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Model selection for the Tibetan plateau water balance monitoring system

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Preface

This report is written in the framework of the "Coordinated Asia-European long-term Observing system of Qinghai–Tibet Plateau hydro-meteorological processes and the Asian-monsoon systEm with Ground satellite Image data and numerical Simulations" (CEOP-AEGIS) project funded by the 7th framework programme of the European commission (EU-FP7). The report describes an assessment of several hydrological models that will be used in combination with remote sensing datasets of precipitation, evapotranspiration, soil moisture and the cryosphere in the assessment of the water tower function of the Tibetan plateau. The authors would like to acknowledge the financial support of the European Union (EU FP7 FP7 ENV.2007.4.1.4.2 under Grant Agreement Number 212921).

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1 Introduction

CEOP-AEGIS stands for "Coordinated Asia-European long-term Observing system of Qinghai–Tibet Plateau hydro-meteorological processes and the Asian-monsoon systEm with Ground satellite Image data and numerical Simulations". It is a Collaborative Project / Small or medium-scale focused research project – Specific International Co-operation Action financed by the European Commission under FP7 topic ENV.2007.4.1.4.2 "Improving observing systems for water resource management", and is coordinated by the Université Louis Pasteur, Strasbourg, France.

Human life and the entire ecosystem of South East Asia depend upon the monsoon climate, its linkage to major rivers and its predictability. The headwater areas of the Yellow River, Yangtze, Mekong, Salween, Irrawaddy, Brahmaputra and Ganges, are located in the Tibetan Plateau. However, estimates of the Plateau water balance rely on sparse and scarce observations that cannot provide the required accuracy, spatial density and temporal frequency. Integrated use of satellite and ground observations is necessary to support water resources management in SE Asia and to clarify the interactions between the land surface and the atmosphere over the Tibetan Plateau in the Asian monsoon system.

The goal of this project is two-fold:

- To construct out of existing ground measurements and current / future satellites an observing system to determine and monitor the water yield of the Plateau, i.e. how much water is finally going into the seven major rivers of SE Asia;
- To monitor the evolution of snow, vegetation cover, surface wetness and surface fluxes and analyze the linkage with convective activity, (extreme) precipitation events and the Asian Monsoon.

The effort of this project builds upon 10 years of experimental and modelling research and the consortium includes 17 partners from 8 countries, all key-players and pioneers of this long term research initiative. Three main elements are foreseen:

- Observations of the terms of the water balance: precipitation, melt water from snow and glaciers, changes in soil water content and evaporation for a period of three years will be generated by integrating ground and satellite measurements on weekly and monthly basis.
- Radiative transfer models and algorithms will be developed for different regions of the electro-magnetic spectrum.

- The water balance of the Plateau will be calculated with a distributed hydrological model. Interactions of land surface hydrology with convective activity and the Asian Monsoon will be investigated by using a meso-scale atmospheric model.
- The time-series of image data will be used to demonstrate a Drought and a Flood Early Warning Systems.

The project will deliver a prototype Water Balance Monitoring System (WBMS) and a three year data set including observations of the water balance terms on weekly and monthly basis. The system will reply on an existing and expanding network of observatories and on space-borne observing systems for which data continuity is guaranteed. A Database Management System will be put in place in Lhasa and operated by a research organization. It is highly likely that the system will remain in operation beyond project completion. These observations will contribute to clarify the role of Plateau hydrology in the onset and intensity of the Asian Monsoon and in intense precipitation. The time-series of hydrological satellite data products will be used to demonstrate an Early Warning system on droughts and one on floods.

The project is organized in 11 different work packages:

- WP0: Project management
- WP1: Ground based observations of radiative and convective turbulent fluxes and soil moisture
- WP2: Satellite observation of vegetation cover, of surface albedo and temperature
- WP3: Satellite based estimates of energy and water fluxes
- WP4: Satellite based estimates of top soil moisture
- WP5: Integrated ground and satellite observations of precipitation
- WP6: Estimation of glaciers and snow melt water
- WP7: Numeric weather and climate prediction modelling system
- WP8: Monitoring the water balance and water yield of the plateau
- WP9: Satellite based drought monitoring system of pilot areas
- WP10: Satellite based flood monitoring system of pilot areas
- WP11: Dissemination and stakeholder's panel

This report focuses on WP8 which brings together data from other WPs in a WBMS. As a first step the modelling system that forms the core of the WBMS will be selected. This report first describes WP8 in detail and the requirements for such a WBMS. Then a number of candidate models are evaluated and a model is selected.

2 Monitoring the water balance and water yield of the plateau

Quantifying the spatial and temporal relationships between the different water balance terms for the entire Tibetan Plateau is a key-focus of the project. WP8 aims at the integration between a conceptual, distributed hydrological model and the spatial information that will be provided by E.O. in other work packages on vegetation cover, albedo, energy fluxes, precipitation, snow-melt and top soil moisture. The final result will be a prototype water balance observation system for the entire Tibetan plateau that enables straightforward quantification of the water yield being supplied to downstream areas. A spatio-temporal water balance will be derived after standardizing and re-scaling the E.O. products derived in other WPs. A hydrological model will be build that embeds the E.O. data and provides insight in the runoff accumulation across the Tibetan plateau also for large tracts of the Plateau that are ungauged. Finally, the effects of climate change in the water yield of the plateau will be quantified using the thus calibrated water balance observation system.

There are three key considerations to be taken into account when embedding E.O. products in a hydrological model.

2.1 Integration with E.O. products

Firstly, EO products can be integrated in hydrological modelling in different ways (Immerzeel and Droogers, 2007). In this project priority will be given to the use of EO products in model forcing (Droogers and Bastiaanssen, 2002; Boegh et al., 2004; Houser et al., 1998; Kite and Pietroniro, 1996; Shuttleworth, 1998; D'Urso, 2001) and validation (Schuurmans et al., 2003; Campo et al., 2006; Immerzeel and Droogers, 2007). The direct integration with deliverables from other work packages is described in detail below.

2.1.1 Model forcing

The EO forcing parameters will consist of direct inputs into the model such as precipitation, evapotranspiration, snow and ice dynamics and vegetation and land cover parameters. This data will be produced under the other work packages:

- WP5 will produce a continuous set of precipitation maps with a high temporal and spatial resolution by integrating the Doppler radar network on the Tibetan plateau, satellite data and ground rain gauge data. These data will be used to force the distributed hydrological model with a pixel size of approximately a few square kilometres.
- WP6 will provide a validated dataset on daily snow cover extent, snow water equivalent, glacial area and storage dynamics for a multi-year period. These datasets will be used to force the hydrological model by either directly linking snow and ice extents on a daily basis or by expressing the snow and ice dynamics as water equivalent and force them on the model as a boundary condition. This depends on the final model selection.
- WP2 will produce a continuous dataset for a three year period that include important model parameters such as vegetation cover, surface albedo and leaf area index. The data can be directly used to parameterise the model. The level of integration will depend on the choice of model.
- WP3 will produce low resolution maps of all components of the energy balance based for the entire Tibetan plateau with a target frequency of one week. The latent heat flux, specifically, will be used subsequently to force the hydrological model after conversion to actual evaporation rates.

2.1.2 Calibration and validation

Most hydrological models are sensitive to effective rooting depth, infiltration capacity, water holding capacity and curve numbers. These common model parameters will be optimized used advanced mathematical tools developed for this purpose. Different sources of information will be used to calibrate and validate the model depending on data availability. Firstly, top soil moisture will be derived in WP4 by combining passive and active microwave sensor and the Chinese geostationary satellite Fengyun. Secondly, data on river discharges (pending availability) will be used to further refine model parameterization.

2.2 Model selection

There is a wide variety of hydrological models available and the choice of model depends on the physical and spatial scale required for the field of application. Since, a major objective of the project is the development of an E.O. based water balance observation system for the entire Tibetan plateau with a specific focus on the water yields to downstream areas. This report describes the assessment of different models and a set of candidate models will be judged on a set of different criteria.

2.3 Spatial and temporal scale

There is also a spatial scale issue to be addressed. The E.O. products produced by WP2 to WP6 all have specific temporal and spatial resolutions depending on the sensors and underlying algorithms. For example, precipitation products have an approximate spatial resolution of 25 km and temporal resolution of an hour, while latent heat fluxes have weekly frequency and a resolution of one kilometre and top soil moisture is 25 km. At the same time, the spatial discretization of the hydrological model network is varying greatly between the models. The spatial and temporal resolution of the E.O. products needs to be matched to a single optimum value by developing and implementing a number of down-scaling and disaggregating methodologies. This is a rather new field of research where multiple GIS and EO data layers co-exist (e.g. soil type, terrain elevation, land cover, surface temperature etc.). The guiding principle is to prevent loss of information in time or space. This continuous dataset will then be used in forcing and calibrating the model. While the EO data are all raster based, most hydrological models divide a catchment into sub-areas separated by water divides and discretize the area into specific combinations of soil type and land use. The resulting calculation units or Hydrological Response Units do physically exist only in the case of contiguity; in composite landscapes, elements of the landscape are computed separately, and are afterwards hydrologically connected by groundwater and surface water flow routing. These individual hydrological units - for which vertical water balances are computed - have the character of a polygon, being a basic mismatch with the raster data from EO.

The calibrated model will be used to monitor all water balance components across the plateau and will subsequently be used to model the potential impacts of climate on the water yield by forcing the model with a downscaled set of climate model simulations for the major storylines reported by IPCC (2007).

The development of the WBMS is schematically shown in Figure 1.

