WaSiM – History and Recent Developments

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WaSiM is a physically based, distributed hydrologic model (WaSiM = **Wa**ter balance **Si**mulation **M**odel) that runs on a regular grid and uses a modular system of sub-models to offer the possibility of creating a problem and scale adequate setup. Spatial and temporal resolutions can widely vary from some minutes to some days and some centimeters to some kilometers, respectively, so almost every hydrologic problem can be addressed using an appropriate combination of sub-models in an appropriate resolution. That also means, that effective parameters for the dominating processes must be estimated and that the cells must be sized according to that process (a so called elementary area) and that the model must run in a matching temporal resolution. Internally, many processes are even able to automatically run on much shorter sub time steps.

WaSiM is a portable application, able to run on almost every hardware platform. There are versions for 32 and for 64 bit operating systems, running on Windows, Linux/Unix, Android and even on High Performance Computers (HPC, also called supercomputers). WaSiM is available in versions for parallel processing by either using OpenMP (**open** **M**ulti**P**rocessing) or MPI (**M**essage **P**assing **I**nterface) or a combination of both. Thus, WaSiM is ready to be used for even extremely large model domains of multiple Millions of cells - if sufficient hardware resources are available. WaSiM and it's help tools (e.g. tanalys, grid-tools, time series tools) are freely available to be used for any purpose.

The development of WaSiM started in 1995. Between 1995 and 1999 the above described basic concepts were established which are still valid today. The first version using the Topmodel-approach for soil moisture and runoff modeling was complemented in 1999 by the much more sophisticated Richards-version, which was the basis for a number of new modules like the multi-layer 2D-groundwater model, the tracer and solutes component, silting up, surface routing and heat transfer module. Today, both versions are still supported, although newly implemented features will be provided for the Topmodel version only if they are completely independent of the soil model (e.g. glaciers).

Actual implementation encompass small scale applications for basic research in arctic research areas or on habitat scale in warmer climates, watershed scale rainfall-runoff studies, basin scale flood forecasting applications and various scenario analyses, either for short time flood forecasting or for long term climate change, including glacier retreats. Anthropogenic impacts on flow regimes can be handled by managing reservoirs, abstractions and inflows as well as by using irrigation schedules or time variant land use schemes.

Near future developments will focus on physically based processes of heat and water transport through the snow cover, solving the energy balance at the surface and modelling ice on lakes and rivers. Also, a module supporting the user during the calibration by providing some semi-automated calibration is planned.

Areal hydrological modelling of Bavaria within the cooperation project KLIWA

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The cooperation project KLIWA

The Bavarian Environmental Agency (LfU) has been analysing the consequences of climate change for water management within the project KLIWA (Klimaveränderung und Konsequenzen für die Wasserwirtschaft) since 1999. Together with its partners in the administrations of Baden-Württemberg and Rheinland-Pfalz as well as the German Meteorological Service it is focussing on estimating the impact of climate change on the hydrology of river basins. The consequences for the different catchments are assessed in detail in order to derive regional adaptation recommendations and sustainable concepts for water management policy (www.kliwa.de).

Methodological approach

For the analysis of future changes in hydrology due to climate change, regional climate projections coupled with hydrological modelling are essential. Therefore, since 2001, the LfU has either set up or commissioned the assembling of a total of 18 hydrological models with WaSiM for about 90.000 km². The modelling on a daily time step and a 1x1 km resolution had to incorporate the inflows to Bavaria like the Upper Danube or the River Inn in addition to the total area of Bavaria itself.
In the beginning, the hydrological models were implemented with the TOPMODEL soil model and set up one after another. In 2009 the LfU switched to the Richards-Version of the soil model. With this there was also a shift to implementing several hydrological models with WaSiM at once, allowing for a more homogenous parameterization between the several models, but also raising new challenges such as the performance of WaSiM in the process. Since 2001 much experience could be gained in using hydrological models in WaSiM, on which further modelling and analysis oriented itself. For example, developing expansions for the meteorological interpolation (regional superposition) or the implementation and regulation of reservoirs was necessary for modelling some Bavarian catchments sufficiently at all.
At the same time, other sometimes better, input data became available. For example additional meteorological reference datasets, which had to be assessed and if applicable incorporated into the models. The demands of the LfU on hydrological modelling and therefore on the WaSiM-models itself have changed as well. With this, the applied calibration strategy developed: at the moment, good results are produced using automated calibration for a high number of catchments and a simultaneous optimisation of several sub basins at once. Aims of the calibration are a good reproduction of the water balance as well of the high and low flows.
Present questions are raised in particular with further use of climate projections, like the sensitivity of the hydrological model towards biased meteorological input data of climate projections. There are also weaknesses in the snow modelling over very long time periods, which have to be addressed.

