Developing an integrated hydrological model of a steep, geologically complex, snow-dominated Alpine catchment

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Ongoing climate change is threatening the established function of the European Alps as "water towers" [1,2]. At present, attempts to replicate the functioning of such environments and then make future predictions involve the application of hydrological models that have highly simplified representations of the subsurface and groundwater processes [e.g. 3,4,5]. This is unsatisfactory because: i) mountainous regions often present geometrically complex bedrock arrangements, including folding (as a result of the intense tectonic processes that led to their formation), and; ii) this geological heterogeneity is known to exert a profound influence on subsurface flows, most particularly where karstified limestones are present [6] – as is the case across much of the Alps.

More complex, physically-based, integrated models such as HydroGeoSphere (HGS)[7] discretise the subsurface and solve the attendant groundwater flow equations explicitly in 3D, in addition to simultaneously representing 2D surface flows. They therefore hold considerable potential for elucidating the modulating effect that complex bedrock arrangements might exert on the mountainous hydrological cycle, all whilst not neglecting surface flows that can be important for sediment dynamics and flood risk. They also theoretically enable the simulation of the complex web of conceivable interactions and feedbacks between groundwater, snow, vegetation, soils and geomorphology; these interactions can also ultimately affect the quantity and timing of water availability, yet the response of this system to climate change is likely to be rather nuanced.

Perhaps surprisingly, it remains typical practice to force catchment scale integrated models with meteorological data that have been averaged across large areas (frequently entire catchments) and time periods (e.g. daily or monthly). In light of pronounced spatio-temporal variability (with elevation as well as on diurnal, seasonal and meteorological event timescales) in variables such as temperature, precipitation and potential evapotranspiration, the validity of this approach is especially questionable in mountains terrain. Furthermore, it is crucial that snow accumulation and melt processes are represented in a spatially-distributed fashion (most simply as functions of temperature and precipitation); such capability has only recently been included in HGS. These factors, along with challenges sourcing the necessary input data and runtime concerns, may be largely responsible for the extremely limited application of integrated hydrological models in mountainous settings to date.

In this context, we present the ongoing development of a catchment scale model for a steep, geologically complex region that integrates snow accumulation and melt, surface flow and subsurface flow. The region in question is located in the Western Swiss Alps, and has a surface area of approximately 37 km^2. It lies within the inverse and frontal zones of the Nappe de Morcles – a world-renowned, large recumbent thrust fault composed of alternating layers of limestones, shales and marls. Quaternary sediments of glacial and post-glacial origin fill the valley floors, slopes are steep and geomorphologically active, and the diversity of surface land cover is high. Annual mean precipitation is in excess of 1800mm (fairly evenly distributed throughout the year) and winter temperatures consistently below freezing, resulting in a substantial winter snowpack. As a consequence, a number of small glaciers remain in the uppermost sections of the catchment.

Our contribution shall focus in particular on the integration of a 3D representation of the bedrock geology, which has been used to define subsurface zones (Figure 1), as well as on the preparation of meteorological data having a spatial and temporal resolution that are appropriate for the task at hand (generated via interpolation from a dense network of station observations). The definition of hydrological zones in the surface domain on the basis of high-resolution land cover mapping, and subsequent assignment of roughness and snow model parameters, will also be briefly described. Thereafter, the capability of the model to reproduce various observations will be evaluated. These include: continuous groundwater levels and streamflows measured at internal point locations, "snapshot" spatial patterns of actual 24-hour evapotranspiration on summer days (calculated by applying the METRIC algorithm [8] to Landsat 8 images), and snow extent (estimated using the NDSI, again from Landsat 8 imagery). Ultimately, the aim is to minimize equifinality as far as the data allows, and thus improve the chances that our model produces the "right answer for the right reasons" [9].

In conclusion, we will reflect on certain persistent challenges associated with explicit 3D modelling in such environments, such as the difficulty of obtaining field data for parameterization and evaluation, the presence of extremely steep slopes and very thick unsaturated zones, the requirement for finely discretised meshes to resolve the complex surface and subsurface geometries, as well as the implications of long runtimes with respect to automated parameter estimation and uncertainty analysis.

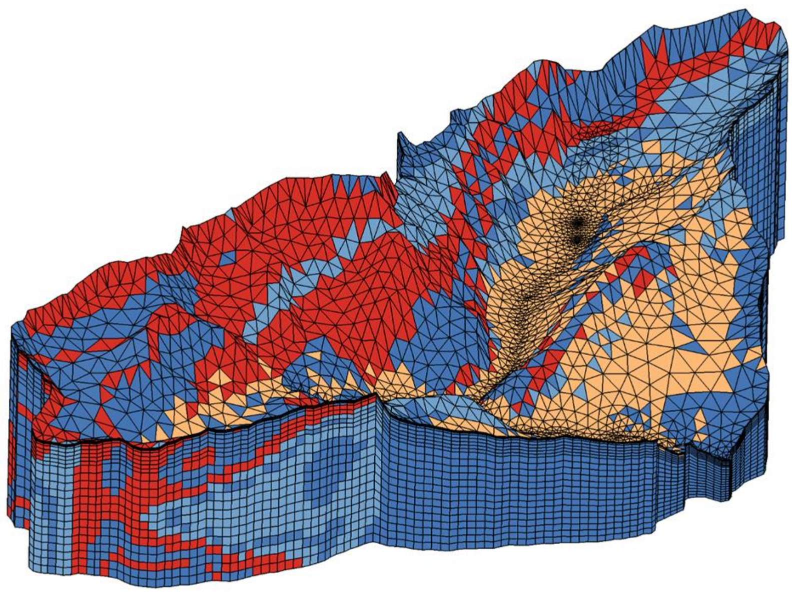

Figure 1. 3D model of bedrock geology for the Vallon de Nant / Vallon de La Vare, Switzerland (looking towards the south-west) transferred onto a finite element mesh with initial hydraulic conductivity values assigned (red:high, blue:low).

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