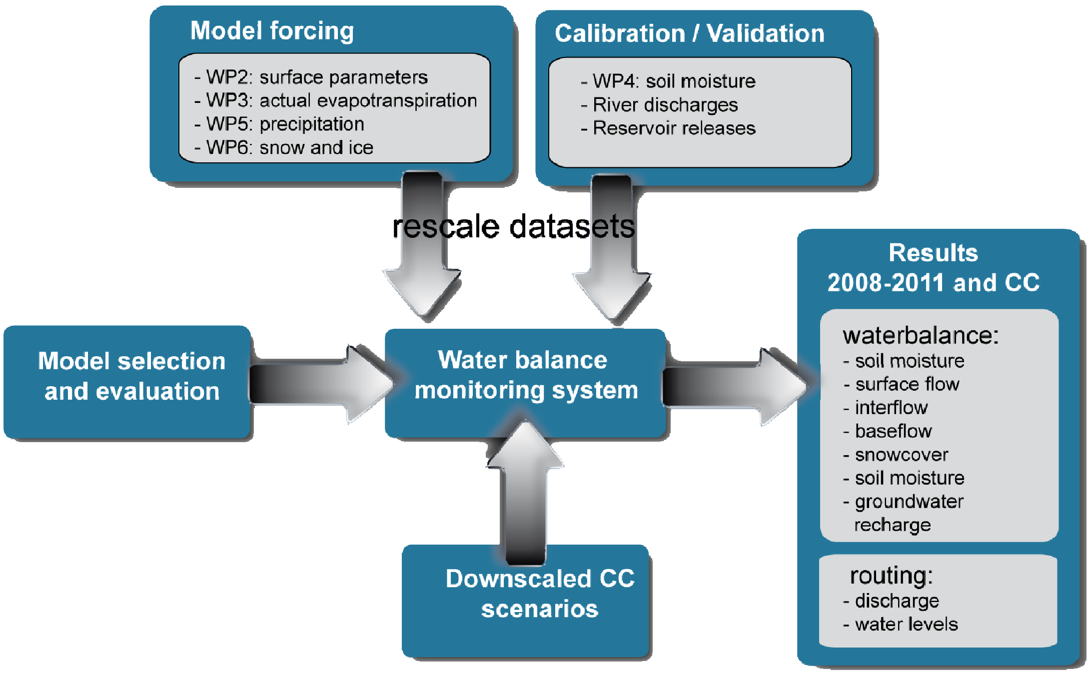


Figure 1: Schematic representation of the WBMS development

The objectives of WP8 can be summarized as:

- Integrated analysis of ground and satellite observations to estimate the Plateau water balance
- Develop and demonstrate a prototype observation system to monitor Plateau water yield
- Investigate potential impact of climate change of the Plateau water balance

3 Model requirements

3.1 Assessment criteria

The basic criteria for the model can be summarized as follows:

- The spatial land surface schematisation of the model should be detailed in such a manner that integration with E.O. products is warranted.
- The model should recognize direct forcing of daily grids of ET, precipitation and snow cover
- Model outputs include all components on the water balance at sufficient level of temporal and spatial detail. This is specifically true for top soil moisture, which will be used for validation.
- The model includes algorithms related to snow melt, infiltration, surface runoff, drainage, percolation and groundwater base flow.
- The model should be able to incorporate glacial melt in a lumped mode.
- The model should be able to deal with permafrost processes.
- The model needs to include a (horizontal) routing component that allows accumulation of runoff across the Tibetan plateau.
- The Tibetan plateau includes number of large lakes and artificial reservoirs. The model routing component needs to be able to take into account storage variation in lakes and artificial reservoirs and the resulting delay in water yield.
- The model source code must be accessible and customizable.

Each candidate model is described according to the basic criteria above and based on these criteria an indicator list is composed that is used to make the final selection of the model. The different indicators have different weights. Besides the criteria discussed above a number of soft criteria such as model efficiency, code availability and support from the developers have been included as these are crucial in successful model development.

Table 1 Weight of the different indicators

Indicator	Weights
Spatial discretization	5
Soil water balance	4
Data requirements	4
Permafrost	1
Forcing P by EO	3
Forcing ET by EO	4
Forcing snow by EO	1
Routing	5
Lumped glaciers	2
Lakes and reservoirs	3
Detailed outputs	3
Model efficiency	4
Code availability	5
Support from developers	5

3.2 Spatial domain

Tibet is situated in the south-western part of China between 27.20 and 36.70 degrees latitude and 78.20 and 99.10 degrees longitude and borders India, Nepal and Bhutan. The total area is over 1.2 million square kilometres. The elevation ranges from 700 meter above sea level (m.a.s.l.) in the south-east to the summit of Mt. Everest at 8848 m.a.s.l, with an average elevation over 4000 m.a.s.l.. (Figure 2).

The mountains of Tibet constitute the headwaters of many of Asia's major rivers (Mekong, Indus, Ganges, Salween, Brahmaputra, Yellow river, Yangthze). Tibet's high altitude, huge landmass and vast glaciers endows it with the greatest river system in the world. Tibet's rivers flow into the most populous regions of the world, supplying fresh water to a significant proportion of Asia's population. Historically, negligible utilisation rates in Tibet meant that nearly all of this water was transferred to countries in downstream basins including India, Nepal, China, Bangladesh, Pakistan, Bhutan, Vietnam, Burma (Myanmar), Cambodia, Laos and Thailand.

Tibet's fresh water availability in the river systems is relative high while precipitation is low (~600 mm/year). A major part of river flow originates from glaciers, with a total area of approximately 43,000 km^2 and groundwater sources. These sources make river flow less dependent of rainfall and result in a stable base flow. Since Asia is dominated by monsoon patterns of rainfall, bringing rain for only a few months (usually three months) of the year, the perennial flow of its rivers relies upon the constant flux of glaciers on the Tibetan Plateau.

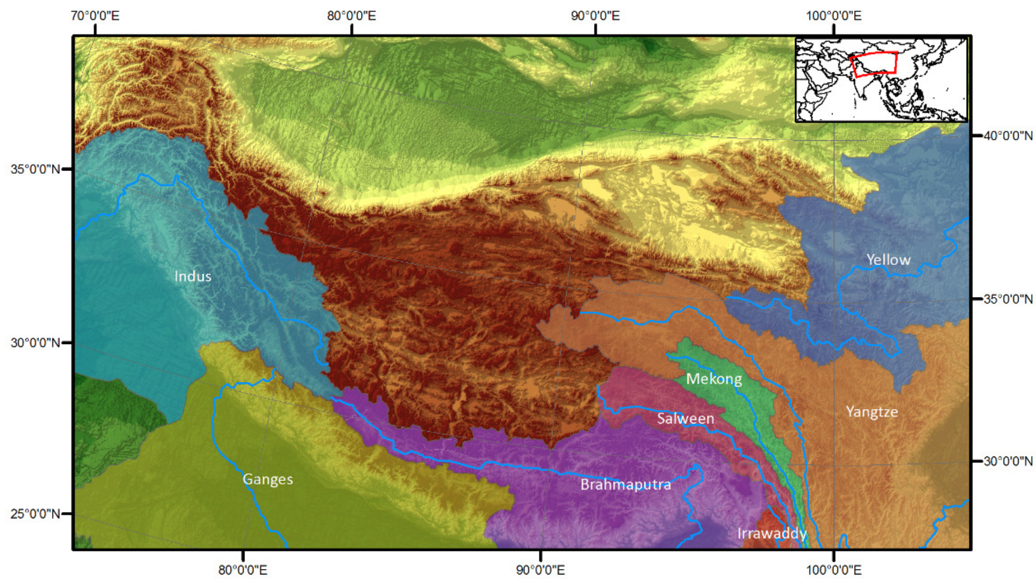


Figure 2: Spatial domain and basin boundaries of major Asian river basins.

The WBMS will cover the entire domain of the Tibetan plateau including all headwater of the major river systems as shown in Figure 2.

3.3 Resolution

The resolution is a compromise between the outputs of the different RS algorithms, the model to be used and the required level of detail. A raster based model is a prerequisite for the WBMS and a grid size between 5-25 km is desirable. The final choice depends on the selected model and the model efficiency.

3.4 Projection

The features on a map reference the actual locations of the objects they represent in the real world. The positions of objects on the earth's spherical surface are measured in geographic coordinates. While latitude and longitude can locate exact positions on the surface of the earth, they are not uniform units of measure; only along the equator does the distance represented by one degree of longitude approximate the distance represented by one degree of latitude. To overcome measurement difficulties, data is often transformed from three-dimensional geographic coordinates to two-dimensional projected coordinates.

Because the earth is round and maps are flat, getting information from a curved surface to a flat one involves a mathematical formula called a map projection. This process of flattening the earth will cause distortions in one or more of the following spatial properties:

- Distance
- Area
- Shape
- Direction

No projection can preserve all these properties; as a result, all flat maps are distorted to some degree. Each projection is distinguished by its suitability for representing a particular portion and amount of the earth's surface and by its ability to preserve distance, area, shape, or direction. Some map projections minimize distortion in one property at the expense of another, while others strive to balance the overall distortion.

Map projections can be generally classified according to what spatial attribute they preserve.

- Equal area projections preserve area. Many thematic maps use an equal area projection. Maps of the United States commonly use the Albers Equal Area Conic projection.
- Conformal projections preserve shape and are useful for navigational charts and weather maps. Shape is preserved for small areas, but the shape of a large area, such as a continent, will be significantly distorted. The Lambert Conformal Conic and Mercator projections are common conformal projections.
- Equidistant projections preserve distances, but no projection can preserve distances from all points to all other points. Instead, distance can be held true from one point (or a few points) to all other points or along all meridians or parallels.
- Azimuthal projections preserve direction from one point to all other points. This quality can be combined with equal area, conformal, and equidistant projections, as in the Albers Equal Area Azimuthal, Lambert Equal Area Azimuthal and the Azimuthal Equidistant projections.
- Other projections minimize overall distortion but don't preserve any of the four spatial properties of area, shape, distance, and direction.

In case of the Tibetan plateau the choice of projection is very important because we deal with an extremely large area (over 1 million km^2) that is irregularly shapes and is wider in east-west direction than in north south direction. For hydrological analysis purposes conservations of area is more important than distance, shape or direction. Given these prerequisites the Albers Equal Area is proposed.

3.5 Forcing data

Figure 1 shows that the WBMS will be forced using data from the other work packages. The surface parameters will be provided by WP2, WP3 will provide daily time series of actual evapotranspiration. WP5 will provide daily precipitation fields from the Doppler radar network and WP6 will provide data on snow and ice observations and potential future evolutions. These required links with remote sensing outputs pose serious constraints on the model to be selected for the WBMS.

4 SWAT

4.1 Background

SWAT is the acronym for Soil and Water Assessment Tool, a river basin model developed originally by the USDA Agricultural Research Service (ARS) and Texas A&M University that is currently one of the worlds leading spatially distributed hydrological models. SWAT is a physically based distributed hydrological model that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds (Arnold and Fohrer, 2005; Arnold et al., 1998; Srinivasan et al., 1998). A comprehensive SWAT review paper summarizing the findings of more than 250 peer-reviewed articles is written by Gassman et al., 2007. SWAT represents all the components of the hydrological cycle including rainfall, snow, interception storage, surface runoff, soil storage, infiltration, evaporation, lateral flow, percolation, pond and reservoir water balances, shallow and deep aquifers and channel routing (Figure 3). It also includes land use management such as irrigation.