Application of the WaSiM-models – changes in hydrology

The results of the hydrological modelling with regional climate projections are regional runoff projections. They characterize a possible future hydrological regime over a certain time period, dependent on the chosen scenario. Therefore, only runoff averaged over a time period of a minimum of 30 years can be analysed, to differentiate between natural variability and long term changes. Usually, the averages of 30 year periods are compared, for example 1971-2000 and 2021-2050, to identify the changes in the hydrological regime. The current modelling results in regard to climate related changes in hydrology will be published shortly in regional runoff reports for Bavaria.

Use of WaSiM within the operational flood forecasting system of Switzerland

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For more than six years the Swiss Federal Office for the Environment (FOEN) provided operational discharge and water level forecasts based on the coupling of high-resolution weather prediction products and hydrological models. At the beginning hydrological forecastings were limited to the use of a rather simple conceptual HBV model approach and not available for whole Switzerland but only for its northern part.
Since 2010 some effort has been invested to reduce these deficiencies within the operational forecasting system at FOEN. The work, which is not yet finished, mainly focuses on two objectives: (a) to improve the hydrological model tool box and (b) to expand the forecasting area from the Swiss Rhine river basin to the river basins covering the total area of (hydrological) Switzerland.
One of the tools newly entered in the forecasting system of FOEN is the area-distributed model WaSiM. Not long ago it has been even selected to apply to whole Switzerland. The reasons for this model choice were manifold. First of all, WaSiM is well-equipped to deal with the special hydrological conditions found in many alpine river basins (e.g. glaciers, lake control mechanisms or hydrological impacts of hydropower stations). Secondly, there is a large pool of model experiences because WaSiM has been tested and applied to several pre-alpine and alpine river basins in Switzerland over the last two decades. And thirdly, the model could be successfully integrated into the FOEN forecasting system. Herein it is configured to simulate three Swiss river basins of different hydrological characteristics and with area sizes between 1'000 and 6'000 km^2.
The presentation will focus on these WaSiM applications. It will be shown the hydrological specialities of the three pre-alpine and alpine river basins (Emme, Rhone, Alpenrhein) as well as the developed model setups and obtained results. Finally, it will be presented the further working plans with WaSiM at FOEN.

Process-based simulation of distributed flood control measures

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This thesis deals with a process-based simulation of distributed flood control measures like land use changes or differing soil tillage practices, small retention ponds and restoration of rivers to quantify their flood reducing effects. In this context various challenges have to be met because these measures have different impacts on the total rainfall runoff process including runoff generation, runoff concentration and flood routing. For this a combined modeling approach is chosen, containing the physically based rainfall runoff model WaSiM (Version 8.4.2, SCHULLA 1997) and the 2D hydrodynamic numerical model HYDRO_AS-2D (NUJIC 1998). Inter alia the models are parameterized by the results of field studies.

These measurements are used to prove the influence of the different types of land use (grassland, forest, arable land) on soil hydraulic properties. Therefore they are necessary to get a land use depending parameterization of the soil model in WaSiM-ETH. The measurement results show that grassland soils have the best infiltration and water storage properties compared to the other types of land use. Furthermore, the collected data contribute to identify the best fitting pedotransfer function for the study area, which is important to minimize uncertainties regarding the use of different types of pedotransfer functions in a physically based rainfall runoff model.

After constructing, parameterizing and calibrating the models, they are coupled with an offline-connection by adding the runoff of each sub basin in WaSiM-ETH to HYDRO_AS-2D as boundary conditions. The calibration results with a high fitting quality demonstrate that the chosen coupled modeling approach can be applied for further research.

