Towards improved observations and modelling of catchment-scale hydrological processes: bridging the gap between local knowledge and the global problem of ungauged catchments

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Abstract The search for generalized theories to cope with the inherent spatial scale problem of hydrological prediction has been largely unsuccessful to date. The modelling of flow processes in catchments is hampered by this scale problem, and therefore results in poor predictions in the ubiquitous ungauged catchment (a catchment devoid of any streamflow measurements). Until now, observations of streamflow have been required to calibrate the rainfall–runoff models that are central to most strategies for hydrological prediction. In ungauged catchments other methods must be used. Catchment characteristics play a central role in this. The IAHS Predictions in Ungauged Basins (PUB) initiative aims at the development of science and technology to provide data and/or knowledge for ungauged or poorly gauged basins. The Hydrology and Quantitative Water Management (HWM) group of Wageningen University is very active in this field. In this paper some examples show how the group develops new measuring techniques, statistical techniques, and modelling and data assimilation procedures.

Key words advanced data collection techniques; hillslope storage dynamics; model diagnostics; modelling

INTRODUCTION

Society is facing growing water resource needs (e.g. hazard mitigation) in a changing global environment. The postulated acceleration of the water cycle places hydrological science at centre stage in the climate change debate. In IPCC reports, climate change predictions are more reliable for temperature as compared to precipitation, river flows and aquifer levels. Most hydrological understanding is based at the point scale, whilst our needs for predictive modelling are at catchment scales. There is an urgent need for improved hydrological predictions at that scale. Solving this spatial scaling problem requires a new approach along different lines of research that coincide with the PUB scientific programme.

The PUB scientific programme emphasizes four themes: (1) theoretical hydrology, (2) observational hydrology, (3) model diagnostics and intercomparison, and (4) advanced data collection technologies. The definition of PUB demands a new view of catchments, given the condition that local tuning or calibration is not possible. A first and simple reaction to this objective could be "no information about a catchment implies that nothing can be predicted". Fortunately, there are no catchments without any information. The question is then: what information is available and how can we make the most out of it?

The Hydrology and Quantitative Water Management Group of Wageningen University is active in several fields that could be beneficial for the PUB objective:

- Hydrological modelling at the catchment scale with applications of remote sensing and data assimilation.
- Floods and droughts (including hydrogeological processes).
- Solute transport at the catchment scale.
- Demand and supply of information for decision making on river basin water resources.

Special emphasis is put on the development of physically-based, conceptual and stochastic models of surface and subsurface flow processes to examine the hydrological system and its component processes and to study the effect of climate change and other human influences on floods, droughts, and solute balances. At the input-side of hydrological modelling, fundamental efforts are undertaken concerning the applicability of Earth observation from space and weather radar. The nature of the work covers fundamental, strategic, as well as more application oriented research.

It is the aim of the group to contribute to understanding of fundamental hydrological processes at the catchment scale and the functioning of river basins. In order to achieve this objective, research activities are focusing on laboratory experiments and intensive field work on hydrological and hydrogeological processes (Hupsel brook, Noor brook), the development of new modelling concepts (hillslope-storage dynamics), making use of new spatial information technology (such as remote sensing and GIS), advanced data mining (e.g. neural networks) and data assimilation (e.g. Kalman filtering) procedures, and decision support tools for integrated catchment management. In this paper, the HWM group's research programme related to the PUB initiative will be presented and several examples of activities will be given.

STATISTICAL ANALYSIS OF CATCHMENT BEHAVIOUR

Research groups like the Institute of Hydrology (Wallingford, UK) carried out comprehensive studies to relate flood indices to catchment characteristics in gauged catchments (Gustard *et al*., 1989). Based upon streamflow time series of about 1100 gauged catchments the mean annual peak flood was derived, taking into account the catchment area, the base flow index, the stream channel slope, the portion of the catchment under urban development, the weighted lake percentage and the annual average rainfall.