SWAT has been used throughout the world in a wide range of conditions. The source code is publicly available and changes to model that are required to link the remote sensing products to the model (e.g. bypass the evapotranspiration calculation and use remotely sensed data instead) can be implemented. SWAT is well documented and accompanied by a GIS interface that allows easy set-up of the model.

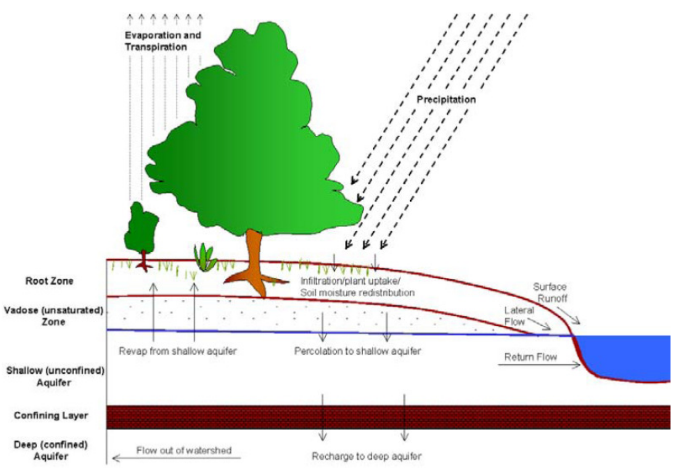


Figure 3: Overview of the hydrological cycle as modelled by SWAT

4.2 Discretization

SWAT divides a catchment into smaller discrete calculation units for which the spatial variation of the major physical properties are limited and hydrological processes can be treated as being homogeneous. The total catchment behavior is a net result of manifold small sub-basins. The soil map and land cover map within sub-basin boundaries are used to generate unique combinations, and each combination will be considered as a homogeneous physical property, i.e. Hydrological Response Unit (HRU). The water balance for HRU's is computed on a daily time step. Hence, SWAT will distribute the catchment into units that have similar characteristics in soil, land cover and that are located in the same sub-basin. These HRUs are the fundamental units of calculation and a major disadvantage for the CEOP-AEGIS project is the fact the HRUs are irregularly shaped and of unequal size. Therefore integration with earth observation products is less straightforward than in the case of a raster based model and this is the major disadvantage of SWAT for use in the project.

4.3 Processes

Precipitation can fall in the form of snow or rain. Part of the precipitation is intercepted by vegetation, part of it is removed as runoff and the remaining part enters the soil. Water that enters the soil may move along several different pathways. The water may be removed from the soil again by plant transpiration or soil evaporation. It can percolate past the bottom of the soil profile and ultimately become aquifer recharge. Or water may move laterally in the profile and contribute to stream flow.

4.3.1 Runoff

Surface runoff, or overland flow, is flow that occurs along a sloping surface. Using daily or subdaily rainfall amounts, SWAT simulates surface runoff volumes and peak runoff rates for each HRU. Runoff is computed using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972) or the Green and Ampt infiltration method (Green and Ampt, 1911). In the curve number method, the curve number varies non-linearly with the moisture

content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation. The Green and Ampt method requires sub-daily precipitation data and calculates infiltration as a function of the wetting front matric potential and effective hydraulic conductivity. Water that does not infiltrate becomes surface runoff. SWAT includes a provision for estimating runoff from frozen soil where a soil is defined as frozen if the temperature in the first soil layer is less than 0°C. The model increases runoff for frozen soils but still allows significant infiltration when the frozen soils are dry.

4.3.2 Infiltration

Infiltration refers to the entry of water into a soil profile from the soil surface. As infiltration continues, the soil becomes increasingly wet, causing the rate of infiltration to decrease with time until it reaches a steady value. The initial rate of infiltration depends on the moisture content of the soil prior to the introduction of water at the soil surface. The final rate of infiltration is equivalent to the saturated hydraulic conductivity of the soil. Because the curve number method used to calculate surface runoff operates on a daily time-step, it is unable to directly model infiltration. The amount of water entering the soil profile is calculated as the difference between the amount of rainfall and the amount of surface runoff. The Green and Ampt infiltration method does directly model infiltration, but it requires precipitation data in smaller time increments.

4.3.3 Drainage

Drainage, lateral subsurface flow, or interflow, is streamflow contribution which originates below the surface but above the zone where the soil is saturated with water. Lateral subsurface flow in the soil profile (0-2m) is calculated simultaneously with redistribution. A kinematic storage model is used to predict lateral flow in each soil layer. SWAT incorporates a kinematic storage model for subsurface flow developed by Sloan et al. (1983). This model simulates subsurface flow in a two-dimensional cross section along a flow path down a steep hill slope. The model accounts for variation in conductivity, slope and soil water content.

4.3.4 Groundwater

SWAT can deal with standard groundwater processes. Water enters groundwater storage primarily by infiltration/percolation, although recharge by seepage from surface water bodies is also included. Water leaves groundwater storage primarily by discharge into rivers or lakes, but it is also possible for water to move upward from the water table into the capillary fringe, i.e. capillary rise. Water can also be extracted by mankind for irrigation purposes. SWAT distinguishes recharge and discharge zones.

Recharge to unconfined aquifers occurs via percolation of excessively wet root zones. Recharge to confined aquifers by percolation from the surface occurs only at the upstream end of the confined aquifer, where the geologic formation containing the aquifer is exposed at the earth's surface, flow is not confined, and a water table is present. Irrigation canals can be connected to the groundwater system; this can be an effluent as well as an influent stream.

Water may leave the shallow aquifer and drain into a nearby river. The remaining part of the soil moisture can feed into the deep aquifer; from it can be pumped back. The total return flow thus consists of surface runoff, lateral outflow from root zone and aquifer drainage to river (Figure 4).

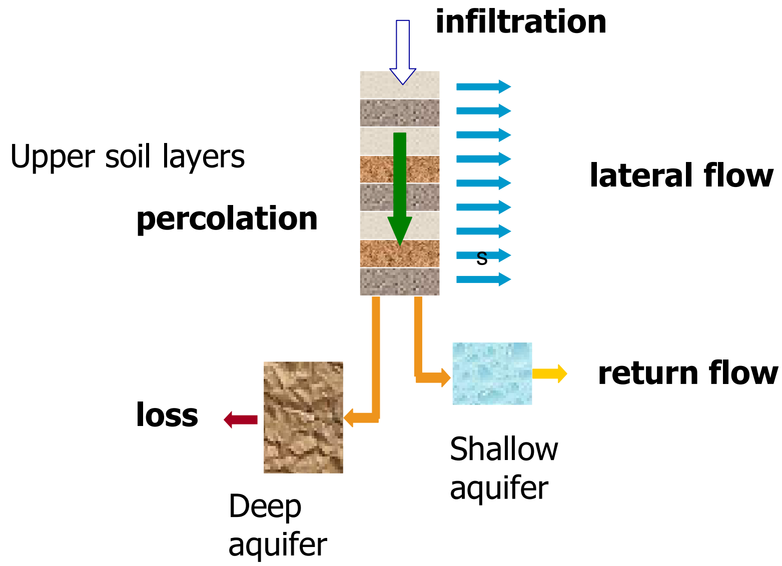
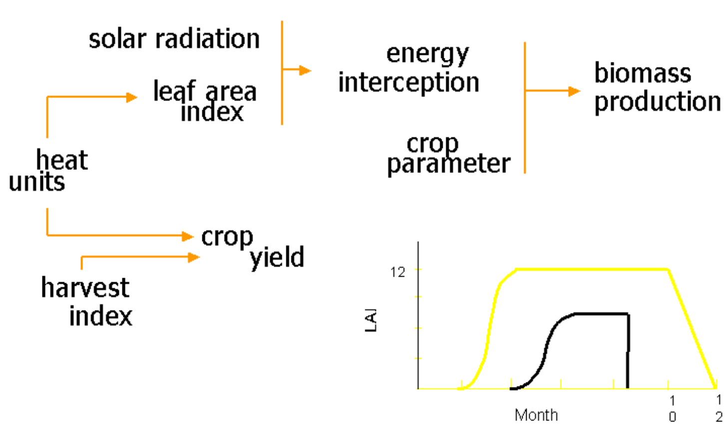


Figure 4: Schematic diagram of the sub-surface water fluxes

Percolation is calculated for each soil layer in the profile. Water is allowed to percolate if the water content exceeds the filled capacity water content for that layer. When the soil layer is frozen, no water flow out of the layer is calculated. Recharge below the soil profile is partitioned between shallow and deep aquifers. Water that recharges the deep aquifer is assumed lost from the system.

4.3.5 Plant growth

For each day of simulation, potential plant growth, i.e. plant growth under ideal growing conditions is calculated. Ideal growing conditions consist of adequate water and nutrient supply and a favorable climate.



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First the Absorbed Photosynthetic Radiation (APAR) is computed from intercepted solar radiation, followed by a Light Use Efficiency (LUE) that is in SWAT essentially a function of carbon dioxide concentrations and vapor pressure deficits. The crop yield is computed as the harvestable fraction of the accumulated biomass production across the growing season.

4.3.6 Permafrost

Soil temperature impacts water movement and the decay rate of residue in the soil. Daily average soil temperature is calculated at the soil surface and the center of each soil layer. The temperature of the soil surface is a function of snow cover, plant cover and residue cover, the bare soil surface temperature, and the previous day's soil surface temperature. The temperature of a soil layer is a function of the surface temperature, mean annual air temperature and the depth in the soil at which variation in temperature due to changes in climatic conditions no longer occurs. This depth, referred to as the damping depth, is dependent upon the bulk density and the soil water content. In case the daily soil temperature is below zero, no water flow is calculated.

4.4 Model outputs

SWAT generates daily outputs for sub-basins, streams and reservoirs. The outputs include all water balance data, but also data on water quality, sediments, biomass production and crop yields at different aggregation levels.

4.5 Forcing

Climatic inputs used in SWAT are parameterized on sub-basin level and include daily precipitation, maximum and minimum temperature, solar radiation data, relative humidity, and wind speed data, which can be input from measured records and/or generated using a weather generator. The fact that climate data are input at sub-basin level is also a disadvantage. In this case evapotranspiration and precipitation are available as rasters with a high level of spatial detail compared to the generalized sub-basins. This would also require source code changes.

