ALTERED HYDROLOGICAL AND SEDIMENT DYNAMICS IN HIGH-ALPINE AREAS – EXPLORING THE POTENTIAL OF MACHINE-LEARNING FOR ESTIMATING PAST AND FUTURE CHANGES

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Abstract

Climate change fundamentally transforms glaciated high-alpine regions, with well-known cryospheric and hydrological implications, such as accelerating glacier retreat, transiently increased runoff, longer snow-free periods and more frequent and intense summer rainstorms. These changes affect the availability and transport of sediments in high alpine areas by altering the interaction and intensity of different erosion processes and catchment properties.

Gaining insight into the **future alterations in suspended sediment transport by high alpine streams** is crucial, given its wide-ranging implications, e.g. for flood damage potential, flood hazard in downstream river reaches, hydropower production, riverine ecology and water quality. However, the current understanding of how climate change will impact suspended sediment dynamics in these high alpine regions is limited. For one, this is due to the scarcity of measurement time series that are long enough to e.g. infer trends. On the other hand, it is difficult – if not impossible – to develop process-based models, due to the complexity and multitude of processes involved in high alpine sediment dynamics. Therefore, knowledge has so far been confined to conceptual models (which do not facilitate deriving concrete timings or magnitudes for individual catchments) or qualitative estimates (‘higher export in warmer years’) that may not be able to capture decreases in sediment export. Recently, machine-learning approaches have gained in popularity for modeling sediment dynamics, since their black box nature tailors them to the problem at hand, i.e. relatively well-understood input and output data, linked by very complex processes.

Therefore, the **overarching aim** of this thesis is to estimate sediment export from the high alpine Ötztal valley in Tyrol, Austria, over decadal timescales in the past and future – i.e. timescales relevant to anthropogenic climate change. This is achieved by informing, extending, evaluating and applying a **quantile regression forest (QRF)** approach, i.e. a nonparametric, multivariate machine-learning technique based on random forest.

The first study included in this thesis aimed to understand present sediment dynamics, i.e. in the period with available measurements (up to 15 years). To inform the modeling setup for the two subsequent studies, this study identified the most important predictors, areas within the catchments and time periods. To that end, water and sediment yields from three nested gauges in the upper Ötztal, Vent, Sölden and Tumpen (98 to almost 800 km² catchment area, 930 to 3772 m a.s.l.) were analyzed for their distribution in space, their seasonality and spatial differences therein, and the relative importance of short-term events. **The findings** suggest that the areas situated above 2500 m a.s.l., containing glacier tongues and recently deglaciated areas, play a pivotal role in sediment generation across all sub-catchments. In contrast, precipitation events were relatively unimportant (on average, 21 % of annual sediment yield was associated to precipitation events). Thus, the second and third study focused on the Vent catchment and its sub-catchment above gauge Vernagt (11.4 and 98 km², 1891 to 3772 m a.s.l.), due to their higher share of areas above 2500 m. Additionally, they included discharge, precipitation and air temperature (as well as their antecedent conditions) as predictors.

The second study aimed to estimate sediment export since the 1960s/70s at gauges Vent and Vernagt. This was facilitated by the availability of long records of the predictors, discharge, precipitation and air temperature, and shorter records (four and 15 years) of turbidity-derived sediment concentrations at the two gauges. **The third study** aimed to estimate future sediment export until 2100, by applying the QRF models developed in the second study to pre-existing precipitation and temperature projections (EURO-CORDEX) and discharge projections (physically-based hydroclimatological and snow model AMUNDSEN) for the three representative concentration pathways RCP2.6, RCP4.5 and RCP8.5.

The **combined results of the second and third study** show overall increasing sediment export in the past and decreasing export in the future. This suggests that peak sediment is underway or has already passed – unless precipitation changes unfold differently than represented in the projections or changes in the catchment erodibility prevail and override these trends. Despite the overall future decrease, very high sediment export is possible in response to precipitation events. This two-fold development has important implications for managing sediment, flood hazard and riverine ecology.

This thesis shows that **QRF can be a very useful tool** to model sediment export in high-alpine areas. Several validations in the second study showed good performance of QRF and its superiority to traditional sediment rating curves – especially in periods that contained high sediment export events, which points to its ability to deal with threshold effects. A technical limitation of QRF is the inability to extrapolate beyond the range of values represented in the training data. We assessed the number and severity of such out-of-observation-range (OOOR) days in both studies, which showed that there were few OOOR days in the second study and that uncertainties associated with OOOR days were small before 2070 in the third study. As the pre-processed data and model code have been made publically available, **future studies** can easily test further approaches or apply QRF to further catchments.