The statistical approach is also used to compute low flow indices from catchment characteristics. In the context of FRIEND (Flow Regimes from International Experimental and Network Data), the HWM group is actively participating in low flow research (Van Lanen & Demuth, 2002). Low flow indices can be: (a) the daily flow exceeded by 95% of average discharges, (b) the mean annual 10-day minimum, and (c) the Base Flow Index. In principle, such equations can be applied in other regions, if the appropriate regressions are available and the relevant catchment characteristics are known. Such statistical equations enable low flow and peak flow estimation at any ungauged site. Moreover, the impact of some human influences, such as surface water abstractions, on low flow can be evaluated. However, statistical methods enable prediction of some quantitative flood and low flow characteristics, but they cannot assess the hydrological response of a catchment in terms of continuous time series.

REGIONALIZATION OF CATCHMENT BEHAVIOUR

Regionalization of catchment behaviour relies on some basic, spatially-distributed thematic data of the ungauged basin. These data include: (a) morphometric and topographic data, (b) land use data, (c) soil data, (d) geological data and hydrogeological data, and (e) climate characteristics. In the framework of the EU project *Assessment of the Regional Impact of Droughts in Europe* (ARIDE), detailed tables have been compiled. A qualitative assessment can be made of flood and drought risk using basic themes. Expert tables, based upon decision rules, might be used to assess risks. An example is presented in Table 1.

Table 1 Provisional expert table for assessing risk of streamflow droughts (+++ very high, ++ high, + moderate, 0 low).

Slope	Depth of impermeable layer	Soil texture: Coarse				Fine			
		Average annual rainfall: Low		High		Low		High	
		Rainfall intensity: Low	High	Low	High	Low	High	Low	High
0–2°	Shallow	++	++	+	+	++	+++	++	++
	Deep	+	++	0	0	++	++	+	++
>8°	Shallow	++	+++	+	++	+++	+++	+++	+++
	Deep	++	++	0	0	++	++	++	++

These expert tables are compiled on the basis of observations and measurements in gauged catchments. A quick and intensive response of the discharge on a storm event implies that the majority of the rainfall leaves the catchment as overland flow and shallow subsurface flow. In these catchments the recharge of the aquifer, if any is present, is low. Consequently, when hardly any response is measured in the stream, the recharge is high and the streams receive a sustained groundwater recharge from the aquifer.

PHYSICALLY-BASED DISTRIBUTED MODELLING OF UNGAUGED BASINS

Different types of physically-based models are available to simulate continuous time series of streamflow at ungauged sites. Most of these models require a lot of spatially-distributed catchment data (e.g. morphometric and topographic data, land use data, soil data, geology and hydrogeology) as well as time series (e.g. meteorological data and abstractions).

For flood prediction, usually different types of models are applied than for low flow and drought studies. Rainfall–runoff models are appropriate to simulate peak flow. However, for routine simulation, modelling experience in similar gauged catchments is a prerequisite. A restriction of most rainfall–runoff models, especially the lumped ones, is the need for at least a short time series of streamflow data to calibrate the models. In fact, even the more parsimonious models like TOPMODEL (Beven, 1986) and MOGROW (Querner, 1994) need (huge amounts of) input data, that typically are not collected in ungauged catchments. For the simulation of time series of streamflow with an emphasis on low flows, spatially distributed and lumped groundwater models are also applied. Differences from the rainfall–runoff models consist of the more comprehensive representation of the groundwater system and the longer time step. Strictly speaking, models like MODFLOW (Clausen *et al.*, 1994) and SIMGRO (Querner & van Lanen, 2001) need no calibration with streamflow data. In some cases uncalibrated models provide reasonable results, as illustrated in Fig. 1, which shows the flow duration curve (FDC) for a period of three years for two Dutch catchments. The FDCs are derived both from measured and simulated data with SIMGRO (Querner & van Lanen, 2001). The model results agree very well with the measured data for this short period.