4.5.1 Precipitation

The average air temperature is used to determine if precipitation should be simulated as snowfall. The maximum and minimum temperature inputs are used in the calculation of daily soil and water temperatures. Measured or generated sub-daily precipitation inputs are required if the Green-Ampt infiltration method is selected.

4.5.2 Evapotranspiration

In SWAT actual evapotranspiration cannot be supplied to the model as input but it is calculated using potential evapotranspiration as basis, which is then constrained by either water, nutrient or environmental stress. This would consider source code changes. In SWAT evapotranspiration includes evaporation from rivers and lakes, bare soil, and vegetative surfaces; evaporation from within the leaves of plants (transpiration); and sublimation from ice and snow surfaces. The model computes evaporation from soils and plants separately as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index (area of plant leaves relative to the area of the HRU). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration (based on either Hargreaves (Hargreaves and Samani, 1985), Priestley-Taylor (Priestley and Taylor, 1972) or Penman-Monteith (Monteith, 1965)) and leaf area index.

4.5.3 Snow cover

The snow cover component of SWAT has been updated from a simple, uniform snow cover model to a more complex model which allows non-uniform cover due to shading, drifting, topography and land cover. The user defines a threshold snow depth above which snow coverage will always extend over 100% of the area. As the snow depth in a subbasin decreases below this value, the snow coverage is allowed to decline non-linearly based on an areal depletion curve. Snow melt is controlled by the air and snow pack temperature, the melting rate, and the areal coverage of snow. If snow is present, it is melted on days when the maximum temperature exceeds 0°C using a linear function of the difference between the average snow pack maximum air temperature and the base or threshold temperature for snow melt. Melted snow is treated the same as rainfall for estimating runoff and percolation. For snow melt, rainfall energy is set to zero and the peak runoff rate is estimated assuming uniformly melted snow for a 24 hour duration. The model allows the subbasin to be split into a maximum of ten elevation bands. Snow cover and snow melt are simulated separately for each elevation band. By dividing the subbasin into elevation bands, the model is able to assess the differences in snow cover and snow melt caused by orographic variation in precipitation and temperature (Fontaine et al. , 2002). For this project daily imagery with snow cover will be used as direct input for the model and source code changes are required to accommodate this.

4.6 Routing

SWAT has two routing methods: the variable storage routing method and the Muskingum routing method. The latter models the storage volume in a channel length as a combination of wedge and prism storages.

4.6.1 Surface water

Each sub-basin is linked to a single reach and all HRUs in a sub-basin drain their water into that reach by surface runoff, drainage and ground water flow. Subsequently the water is routed through the catchment from upstream to downstream using either the variable rate storage method (Williams, 1969) or the Muskingum method (Neitsch et al., 2002), which are both variations of the kinematic wave approach.

4.6.2 Lumped glaciers

Glaciers are not modelled in SWAT.

4.6.3 Reservoirs and lakes

SWAT models four types of water bodies: ponds, wetlands, depressions/potholes, and reservoirs. Ponds, wetlands, and depressions/potholes are located within a subbasin off the main channel. Water flowing into these water bodies must originate from the sub-basin in which the water body is located. Reservoirs are located on the main channel network. They receive water from all sub-basins upstream the water body. The model offers three alternatives for estimating outflow from the reservoir. The first option allows the user to input measured outflow. The second option, designed for small, uncontrolled reservoirs, requires the users to specify a water release rate. When the reservoir volume exceeds the principle storage, the extra water is released at the specified rate. Volume exceeding the emergency spillway is released within one day. The third option, designed for larger, managed reservoirs, has the user specify monthly target volumes for the reservoir. The conceptual design for reservoir in SWAT is shown in Figure 6: Reservoir concept in SWAT.

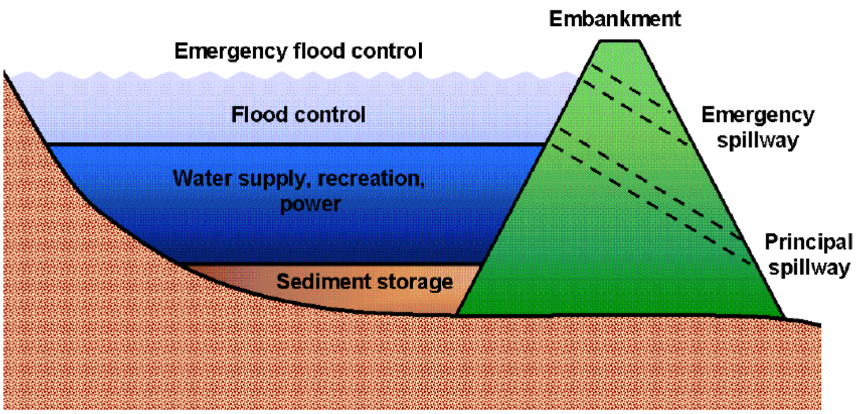

Figure 6: Reservoir concept in SWAT.

5 HBV

5.1 Background

The HBV-model is the abbreviation of Hydrologiska Byråns Vattenbalansavdelning (Hydrological Bureau Waterbalance-section). This was the former section at SMHI, the Swedish Meteorological and Hydrological Institute, where the model was originally developed in the early 70´s to assist hydropower operations. The aim was to create a conceptual hydrological model with reasonable demands on computer facilities and calibration data. The model is publicly available for research applications.

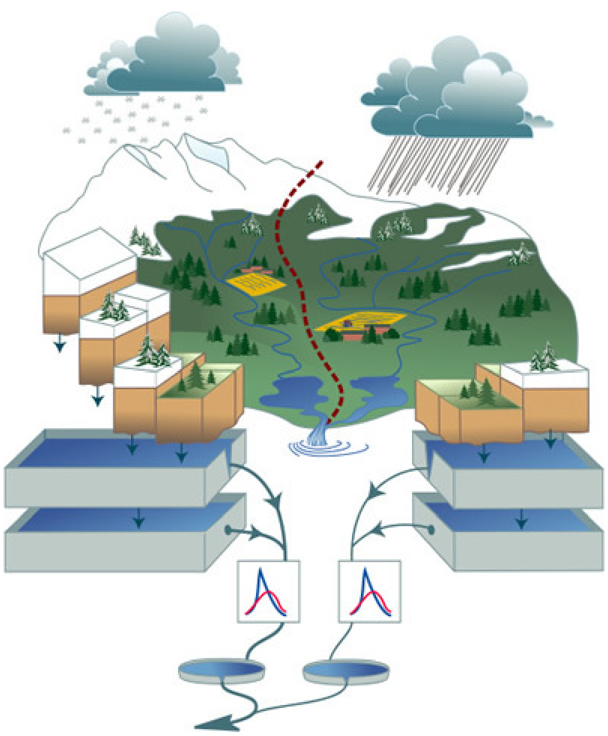

Figure 7: Overview of the hydrological cycle as modelled by HBV.

The HBV model (Bergström, 1976, 1992) is a rainfall-runoff model, which includes conceptual numerical descriptions of hydrological processes at the catchment scale (Figure 7). The general water balance can be described as:

$$P - E - Q = \frac{d}{dt}\left[SP + SM + UZ + LZ + lakes\right]$$

In which P = precipitation, E = evapotranspiration, Q = runoff, SP = snow pack, SM = soil moisture, UZ = upper groundwater zone, LZ =lower groundwater zone, lakes = lake volume

HBV has been used around the world in several climatic conditions, e.g. Sweden, Zimbabwe and India. The model is applied to several spatial scales: from plot scale to the entire Baltic Sea drainage basin (Bergström and Carlson, 1994; Graham, 1999). The HBV model is used for several purposes: flood forecasting and spillway design floods simulation (e.g. Bergström et al., 1992), water resources evaluation (e.g. Jutman, 1992) and nutrient load estimates.

5.2 Discretization

HBV can be used as a semi-distributed model by dividing the catchment (called a district) into sub-basins. Each sub-basin can be further divided into zones according to altitude, lake area and vegetation. The zone area is proportional to the occurrence of its characteristic in the sub-basin. Hence, zones cannot be geographically localised. The fact that HBV divides the area in irregularly shaped areas of different sizes is a major disadvantage for the CEOP-AEGIS project. Integration of the HBV model and earth observations products that are raster based, is less straightforward than in case of a raster based model.

5.3 Processes

Figure 8 gives an overview of the main processes that are modelled by the HBV model. The HBV model needs input data of precipitation, (reference) evapotranspiration and air temperature. Calculations on a temporal resolution higher than one day are possible.

Precipitation can be either rain or snow, depending on the elevation and temperature. In case of rainfall, part is intercepted by vegetation and can be evaporated from that vegetation. In case of snowfall, a snowpack accumulates or melts (in that case treated as rainfall), depending on the temperature. Rainfall that is not intercepted is divided into infiltration (filling up the soil zone) and recharge (upper groundwater zone) depending on the actual soil moisture content. From the soil zone water leaves the model as evaporation. From the upper response box part of the water leaves the model as fast runoff, another part percolates further to the lower groundwater zone from where the water leaves the model as slow runoff.

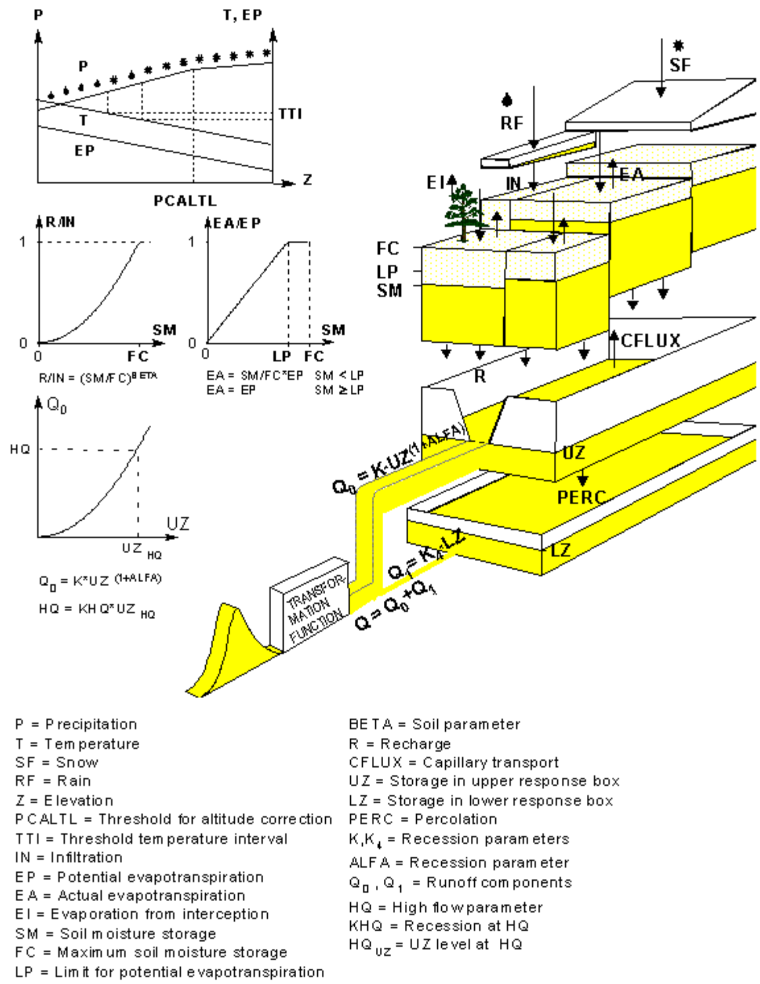

Figure 8: Schematic structure of one sub-basin in the HBV-96 model (Lindström et al., 1997), with routines for snow (top), soil (middle) and response (bottom).