The distributed flood control measures are parameterized by the use of field and laboratory data, different literature sources and historical marshland and drainage maps. Subsequently their flood reducing effectiveness is quantified for different flood events and the rurally characterized mesoscaled study area of the Windach catchment (AEZG = 65 km²). The simulation results show that this effectiveness is influenced by different parameters, e.g. the course of the hydrograph, the peak flow or the runoff volume, depending on the respective measure. The measures show the highest potential when realized in the form of an integrated concept including retention ponds, restoration of rivers and marshlands as well as afforestation. In this case the peak flow can be reduced by 11 % (HQ100 advective event) to 26 % (HQ60 convective event). The small retention ponds (max. 50000 m³) have turned out to be the most effective individual distributed flood control measure, which all principally have the highest potential in the case of a convective event.

The assessment of natural flood management measures as a climate change adaptation option through land use scenarios

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Climate change is one of the most pressing issues facing civil society. Greater variability and more frequent extremes of temperature and precipitation will result in increased flood risk and corresponding social, economic and environmental impacts. Complementing more traditional structurally-based engineering interventions, an important additional adaptation strategy is through natural flood management (NFM) measures utilising natural soil, wetland and groundwater storage at the catchment scale to attenuate runoff generation and downstream flooding. Such schemes have multiple co-benefits including improved water quality, biodiversity and amenity and so contribute to greater resilience to uncertain climate futures. As a case-study of a more integrated approach to land use planning, we here consider the policy target of the Scottish Government to expand woodland in Scotland by 100,000 ha by 2025. In this paper we examine runoff response under different woodland expansion scenarios using climate projections obtained from the UK Climate Projections (UKCP09). Woodland creation has recognised potential as a NFM measure, but locating this new planting is constrained by physical and cultural constraints. Land use choices in the future will also strongly reflect emergent socio-economic contexts, here captured using scenario analysis. The distributed hydrological model WaSiM-ETH was utilised for the analysis using the case-study of the Tarland catchment, a tributary of the River Dee. Terrain data were obtained on a 50 m grid and the model calibrated using meteorological and river gauge data from 2005 to 2007. This novel approach highlights that land use change should be carefully managed for planned benefits and to avoid unintended consequences, such as changing the timing of tributary flood responses. Whilst woodland expansion may only provide modest gains in flood reductions the co-benefits contribute to a coherent ecosystem-based adaptation strategy promoting landscape resilience at the landscape scale.

Water-balance and runoff components in the Weser river basin simulated by WASIM-ETH - Validation by means of tritium balances

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The demands that are currently placed on water-balance models are increasing, for instance when these are expected to supply valid evapotranspiration data for climate-impact research or coherent runoff components for studies of non-point mass transport. That is why additional information should be included in their calibration and validation besides the measured/simulated runoff time series.
Parameterization and model outputs of the spatially distributed, process-oriented water-balance model WASIM-ETH in the 46,000 km^2 Weser river basin are compared or respectively combined with the results of other approaches. The project under consideration here that dates from the year 2008 uses besides previously not available thematic and hydro-meteorological input data in areal coverage such approaches like the hydrograph-separation method DIFGA2000 to characterize runoff components and their mean retention times (direct flow, interflow) and to validate mass-transport approaches by means of tritium-isotope data and the balancing model TRIBIL. Moreover, the long-term time series of observations and model outputs from 1951 to 2005 allow to analyze changes of water-balance components.

The present paper deals with several aspects of the parameterization of the daily time-step model WASIM-ETH that is available in a version with a 1 km x 1km raster and another one with 2 km x 2 km raster. The coupling with the mass-transport model TRIBIL is achieved by transfer of the water-balance data that are aggregated as monthly values and for eight sub-basins. In comparison with other forcing data of isotope-hydrological modelling, one finds that using the WASIM-ETH generated area-distributed and methodologically based input data achieves a better agreement between simulated and observed tritium concentrations. However, conversely the calibration of the water-balance model WASIM-ETH by means of the outputs of TRIBIL is not possible because of the very different model resolutions and the different storage concepts. For this reason, the mass-transport module of WASIM-ETH was tested additionally. Although it was found to be suitable in principle, there is still a considerable need for modelling efforts regarding the transport of tritium, because certain processes like the isotope fractioning during evapotranspiration cannot be neglected. Nevertheless, it can be assumed that coupled water-balance and mass-transport models together with isotope-tracer measurements can make a valuable contribution to the characterization of subsurface water storage and thus support the quantification of the storage characteristics and ultimately the sustainable use of the water resources.