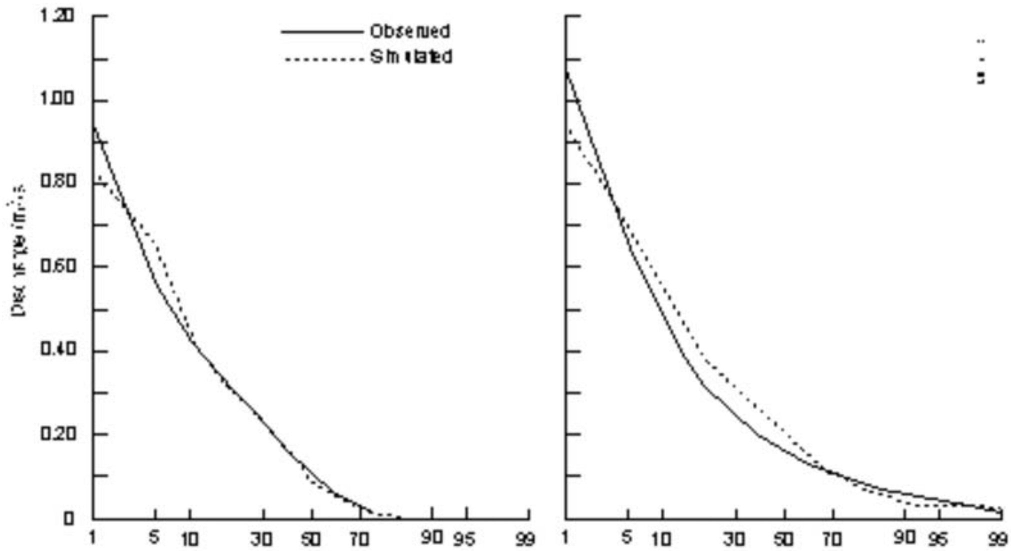

Fig. 1 Observed and simulated flow duration curves with SIMGRO for the Poelsbeek (left) and Bolscherbeek (right) catchments in 1990–1992 (Querner & van Lanen, 2001).

IMPROVED MODELLING OF CATCHMENT-SCALE HYDROLOGICAL PROCESSES

Hillslope-storage dynamics

Solving the scaling problem calls for new approaches in catchment modelling. A river basin is made up of interconnected hillslopes and the channel network. Modelling the dynamic response of the channel network has seen major breakthroughs based on similarity and scaling principles (Rinaldo *et al.*, 1995). Similar approaches to study subsurface flow processes along complex hillslopes are lacking. Understanding the interaction and feedbacks between hillslope forms and the flow processes is of crucial importance for adequate catchment modelling. The central question of this problem is (Duffy, 1996): *Can low dimensional dynamic models of hillslope-scale and catchment-scale flow processes be formulated such that the essential physical behaviour of the natural system is preserved*? Thus far, there are no methods that account for the three-dimensional (3-D) hillslope form while still using simple flow equations.

Some continuous functions were developed in Troch *et al*. (2002) to approximate a given portion of the topographic surface of a catchment (Fig. 2). The profile curvature (in the gradient direction) is important because it reflects the change in slope angle and thus controls the change of velocity of mass flowing down along the slope curve. The plan curvature (perpendicular to the gradient) reflects the change in aspect angle and influences the divergence or convergence of water flow. Nine different hillslopes can thus be defined. It is possible to compare the drainage response functions, as these will reflect the topographical control on the subsurface flow processes, and the relative soil moisture storage. Every type of slope shows very distinct hydrological behaviour, which leads to the conclusion that the response functions derived from the analytical solutions are indeed characteristic for a given hillslope type.