5.3.1 Runoff

HBV models runoff in two parts: a fast runoff component and a slow runoff component. This is however water that is already infiltrated into the ground. Surface runoff, or overland flow, is not taken into account explicitly. It is possible to increase the simulated fast runoff component by minimizing the maximum soil moisture content and increasing the exponent of the non-linear function that defines the amount of recharge.

The runoff production Q is related to the rainfall P and to the soil water content SM in the upper layer by means of the following empirical relationship:

$$\frac{dQ}{dP} = \left(\frac{SM}{FC}\right)^{\beta} \qquad SM < FC$$

$$\frac{dQ}{dP} = 1 \qquad SM \geq FC$$

FC is the field capacity of the soil; the shape the equation is shown in the Fig.8.

5.3.2 Infiltration

Infiltration is the entry of water into a soil profile. In the HBV model net available rainfall is divided into infiltration and percolation (to the upper groundwater zone) based on an exponential function that depends on the actual soil moisture storage and the maximum soil moisture storage. Hence, infiltration is not modeled directly.

5.3.3 Drainage

Drainage, lateral subsurface flow, or interflow, is streamflow contribution which originates below the surface but above the zone where the soil is saturated with water. As can be seen in Figure 8 the HBV model does not explicitly model an unsaturated and saturated zone. Consequently drainage is not modeled.

5.3.4 Groundwater

HBV distinguishes two groundwater zones: the upper and lower zone. Water enters the upper groundwater zone as recharge (non-linear function of actual soil moisture content). From the upper groundwater zone water can move to the soil moisture zone via capillary rise. Additionally water can percolate to the lower groundwater zone, depending on a user defined percolation rate. Finally from the upper groundwater zone the fast runoff component is calculated as a non-linear function of the storage in the upper groundwater zone.

From the lower groundwater zone water can only leave as the slow runoff component. This slow runoff is a linear function of the storage in the lower groundwater zone.

5.3.5 Plant growth

In the HBV up to 15 vegetation types can be defined. For each vegetation type parameter values must be defined for e.g. interception storage and crop factors. The HBV model does not account for development stages of the different vegetation types. No crop growth model is included in the model but vegetation data is only used for interception and evapotranspiration.

5.3.6 Permafrost

Permafrost affects, such as the timing of active layer development can be integrated into the runoff response routine to produce a more accurate physical representation. This would require further source code changes.

5.4 Model outputs

HBV generates output of all the water balance components that are taken into account on a temporal resolution that is user-defined and in line with the temporal resolution of the input data.

5.5 Forcing

5.5.1 Precipitation

Precipitation is input to the model at sub-basin level. In the HBV model spatial optimal interpolation method can be used to interpolate data from meteorological stations and general knowledge of the precipitation and temperature pattern. On can also take into account information about topography and prevailing winds (Johansson, 2002)

5.5.2 Evapotranspiration

The standard HBV model is run with monthly data of long term mean potential evaporation, usually based on the Penman formula (Penman, 1948). These data are adjusted for temperature anomalies. From the interception storage evaporation equal to the potential evaporation will occur as long as water is available, even if it is stored as snow. If the interception routine is used it is also possible to reduce the soil evaporation to avoid values of total evaporation that are too large. The potential evaporation is thus a function of the time of the year, the current air temperature, vegetation, elevation and, as an option, precipitation. Evaporation from lakes is assumed to be equal to the potential evaporation and does not occur as long as there is ice, which is estimated by the model based on air temperature of preceding days (SMHI, 1996).

5.5.3 Snow cover

A threshold temperature (TT) is used to distinguish rainfall from snowfall. It is also possible to use the parameter TTINT. In that case the threshold is extend to an interval in which precipitation is assumed to be a mix of rain and snow, decreasing linearly from 100% snow at the lower end to 0% at the upper end. A snow distribution can be made in each zone by subdividing it into a number of subareas with different snow accumulation. Normally three snow classed are used that account for re-distribution of snow, snowdrift and snow that is trapped in creeks and other irregularities in rugged terrain. The standard snowmelt routine of the HBV model is a degree-day approach, based on air temperature. Melt is further distributed according to the temperature laps rate and is modelled differently in forested and open areas. The snowpack is assumed to retain melt water as long as the amount does not exceed a certain fraction of the snow. When temperature decreases below the threshold temperature, this water refreezes gradually.

5.6 Routing

The HBV model contains three simple routing procedures between the sub-basins and the lakes. It is possible to run the model separately for several sub-basins and then add the contributions from all sub-basins.

5.6.1 Surface water

The whole river basin that is simulated is called a district. The sub-basins that form a district can be linked together with three routing methods:

- Lake routing
- Smoothing with fixed weights
- Smoothing with discharge dependent weights (triangular unit hydrograph)

For the lake routing the user has to define the lake area, lake rating curve coefficient, rating curve zero, rating curve exponent and the part of the catchment (runoff) draining through the lake. The smoothing with fixed weights is a moving average type routing with up to six weights. The discharge dependent weights routing is the original HBV routing and similar to the Muskingum method (Neitsch et al., 2002) that is implemented in SWAT.

5.6.2 Lumped glaciers

Glacier melting follows a day-degree relation as used for snow melting but with another parameter (gmelt). No glaciar melt occurs as long as there is snow in the zone.

5.6.3 Reservoirs and lakes

The HBV model takes into account lakes by defining lake percentages in each altitude interval. Precipitation on lakes will be added to the lake water regardless of ice conditions in the same way for both rain and snow. Evaporation from lakes is equal the potential evaporation but can be modified by a parameter and will occur only when there is no ice. Transformation of runoff is taking place after water routing through the lake according to a rating curve. If no specific rating curve for the lake is given as input, the model will assume a general rating curve.

6 LARSIM

6.1 Background

LARSIM is the acronym for Large Area Run-off Simulation Model and it has been initially developed to describe the terrestrial hydrological cycle of the Baltic regions in the framework of the BALTEX project (1993-2000); successively, it has been used in many studies, mainly in Northern Europe, and it has been implemented by the State Institute for Environmental Protection of Baden-Wuerttemberg as a real-time forecast model for low and mean flow.

The original formulation is described in the Report 11 (Bremicker, 2000) of the Institute of Hydrology, University of Freiburg (Germany). LARSIM is a grid-based meso-scale hydrological model, which simulates the different components of water cycle: interception, snow accumulation and melt, evapotranspiration, soil-water movement, runoff generation, runoff concentration and river routing. Reservoirs and lakes accumulation is also taken into account. Meteorological input obtained from point observation is preliminarily interpolated on the simulation grid. Time interval for the simulation is from 1 hour to 1 day. The main concept in LARSIM is the utilisation of different sub-models for the calculation of water balance terms from easily available input data sets.

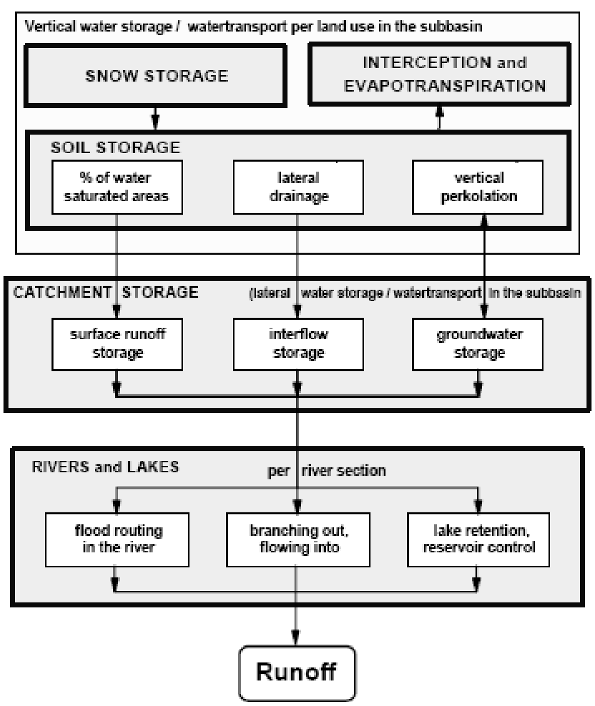

Figura 9. Conceptual scheme of the water balance in LARSIM.

6.2 Discretization

LARSIM consider the catchment divided in calculation units (sub-sectors) which can be irregularly spaced or defined on regular squared grid; to this respect, integration with E.O. input data is straightforward.

Applications to river basins in Europe and Africa cover for a broad range of catchment sizes (280 km² to 1700000 km²) and different spatial resolutions (sub-basin sizes from 1 km² to 325 km²). One of the most robust implementations of LARSIM is concerning the catchment of river Neckar in the southwest of Germany (approx. 14000 km²). In this case, the model has been set up with a raster-based discretization of of sub-sectors covering an area of 1x1 km²; calibration and verification has been made on the basis of daily time steps.

In analogy with other models, each subsector includes areas with homogenous land use and soil type which contributes to the hydrological response of each sub-sector. These homogeneous areas are conceptually similar to the Hydrological Response Units (HRU) of other types of model, in the sense that LARSIM does not consider their geographical position within the corresponding sub-sector.