Observed pan-arctic ice wedge degradation in continuous permafrost and modeled effects on watershed-scale hydrology

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Wetlands underlain by ice wedge polygons occupy a significant portion of Arctic terrestrial landscapes. The different types of ice wedge polygons, i.e. low- and high-centered, with and without well-developed troughs and pits, can cause major differences in the hydrologic cycle that ultimately impacts habitat availability, connectivity and quality of aquatic ecosystems. By using a collection of satellite imagery, ground and aerial photos, we present observations of recent historical ice wedge degradation at multiple locations within the continuous permafrost zones of North America and Eurasia. The subsequent ground subsidence, which is documented at places to have occurred within a10 yr time period or less, has resulted in major surface water alterations leading to increasing moisture contrasts across the landscape. Informed by the satellite, aerial and in-situ image observations, our hydrologic model experiments explore the impacts of polygon, and specifically trough-type, on watershed-scale water balance components with a focus on the extent and duration of surface water availability and connectivity. We are here activating the 1D soil heat transfer (conduction and advection) module, which is linked to the saturated and unsaturated hydrology, and overland flow module in WaSiM. Aimed at simplifying the landscape, the scenarios suggest the importance troughs characteristics in laterally connecting landscape-scale hydrology, controlling heterogeneous distribution of snow and therefore, impacting surface water extent and duration. We propose that not accounting for the ice wedge polygon topography, including ground subsidence or the lack thereof, undermines the effectiveness of any short- (<10 yr) to long-term (>10 yr) projections of local to regional hydrology in the majority of Arctic permafrost lowlands. The hydrology of landscapes underlain by permafrost is likely to respond dramatically to climate change and effective projections require a representation of ice wedge polygon morphology.

Assessing the role of glacier and permafrost on northern hydrology

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Recent observations of melting glaciers and thawing permafrost are impacting cold region hydrology through complex processes. Rarely are permafrost and glaciers studied as part of a coupled hydrologic system, which represents large areas in North America and Eurasia. We are starting a project on Jarvis Creek watershed (~650 km^2), Interior Alaska, to assess the importance of glacier wastage and permafrost on lowland hydrology. Permafrost and glacial features are important for this region so defining their role on watershed scale hydrology provides valuable insights for sustainable development. Here, we are especially interested WaSiM's heat transfer, snow cover and glacial hydrology components, which are crucial for modeling cold region water budgets.

Major goals of our study are a) to assess the hydrologic pathways of glacier wastage within a watershed underlain by discontinuous permafrost; b) to quantify the effect of glaciers and permafrost on watershed-scale hydrologic fluxes (runoff, aquifer recharge) and storage; c) to project the future hydrologic regime using custom designed downscaled climate projections with a special emphasis on potential changes in wetland distribution. We will address the objectives by using WaSiM and field measurements. We will force the model using historical data, field measurements supported by this effort and climate projections. Field measurements of glacier melt, runoff, groundwater levels, snow accumulation and geochemical signatures will support thorough model calibration and validation. An increase in the amount of melt water from the glacier, streamflow, and aquifer recharge may amplify permafrost thawing, which subsequently may affect watershed response on rainfall and glacier melt events.

Permafrost and glaciers are sensitive to climate change and our study aims to provide increased understanding of how northern rivers may react to changes in cryosphere. Ultimately, the general findings may be upscaled or applied to other similar regions.

Potential of modelling rain-on-snow floods with WaSiM

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On October 10th, 2011, a rain-on-snow flood occurred in the Bernese Alps, Switzerland, and caused significant damage. As this flood peak was unpredicted by the flood forecast system, questions were raised concerning whether this flood was predictable with other hydrological models, such as WaSiM.