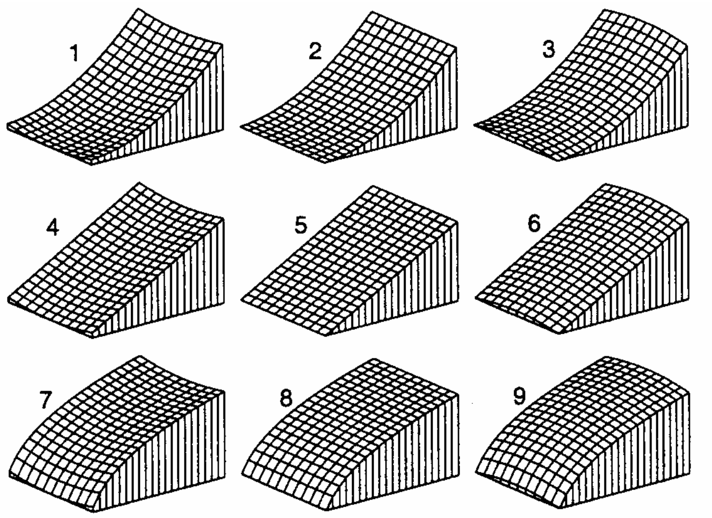

Fig. 2 Three-dimensional view of different hillslopes.

Recently, Troch *et al*. (2002b) developed storage-based equations able to capture the flow processes of all elementary hillslopes by simple scaling laws pertaining to hillslope length, slope and form. Such a description can give rise to a new generation of distributed rainfall–runoff models because it captures the essential behaviour of the natural system while being low-dimensional and computationally efficient. Figure 3 shows a 3-D view of a convergent hillslope on top of a concave bedrock. Hillslope response has traditionally been studied by means of the hydraulic groundwater theory. Solving the 3-D Richards equation for different hillslopes within a catchment is a

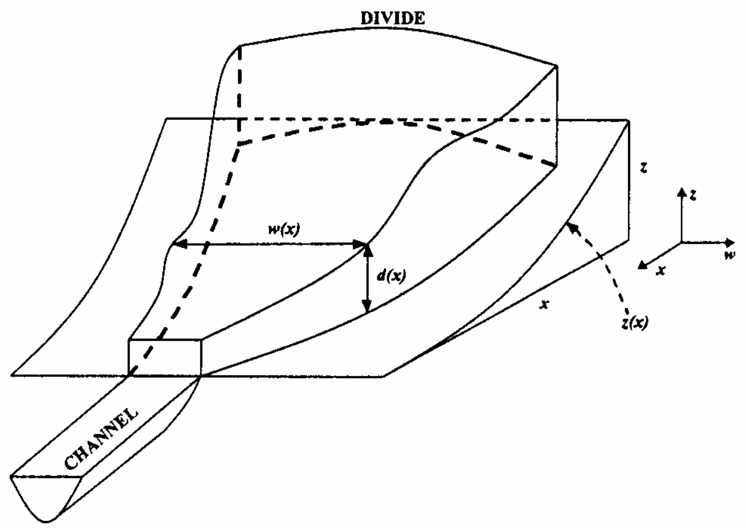

Fig. 3 Three-dimensional view of a convergent hillslope on top of a concave bedrock profile (Troch *et al.*, 2002).

complex task. Fan & Bras (1998) presented a way to transfer the 3-D soil mantle into a 1-D profile. Continuity and a kinematic form of Darcy's law lead to quasi-linear wave equations for subsurface flow, solvable with the method of characteristics. Adopting a power function of the form proposed by Stefano *et al.* (2000) to describe the bedrock slope, Troch *et al.* (2002a) derive more general solutions to the hillslope-storage kinematic wave equation for subsurface flow, applicable to a wide range of complex hillslopes. Characteristic drainage response functions for the nine distinct hillslope types of Fig. 2 are computed.