The water balance is calculated by using deterministic algorithms (described in the following sections) for each HRU, which contributes to the runoff of the corresponding sub-sector. Meteorological input are required for each sub-sector. Other spatial elements in LARSIM are the routing channels (streams) and water accumulation points, such as lakes and artificial reservoirs.

6.3 Processes

The soil in LARSIM is schematised as a three-component reservoir, The basic equation of water balance at the generic time step *t* for each sub-sector in LARSIM is written as follows:

$$W_0(t+1) = W_0(t) + P(t) - E_a(t) - QS_D(t) - QS_I(t) - QS_G(t) \quad (0.1)$$

W_0 [mm] is the soil water content

P [mm] is the precipitation (including snow)

E_a [mm] is the actual evapotranspiration

QS_D [mm] is the infiltration excess and overland water volume

QS_I [mm] is the lateral drainage (interflow)

QS_G [mm] is the groundwater percolation.

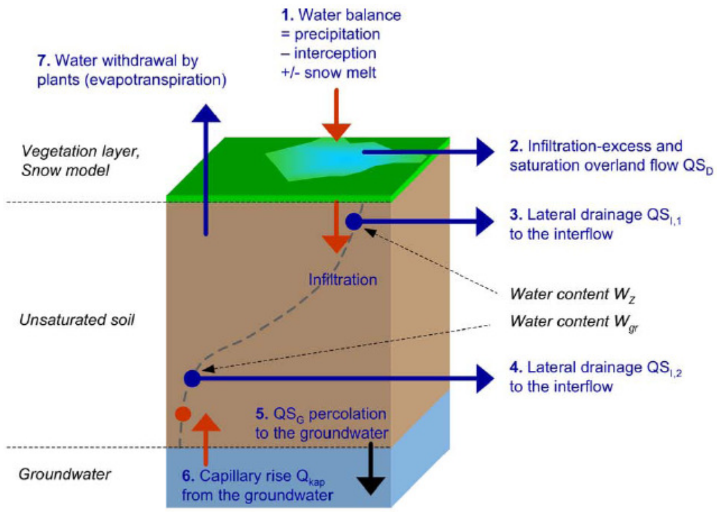

Figure 10: Soil water balance in LARSIM.

This three component soil water balance model is considered as adequate when adopting daily time steps; for smaller time interval, a more complex schematisation could be chosen.
The simulation of the soil water content is based on the Xinanjiang model, developed by Zhao (1992); according to this model, the relative saturated portion of the sub-sector surface (s/S in the equation below) is a function of the relative soil water content:

$$\frac{s}{S} = 1 - \left(1 - \frac{W_0}{W_m}\right)^b \qquad (0.2)$$

with W_m indicating the maximum soil water content in the soil. This function is called SMSA in the original Xinanjiang model (*soil moisture saturated areas*). The value of field capacity is usually taken for W_m. The parameter *b* varies between 0.1 and 2. Different expressions can be found in the literature for determining the value of *b*; the following expression has been used in several implementations of the LARSIM model:

$$b = \min\left[\left(0.0225 + 0.2177 f + 0.0273\Delta z\right)^{-1}; 0.5\right] \qquad (0.3)$$

where *f* is the percentage of forest cover in the sub-sector and *Δz* is the elevation variation in the main streams of the considered sub-sector. Small values of the parameter *b* (0.1; 0.2) indicate that the saturated areas are relatively small until the soil water content does not reach relatively high values; diversely, *b* values greater than 1 produce large saturated areas with relatively low soil water contents.

6.3.1 Runoff (overland flow)

As shown in Eq.(0.1), the total runoff is divided into three components: overland flow, interflow (drainage), and groundwater. These quantity are calculated as volumes, which then contributes to the flow routed to the channel network. This partitioning is related to the relative soil water content on the basis of Eq.(0.2). Overland flow increases with soil wetness and it is not dependent on the rainfall intensity; rainfall is entirely transferred to runoff in the case of $W_0=W_m$ (saturated soil). These characteristics are in common with other models, i.e. HBV. The runoff is dependent on two parameters, W_m and b, and from the values of P and W_0, the latter being calculated at the beginning of each time step.

6.3.2 Drainage (Interflow)

In order to calculate the drainage or interflow, LARSIM introduces additional parameters, namely:

- minimum and maximum infiltration capacity in correspondence of the top filling level of the soil reservoir, D_{min} and D_{max} (mm/h);
- a threshold value of soil water content in the reservoir, W_z (mm) < W_m;
- a threshold value of soil water content at the maximum soil depth, W_B, usually taken equal to 0.05 W_m;
- a parameter c=1.5 (fixed value).

The values of parameters D_{min}, D_{max} and W_z are usually determined in the preliminary calibration of the model. For drainage, three different conditions are identified, depending on the value of W_0 respect to W_z and W_b. In the case of a very dry soil i.e. $W_0 < W_B$ no drainage occurs, that is QS_I=0. For a very wet soil, i.e. $W_0 > W_z$ the drainage is calculated as a function of W_0, W_z, W_m, D_{min} and D_{max}; in the case of an intermediate soil moisture status i.e. $W_B < W_0 < W_z$ the drainage is calculated as a function of W_0 , W_m and D_{min}.

6.3.3 Groundwater

Groundwater in LARSIM is calculated again from the soil water content, in relation to the threshold value W_B introduced above. For a dry soil, corresponding to the condition $W_0 < W_B$, the percolation is null; in the opposite case the following relationship is applied:

$$QS_G = \beta\left(W_0 - W_B\right)\Delta t \qquad (0.4)$$

with β indicating an additional calibration parameter and Δt the calculation time step. LARSIM consider also the possibility of having a capillary rise when the soil water content is below a threshold value, usually assumed equal to 0.1 W_m; a maximum capillary rise is defined depending on the soil type and it is progressively reduced in proportion to $(W_0\text{-}0.1W_m)$.

6.3.4 Plant growth

There is no simulation of plant growth in LARSIM. For each land use, seasonal LAI values (Leaf Area Index) have to be indicated for evapotranspiration and interception estimations.

6.3.5 Permafrost

Soil temperature is not considered into account in LARSIM.

6.4 Model outputs

In the context of the CEOP-AEGIS project, the main output of LARSIM is the simulation of the runoff for each subsector and the total runoff production.

6.5 Forcing

6.5.1 Precipitation

Precipitation input for each sub-sector and time step can be estimated from point measurements by using the Thiessen method. Two types of elaboration are performed on the value of precipitation: a) the estimation of snowfall, and b) the interception by foliage. Snowfall may occurs when air temperatures falls below a threshold value (in LARSIM it is assumed as +1 °C); the amount of intercepted precipitation is calculated as $0.2LAI$, which values (monthly or seasonal series) are required as input for each land use.

6.5.2 Evapotranspiration

The Penman-Monteith equation is applied to determine evapotranspiration. Minimum meteorological input data are temperature and relative humidity at screen height and wind-speed at 10 m; solar radiation can be either directly measured or estimated with conventional methods. Surface albedo and specific parameters for resistances calculation are required for each land use class. Surface resistance may be corrected by using information on the soil water content derived from the water balance module.

6.5.3 Snow cover

The accumulation of snow on the surface affects the soil water balance, and of course the runoff generation. The amount of snowmelt is estimated on the basis of the simplified energy balance model of Knauf (1980). Similar approach is used to evaluate the percentage of evaporation on snowmelt.

6.6 Routing

6.6.1 Surface water

Surface water routing is schematised in LARSIM by considering three parallel reservoirs, corresponding to the three components of run-off generation described in 7.3.1, 7.3.2 and 7.3.3. Drainage water QS_D is converted in the direct runoff flow rate Q_D by introducing a retention time parameter T. This parameter is calculated from the total surface of the considered sub-sector and from the geometric characteristics of the main stream (length L and variation of elevation Δz). Similar calculations are performed to determine the inter-flow rate Q_I and the ground water flow rate Q_G by using additional calibration parameters to calculate the time constant. The total flow rate for each sub-sector is then resulting from the sum of these three terms:

$$Q_{tot} = Q_D + Q_I + Q_G \qquad (0.5)$$

Streams and rivers connecting the different subsectors are schematised as bi-trapezoidal channels. Manning-Strickler friction coefficients are used to calculate stationary flow in the resulting network.

6.6.2 Lumped glaciers

Glaciers are not considered in LARSIM.

6.6.3 Reservoirs and lakes

A simple continuity equation is used to schematise reservoirs and lakes storages:

$$V_S(t+1) = V_S(t) + \frac{\Delta t}{2}\left[Q_{IN}(t+1) + Q_{IN}(t) - Q_{OUT}(t+1) - Q_{OUT}(t)\right] \qquad (0.6)$$

In order to solve iteratively Eq.(0.6) the volume-flow rate function of the reservoir should be known; alternatively, this information could be derived from the volume vs. water level relationship. In addition to this, the maximum yearly depletion volume in the lake and the initial volume are required as input data.

Routines are available in LARSIM to simulate the artificial management of reservoir storage.

7 PCR-GLOBWB

7.1 Background

The name PCR-GLOBWB stands for PCRaster Global Water Balance. The model is developed at the department of physical geography of Utrecht University with the explicit aim to simulate terrestrial hydrology at macro-scales, e.g. continental to global, under various land use and climate conditions with a temporal resolution of one to several days (Van Beek, 2007). This requires that the main terrestrial hydrological processes are described in a physically consistent way so that changes in storages and fluxes can be assessed adequately over time and space. Yet, the scarce and limited nature of the available data asks for a parsimonious model that preserves the physical basis of its parameterization. Therefore, a conceptual, dynamic and distributed model was preferred. The basic version of the PCR-GLOBWB model is written in the meta-language of the PCRaster GIS package (Wesseling et al., 1996). Its origins were based on the HBV-model (Bergström, 1995), with the basic difference that PCR-GLOBWB is fully distributed and implemented on a regular grid. The present model replaces much of its original process-descriptions with newer versions, which in turn were partly based on existing macro-scale hydrological models and common practice. Thus, the PCR-GLOBWB model forms part of a long-standing tradition whilst aiming to improve some recognized weaknesses in the description and parameterization of terrestrial hydrological processes at the macro-scale.