We identified 80 more rain-on-snow events for a meso-scale catchment in the Bernese Alps of the last two decades. These events are both floods and small rain-on-snow events with only little change in the discharge which appeared in different seasons. For the same catchment a model version of WaSiM version 9.2 was set up. The focus of the model set up was in particular on a well simulation of snow accumulation and melt processes. Therefore, in addition to runoff data snow measurements were used for the calibration of the model. The new model section "special_output" was of great help to allow the comparison of modelled snow water equivalent at one point with data from a gauging station. From literature it is known that the simulation of rain-on-snow events requires a snow model which considers latent and turbulent heat flux such as the snow module 3 in WaSiM. The set up model version is able to simulate mean water balance and small rain-on-snow events up to 25 mm liquid precipitation (catchment mean) well but it underestimates rain-on-snow peaks of events with more than 25 mm liquid precipitation.

For that reason a couple of parameters of the existing model version were post-calibrated by two of the identified rain-on-snow events with more than 25 mm liquid precipitation. The resulting second model version simulates the events with more than 25 mm liquid precipitation much better, with a difference in modelled and observed peak of less than +/- 25% for almost all of these events. Not surprisingly the two model versions differ by the two recession parameter for direct flow (Qd) and interflow (Qi). However, the largest difference in the two model versions results from the parameter which determines the fraction of surface runoff from snow melt (SF) followed by the wind dependent melt factor of snow (C2). About half of the improved estimation of rain-on-snow floods with more than 25 mm liquid precipitation results from increasing the parameter SF from 0.28 up to 0.6.

In another alpine catchment, a second retrospective analysis of the rain-on-snow flood partly confirms these results in terms of snow module choice and relevant parameters. In addition, it shows that the parameter SF conceptually represents the fast runoff responses during a rain-on-snow-event. However, detailed sub-catchment scale information about meteorological input variables enables the representation of the flood peak with adjusted c2, Qd, and Qi parameters, only. These applications show that rain-on-flood events can be simulated in meso-scale alpine catchments with WaSiM with the use of the snow model that considers latent and turbulent heat fluxes (snow model 3). The key parameters relevant for simulating processes are identified for further studies. These adjusted models can now be used in the operational forecast or for climate change impact studies focusing on the occurrence of rain-on-flood events.

Comparing WaSiM-ETH to HBV-light in Climate Change Impact Assessments – Advantages and Disadvantages

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As part of the research project „Innovation Network Climate Change Adaptation Brandenburg/Berlin (INKA BB)“, climate change impact assessments are conducted in three subcatchments of the anthropogenically heavily impacted Spree and Schwarze Elster River catchments (Germany). For this purpose, WaSiM-ETH (Model Version 8.5 with Richards equation and 2D groundwater approach) and the lumped conceptual model HBV-light are used in order to estimate the uncertainty related to hydrological models within the climate change modeling chain. In order to concentrate only on the structural model differences, the data input, namely interpolated precipitation, temperature and potential evapotranspiration, is identical between the two models.

WaSiM-ETH was initially parameterized manually. Especially when using the 2D groundwater approach, this is time consuming and requires considerable system understanding. After manual model parameterization of the physical characteristics of the catchment, only four effective parameters were calibrated automatically using the Model Independent Parameter ESTimation program (PEST). The parameters of HBV-light, as characteristic for almost all conceptual models, are not physically measurable. Hence, its parameters are calibrated automatically based on three different objective functions using a genetic algorithm. The calibrated model versions are then applied in an ensemble based climate change impact assessment.

The results of this study show that applying the 2D groundwater approach implemented in WaSiM-ETH can be challenging, especially in low land catchments where surface and subsurface catchment boundaries do not necessarily coincide and may not temporally be fixed. Thus, closing the water balance becomes a difficult task. At the same time, after careful model parameterisation of WaSiM-ETH, high performance indicators concerning discharge are already achieved so that the automated model calibration using PEST, only marginally increases model performance. Yet, a validation of measured groundwater levels was not possible. HBV-light, on the other hand, requires extensive model calibration before achieving high model performance.

Even though both models agree well with the measured discharge after calibration and validation, the partitioning of precipitation in actual evapotranspiration and discharge differs between the two hydrological models. The same is true for the climate change impact assessment; although the long term water balance components of the two hydrological models are overall comparable.

Consequently, when only concentrating on discharge predictions, the application of HBV-light may be sufficient. WaSiM-ETH, however, has the great advantage that it can be used to analyse internal catchment processes, which may be of great relevance for integrated river catchment planning and management, and the formulation of climate change adaptation strategies. This is, however, offset by its high model parameterisation effort and long calculation times.