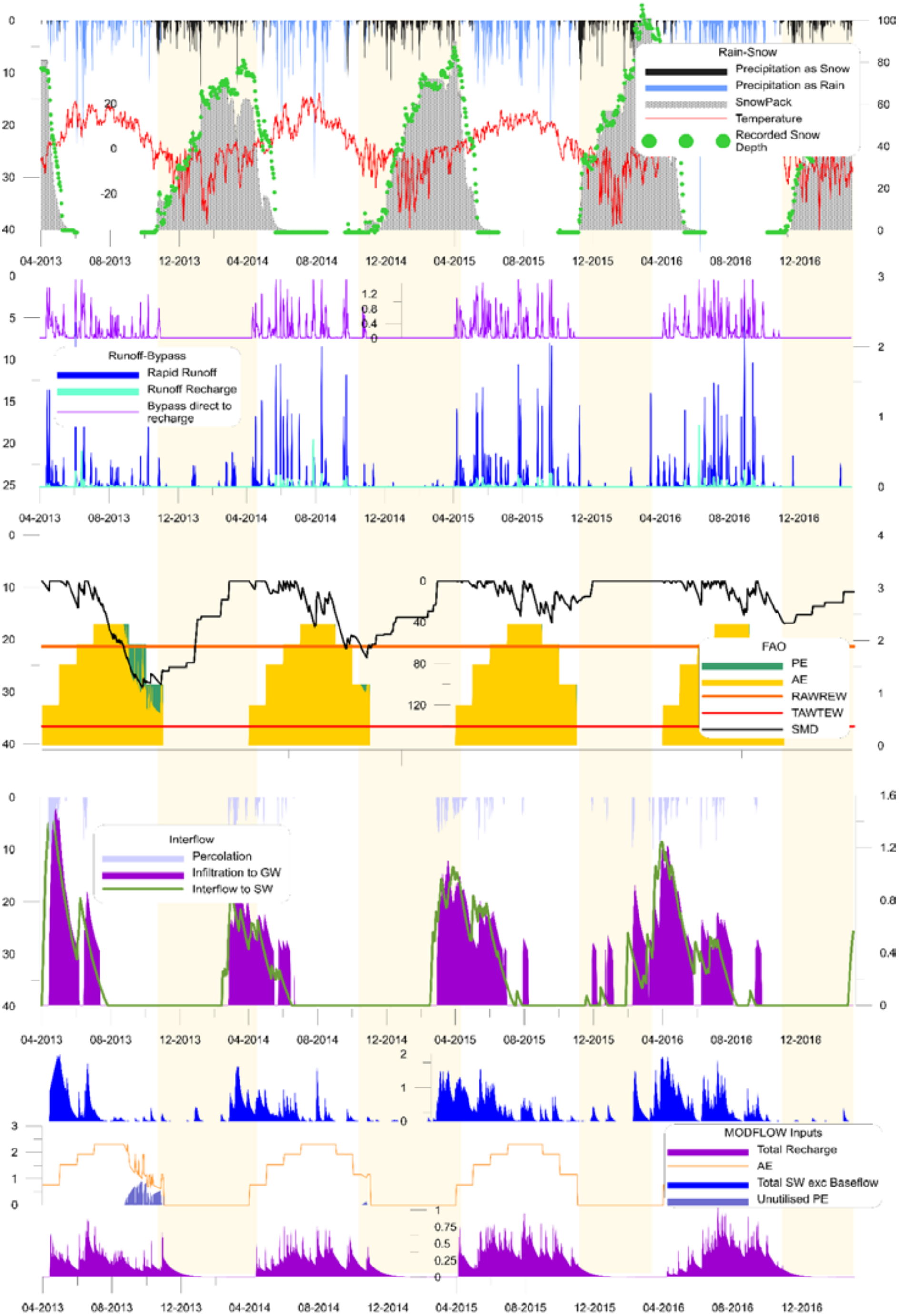

***Figure 3** Break down of the outputs from SWAcMOD processes for a catchment in central Finnish Lapland.*

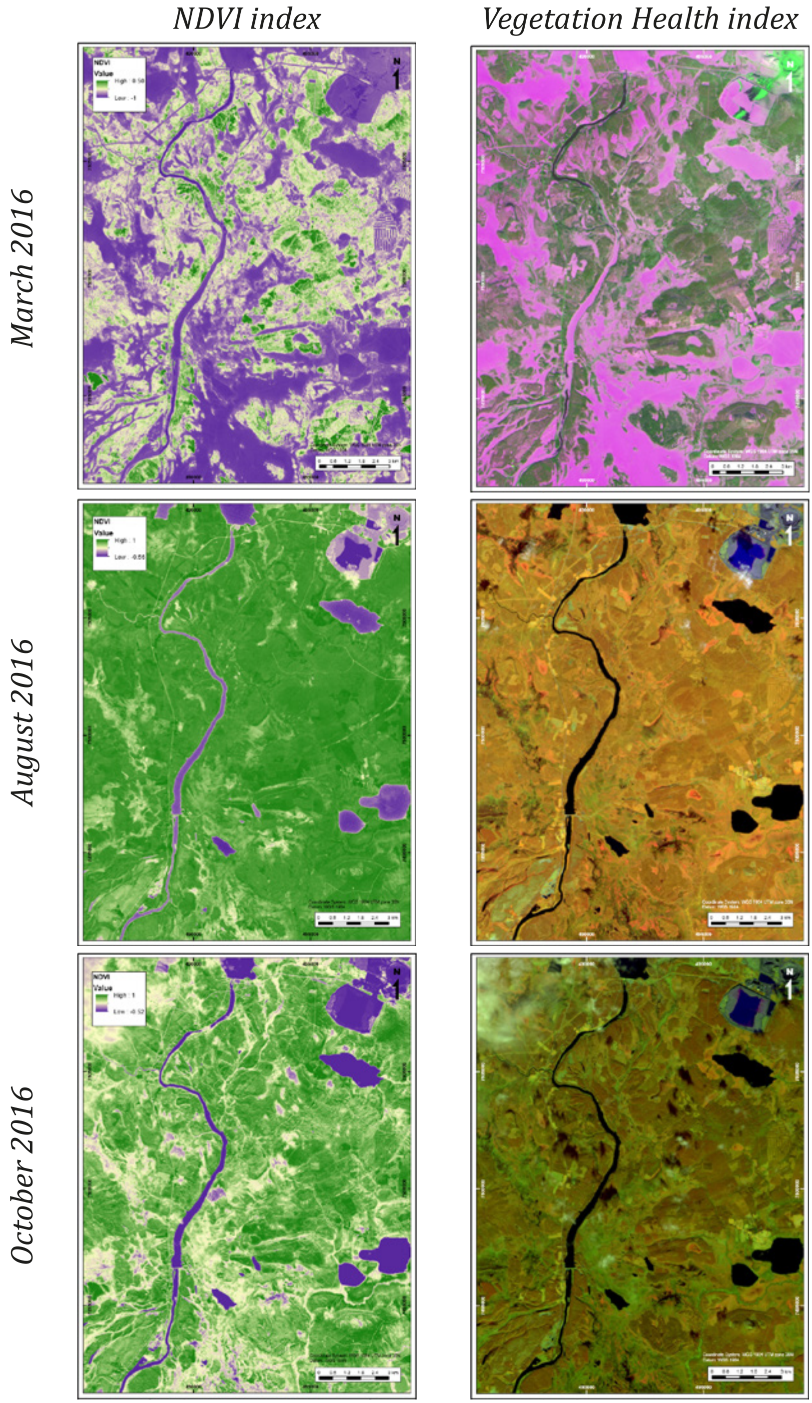

Figure 4 *through 9 NDVI and Vegetation Health Index band combinations from Sentinel 2 data.*

following 3 strategies: *parallelization*, *vectorization with NumPy* and *use of Cython*. Their combined effect is a 25-fold/core speedup of model time, bringing it down to a few milliseconds per node.

Conclusions

Surface Water Accounting Model (SWAcMOD) has been developed to be an open, accessible, adaptable and fast tool to enable better representation of time variant and spatially heterogeneous recharge, actual evapotranspiration and river flows. Alongside a groundwater modelling package like MODFLOW-USG this integrates catchment water balances. SWAcMOD is designed to work in sequence with MODFLOW and is compatible with the newest Unstructured Grid versions. The processes included within the SWAcMOD program are not new and are based on peer reviewed methods. However, the holistic framework to pull the processes together, rapidly parameterise, generate river topology and methods to invoke parallelisation – reducing runtimes – are considered a new development for the water community. In addition, barriers to robust representation of recharge in particular are considered to result from data scarcity in many mining studies. The SWAcMOD program has been designed to make use of newly available high resolution and free satellite datasets which help to constrain several spatially and temporally variable processes. This, in combination with conventional ground station based data, is a significant improvement in what has been openly available in recent years.

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