7.2 Discretization

The model is implemented on a regular grid, and therefore very suitable for integration with remote sensing products in the CEOP-AEGIS project. The global model is setup at a spatial resolution of 0.5°, however the model can be easily setup for specific domains at higher resolution. Initial tests reveal that a spatial resolution of 5 km is a feasible resolution for the water balance monitoring tool. The cell values still represent averages over relatively large areas, but sub-grid variability is taken into account. The most fundamental subdivision is that of each cell into the open water surface and the land surface. The hydrological processes on the land surface (or soil compartment) are confined to a single cell. Within each cell, the parameterization is further subdivided on the basis of vegetation. A distinction is made between short and tall vegetation since tall vegetation more effectively draws water from deeper in the soil and generally incurs higher interception losses. Where a distinction is made between land cover types at the sub-grid level, state variables are stored as the cell average.

7.3 Processes

PCR-GLOBWB simulates the most direct pathways of water that reaches the Earth surface back to the ocean or atmosphere (see figure 2.1); within each cell precipitation in the form of rain or snow either falls on soil or in open water surface.

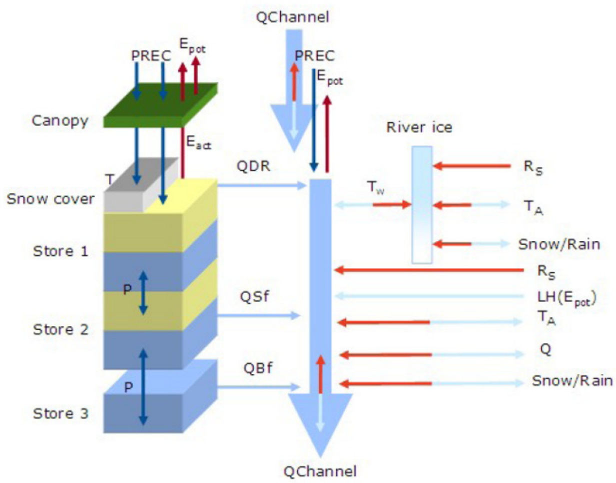

Figure 11 Model concept of PCR-GLOBWB

Figure 11 shows the model concept of PCR-GLOBWB. The left side shows the soil compartment, which is divided in the two upper soil stores and the third groundwater store, and their corresponding drainage components: direct runoff (QDR), interflow (QSf) and base flow (QBf). In the centre of the figure, the resulting discharge along the channel (QChannel) with lateral in- and outflow and local gains and losses are depicted. On the right, the energy balance for the open water surface and the possible formation of ice are shown. Any precipitation that falls on the soil surface can be intercepted by vegetation and in part or in whole evaporated. Snow is accumulated when the temperature is sufficiently low, otherwise it melts and adds to the liquid precipitation that reaches the soil as rain or throughfall. A part of the liquid precipitation is transformed in direct or surface runoff, whereas the remainder infiltrates into the soil. The resulting soil moisture is subject to soil evaporation when the surface is bare and to transpiration when vegetated; the remainder contributes in the long-term to river discharge by means of slow drainage which is subdivided into subsurface storm flow from the soil and base flow from the groundwater reservoir.

7.3.1 Runoff

Liquid water passed on from the snow cover to the soil surface will infiltrate if sufficient storage capacity is available, else it will drain over the surface as direct runoff. Following the concept developed by Zhao (1977) and Todini (1996), the partitioning into infiltration and direct runoff is dependent on the degree of saturation and the distribution of available storage in the soil. The algorithm is described in detail in the LARSIM model, section 6.3.1.

7.3.2 Infiltration

All the precipitation falling over the soil infiltrates unless the soil is either impervious or it has already reached saturation; the proportion of elementary areas which are saturated is described by a spatial distribution function. However, if the potential infiltration rate exceeds the saturated hydraulic conductivity of the top soil, the infiltration excess is passed on to the direct runoff;
When the infiltration rate exceeds the saturated hydraulic conductivity of the first layer, the infiltration excess is passed on to the direct runoff, if the total infiltration exceeds the storage capacity of the first layer, it is handed down to the second store.

7.3.3 Drainage

From the two upper soil compartments water will drain laterally over the height of the saturated wedge that may form over the contact with the third compartment, representing the groundwater reservoir, when the recharge in the upper soil is high, percolation to the groundwater is low and the gradient that drives lateral flow along the slope is high. This lateral drainage, known as *subsurface storm flow* or *interflow*, is modeled here using a simplified approach based on the work of Sloan & Moore (1984) and Ormsbee & Khan (1989) in which the soil is idealized as a uniform, sloping slab with an average soil depth and inclination.

In the application of this theory the simplification is made here that the saturated wedge responds to the percolation rate without delay and that it always will be draining with the available pore space. The percolation itself is the net percolation, being the total of the gains to the second store due to percolation from the topsoil and the capillary rise from the underlying groundwater reservoir as well as the losses due to percolation to the groundwater store and the capillary rise to the upper, topsoil, reservoir.

7.3.4 Groundwater

The third store of the soil compartment represents the deeper part of the soil that is exempt from any direct influence of vegetation and constitutes a groundwater reservoir fed by active recharge. This recharge consists of the net percolation, percolation from the second store minus capillary rise from the third into the second store. Drainage from this groundwater reservoir contributes as base flow to the total discharge. This is described by a linear store, with the drainage, Q_3 in [m·d-1], given by:

$$Q_3 = \alpha S_3 \Delta t ,$$

where α is the recession coefficient in [d^{-1}] and S_3 the storage in the third layer [m].

If required, additional subtractions of groundwater for consumptive water use can be specified.

7.3.5 Plant growth

PCR-GLOBWB has implemented two kinds of vegetation: short and tall vegetation. These two are different in the sense that tall vegetation generates less throughfall and that is can extract soil moisture from deeper layers than the small vegetation. The crop factor are equal and the model does not account for development stages of the different vegetation types.

7.3.6 Permafrost

PCR-GLOBWB has the option to model permafrost by specifying the fractional area where percolation to groundwater store is impeded. By setting this fraction to 1 no water is percolating to the groundwater.

7.4 Model outputs

PCR-GLOBWB returns the resulting states and fluxes of each of the above processes per selected time step.

7.5 Forcing

PCR-GLOBWB requires meteorological input to be specified by an external source (e.g., observations, GCM results etc.) and considers it as uniform over each cell. The model requires the following meteorological input: total precipitation, potential evapotranspiration, both in m water slice, and temperature, in °C, as sums and averages over the duration of the model time step, e.g. per day. The model also has an inbuilt option for direct forcing of actual evapotranspiration. In that case potential evapotranspiration is not required.

7.5.1 Precipitation

A threshold temperature is used to distinguish rainfall from snowfall depending on the temperature input data. Precipitation must be defined for each grid cell but is uniform within the grid cell.

7.5.2 Evapotranspiration

PCR-GLOBWB has an inbuilt option to be forced by actual evapotranspiration otherwise the following method is used. The bare soil evaporation is not limited for the saturated part of the pervious area and occurs at a reduced rate for the unsaturated area. Vegetation extracts water from the soil by transpiration except when the soil is saturated and the lack of aeration prevents root water uptake. The area-averaged transpiration is therefore entirely attributable to the unsaturated area. The actual transpiration rate is partitioned over the upper two soil layers on the basis of root content and limited by local soil water availability, if applicable.

7.5.3 Snow cover

Snow accumulation and melt are entirely temperature-dependent, conform the snow module of the HBV module (Bergström, 1995), with a threshold temperature, TT [°C], deciding whether precipitation accumulates as snow or the accumulated snow layer melts. By default, the threshold temperature is 0°C and the amount of snowfall can be corrected for undercatch and winter evaporation by means of a correction factor. The accumulated snow at the soil surface is represented as a water-equivalent depth with a water-holding capacity proportional to its total depth. Water is added to the liquid storage within the snow cover when precipitation falls as rain or the snow melts. Snow melt is calculated from a simple degree-day factor when the temperature exceeds the threshold temperature. In contrast, part of the stored liquid water can refreeze when the air temperature is below the threshold temperature at a rate equal to the refreezing coefficient. Any liquid water exceeding the water-holding capacity of the snow cover is passed to the soil surface whilst any remaining liquid water in the snow is liable to evaporation losses that are prescribed by the potential bare soil evaporation. Forcing the model with RS snow cover would require additional source code changes.

7.6 Routing

7.6.1 Surface water

The freshwater surface constitutes a separate land cover class for which the process descriptions differ from the land surface proper. The main processes included in the model are the direct input to or withdrawals from the fresh water surface due to precipitation and evaporation, ice formation or water consumption, lake storage and river discharge. Routing of water through the drainage network is prescribed by the local drain direction map (LDD) which allows flow in 8 cardinal directions over 360° (see Figure 12). Channel dimensions, gradient and roughness need to be specified.

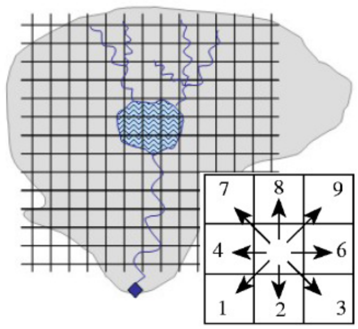

Figure 12 Representation of the open water network

The total runoff from the land surface feeds without any delay into the river network and is lumped with the changes due to consumptive water use, net precipitation and ice formation (see below) from the total open water volume prior to routing. Discharge is calculated from the kinematic wave approximation of the Saint-Venant Equation (Chow, 1988). A numerical solution of the kinematic wave approximation is available as an internal function in PCRaster. It is evident that the river morphology is only described summarily in this manner and that additional roughness effects might be lumped into the value of Manning's n (Dingman, 1984).

7.6.2 Lumped glaciers

Glaciers are not modelled in PCR-GLOBWB.

7.6.3 Reservoirs and lakes

Within the model, reservoirs and lakes are treated similarly by the model as contiguous areas of fresh water that can evaporate freely. Each reservoir or lake is represented as a reservoir with a variable water height, h_{Lake} [m], over its fixed extent, A_{Lake} [m^2]. For each time step, the change in water level is instantaneous over the lake surface and given by:

$$\Delta h_{Lake} = \left(\frac{\Delta Q + \Delta L \cdot q}{A_{Cell}} \right) \Delta t \, ,$$

in which ΔQ is the change in discharge in [$m \cdot s^{-1}$] and q is the total volume of water per unit channel length (lake shore) that is added or subtracted from the surface water network [$m^2 \cdot s^{-1}$] which comprises precipitation, potential evaporation, drainage from the soil compartment and any consumptive water subtractions. These fluxes are multiplied by the appropriate duration of the timestep, Δt, to obtain the change in lake water height in [m].

The change in discharge is the balance of inflow and outflow if the lake interrupts the river network. The inflow is the incoming river discharge, the outflow is calculated in analogy to the weir formula (Bos et al., 1989) as the discharge through a rectangular cross-section:

$$Q_{Out} = C \cdot \tfrac{2}{3}\sqrt{\tfrac{2}{3}\, g}\; b\,(h-h_0)^{3/2}\,\Delta t \approx 1.70\, C \cdot b\,(h-h_0)^{3/2}\,\Delta t\ ,$$

in which b is the breadth of the outlet [m], g is the gravitational acceleration [$m \cdot s^{-2}$] and h and h_0 are respectively the actual lake level and the sill of the outlet [m]. C is a correction factor [$m^{4/3} \cdot s^{-1}$] that corrects among others for the effects of back- and tail waters, viscosity, turbulence and deviations from the assumed uniform flow distribution. The correction factor C has to be determined empirically. The calculated discharge at the outlet is added within the time step to the lateral inflow in the kinematic wave approximation.

8 GRAPES

8.1 Background

GRAPES is the acronym for "Global/Regional Assimilation and PrEdiction System", the numerical weather prediction system of the Chinese Meteorological Administration. As such, GRAPES is conceived to assimilate Earth Observation data at different scales and grids. The system has been developed during the last decade and it is in continuous evolution.

Accordingly to the information available, the land surface model in GRAPES has been extracted from the scheme embedded in the Rapid Update Cycle (RUC) of the NOAA weather prediction system; as such, in the following we will refer to GRAPES/RUC. The Rapid Update Cycle is indeed a family of models, with different levels of complexity in the description of processes.

The basic 6-layers RUC scheme – which is the most likely version embedded in GRAPES-describes the vertical soil water balance and cold-season processes in detail but it does not include a runoff routing procedure, since it is aimed to improving the forecasts of low-level conditions. Recent studies are being developed at Nanjing University to integrate the land surface model of GRAPES in a flood prediction model.

8.2 Discretization

The GRAPES-Meso system with a 30 km horizontal resolution is operational since 2006, and it has been upgraded to a 15 km horizontal resolution in 2007. This spatial resolution is similar to the chosen spatial resolution in CEOP-AEGIS (25x25 km).

8.3 Processes

The 15-km GRAPES/RUC includes a 6-layer soil/vegetation/snow model as shown in the figure. Heat and moisture transfer equations are solved at 6 levels for each grid point. The energy and moisture budget equations for the ground surface are applied to a thin layer spanning the ground surface and including both the soil and the atmosphere with corresponding heat capacities and densities.

Soil water content is calculated from a one-dimensional equation using the vertical moisture gradient and the gravitational force. Data on soil texture categories are needed to define static soil properties at each cell grid; the land vegetation category to specify static canopy properties; and the green vegetation fraction to compute canopy versus bare soil contributions. Although soil texture categories are provided separately for top (0-30 cm) and bottom (30-100 cm) layers, only the top values are used to provide constant soil properties in each entire column.

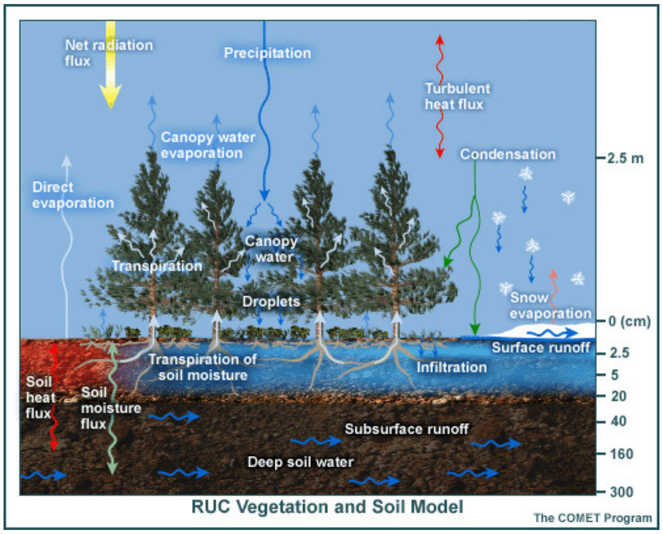

Figure 4: Land surface model in GRAPES/RUC.

8.3.1 Runoff

Excess of precipitation rate over the maximum infiltration rate creates surface runoff. The drying process is described in the section on evapotranspiration

8.3.2 Drainage

It is calculated from the soil water balance, as excess water from the inner soil layers.

8.3.3 Groundwater

It is calculated from the soil water balance, as excess water from the bottom soil layer.

8.3.4 Plant growth

There is no simulation of plant growth in GRAPES. For each land use, seasonal LAI values (Leaf Area Index) have to be indicated for evapotranspiration and interception estimations.

8.3.5 Permafrost

Freezing and thawing processes in soil are described in detail by using the algorithm proposed by Smirnova et al. (2000). The algorithm takes into account the latent heat of phase changes in soil, with freezing characteristics defined for each soil type. The effect of ice in soil on water transport is considered as a disruption of flow paths and it reduces water flow speed.

8.4 Model outputs

In the context of the CEOP-AEGIS project, the main output of GRAPES is the simulation of the runoff for each subsector and the total runoff production.

8.5 Forcing

8.5.1 Precipitation

Precipitation input for each cell-grid, coupled with the meteorological model.

8.5.2 Evapotranspiration

*T*he one-layer canopy model of Pan and Mahrt (1987)*;* variability of vegetation characteristics in the region is from the United States Geological Survey (USGS) 24-category 30-second dataset*.* This formulation allows moisture to be re-leased to the atmosphere via transpiration*; t*he canopy resistance is a function of minimal stomatal resistance (vegetation type-based), leaf area index and effects of *climatic data.* The total evaporation is partitioned into three components:

- direct evaporation from the top layer of bare soil;
- direct evaporation from the vegetation canopy;
- transpiration by plants involving water stored in the root zone of the soil.

8.5.3 Snow cover

The snow density is computed depending on the amount of snow and its temperature (Koren et al. 1999). This value is used to obtain the snow depth from snow water equivalent. The accumulation of snow on the ground surface is provided by the mixed phase microphysics algorithm of the MAPS/RUC forecast scheme (Reisner et al. 1998). It predicts the total amount and distribution of precipitation between the solid and liquid phase. The solid phase is accumulated on the ground/snow surface and is unavailable to the soil until melting begins. Snow evaporates at the maximum possible (potential) rate, as determined by atmospheric conditions, unless the snow layer would all evaporate before the end of the time step. In such a case, the evaporation rate is reduced to a value that would exactly remove the existing snow in the current time step. Heat budgets are also calculated at the boundaries between the snow pack and the soil and the snow pack and atmosphere.

Melting at the snow/soil and snow/atmosphere interfaces occurs if the energy budgets produce temperatures higher than freezing (0°C). In such cases, the snow temperature is set equal to the freezing point, and the residual heat from the energy budget is used to melt snow. Water from melting snow partially remains inside the snow pack, and the rest is available for infiltration into the soil. If the amount available to the soil exceeds the maximum possible value for the given soil type, then the excess water becomes surface runoff.

8.6 Routing

There is no routing component in GRAPES

9 Model evaluation and selection

Based on these analyses a number of general conclusions can be drawn:

- All the models, except SWAT and GRAPES, have similar algorithms for soil water balance and runoff, based on the Xinanjang model of Zhao. SWAT is based on the SCS method and it has probably a slightly more advanced routing, based on Muskingum approach and GRAPES/RUC has a more advanced soil water balance module but no routing.
- Most model require source code changes to allow forcing by remote sensing (precipitation, evapotranspiration, snow), except for PCRGLOB-WB which already has an inbuilt option for pre-described actual evapotranspiration. Some changes are still required to include snow cover forcing.
- GRAPES, LARSIM and PCRGLOB-WB are raster based, but GRAPES has no routing component.
- LARSIM and PCRGLOB-WB are efficient, open source and with very close links to the original developers which allows straightforward customizing in this project context.

In Table 2 the different models are compared and graded between 1 (poor) and 3 (good) for the different indicators.

Table 2 Comparison of different models: 1=poor, 2=average, 3=good

Indicator	SWAT	HBV	GRAPES	LARSIM	PCR-WB
Spatial discretization	1	1	3	3	3
Soil water balance	3	2	3	2	2
Date requirements	1	2	2	3	3
Permafrost	3	2	3	2	3
Forcing P by EO	1	1	3	3	3
Forcing ET by EO	1	1	1	1	3
Forcing snow by EO	1	1	1	1	1
Routing	3	2	1	3	3
Lumped glaciers	1	1	1	1	1
Lakes and reservoirs	3	1	1	2	3
Detailed outputs	3	2	2	3	3
Model efficiency	2	3	2	2	3
Code availability	3	1	1	3	3
Support from developers	2	1	1	3	3

Table 3 shows the weighted scores of the different models based on the weights in Table 1 . Especially the indicators spatial discretization, routing, code availability and support from the developers are deemed important.

Table 3 Weighted scored of the different models

Indicator	SWAT	HBV	GRAPES	LARSIM	PCR-WB
Spatial discretization	5	5	15	15	15
Soil water balance	12	8	12	8	8
Date requirements	4	8	8	12	12
Permafrost	3	2	3	2	3
Forcing P by EO	3	3	9	9	9
Forcing ET by EO	4	4	4	4	12
Forcing snow by EO	1	1	1	1	1
Routing	15	10	5	15	15
Lumped glaciers	2	2	2	2	2
Lakes and reservoirs	9	3	3	6	9
Detailed outputs	9	6	6	9	9
Model efficiency	8	12	8	8	12
Code availability	15	5	5	15	15
Support from developers	10	5	5	15	15
Total score	100	74	86	121	137

From these analysis the conclusion can be drawn that the perfect model is non-existent, but that the PCR-WB model is the most suitable candidate because it is raster based, allows forcing by earth observation datasets, includes a routing schemes with a reservoir/lake scheme, the source code is available and there are very close links with the model developers.

It is therefore recommended to take the PCRGLOB-WB model as a starting point and set it up at a high resolution (e.g. 5 km) for the Tibetan plateau and refine the model as follows:

- Evaluate and possibly modify soil water algorithm (e.g. compare with GRAPES)
- Improve permafrost algorithm
- Incorporate model for glacier melt
- Forcing with CEOP-AEGIS precipitation, ET
- Further detail soil and vegetation parameterization based on RS datasets
- Validation with soil moisture

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