The Boussinesq equation for subsurface flow in an idealized sloping aquifer of unit width has recently also been extended to hillslopes of arbitrary geometry by incorporating the hillslope width function into the governing equation (Troch *et al.*, 2003a). Introduction of a source/sink term allows simulation of storm–interstorm sequences in addition to drainage processes, while a function representing the maximum subsurface water storage can be used to account for surface saturation response in variable source areas activated by the saturation excess mechanism of runoff generation. The model can thus simulate subsurface flow and storage dynamics for non-idealized (more realistic) hillslope configurations. Paniconi *et al.* (2003) assessed the behaviour of this relatively simple, 1-D model in a series of intercomparison tests with a fully 3-D Richards equation model. Special attention is given to the discretization and set up of the boundary and initial conditions for seven representative hillslopes of uniform, convergent, and divergent plan shape. Drainage and recharge experiments are conducted on these hillslopes for both gentle (5%) and steep (30%) bedrock slope angles. The treatment and influence of the drainable porosity parameter is also considered, and for the uniform (idealized) hillslope case the impact of the unsaturated zone is examined by running simulations for different capillary fringe heights. In general terms, the intercomparison results show that the hillslope-storage Boussinesq model is able to capture the broad shapes of the storage and outflow profiles for all of the hillslope configurations. In specific terms, agreement with the Richards equation results varies according to the scenario being simulated. The best matches in outflow hydrographs were obtained for the drainage experiments, suggesting a greater influence of the unsaturated zone under recharge conditions due to transmission of water throughout the hillslope. In the spatio-temporal water table response, a better match was observed for convergent than divergent hillslopes, and the bedrock slope angle was not found to greatly influence the quality of the agreement between the two models.

Field testing

Studies on hydrological processes and anthropogenic changes (e.g. land use and climate changes) at the catchment scale are possible only if detailed information on topography, geology, soil, and vegetation as well as climate are available at that scale. A prerequisite for such hydrological studies is the availability of adequate field data, and it has long been recognized that the quality of hydrological modelling results is dependent on the quality of the input data used. It is also an acknowledged fact that many hydrological studies are hampered by both a lack of data, and a lack of integration of existing data, particularly for studies at the catchment scale. So, the development of new hydrological theories can be accelerated by intense fieldwork in research catchments. The HWM group has, next to some specific short field campaigns, two research basins where hydro(geo)logical processes are studied: the Hupselse Beek catchment and the Noor catchment. The Hupselse Beek catchment has a measurement record from the late 1950s, and it is famous for its geological simplicity. These features make this research basin very suitable for rainfall–runoff modelling and for research on the transport of nutrients and pollutants at the field and catchment scale. The Noor catchment is located in a geologically more complex region and is used for research on flow routes, residence times, transport processes and water balance studies. Catchments like these make it possible to test new theories, such as the hillslope-storage dynamics, in the field.

IMPROVED OBSERVATIONS OF HYDROLOGICAL STATE VARIABLES

New earth observation missions (e.g. ENVISAT, MSG, GRACE, GPM) are expected to revolutionize hydrology by supplying the environmental drivers that have been lacking to date. A primary justification for these satellite missions is to provide spatio-temporal land surface information that, when coupled to hydrological models, allow the estimation of soil moisture and the prediction of river flow.

Gravity derived river basin water storage changes: closing the water balance

In a PhD research study, granted the AGU Horton Research Award of 2002, the possibility of detecting variations in river basin water storage from measurements of the time dependent gravity field were investigated, including an assessment of the accuracy of these estimations based on *in situ* and satellite observations of the gravity field (Hasan, 2006). The hypothesis of this research is that time dependent gravity measurements, both *in situ* and satellite based, contain information about water storage in surface and subsurface reservoirs (the unsaturated zone and aquifers).

Traditionally, the gravity field has been treated as essentially steady-state because 99% of the field from a rotating fluid figure of the Earth's mass is static in historic time. The remaining 1% of the fluctuations of the gravity field is caused by processes that vary on time scales ranging from hours to thousands of years. Temporal variations are caused by a variety of phenomena that redistribute mass, including tides raised by the sun and the moon, and post-glacial rebound. The hydrosphere is the other source of much irregular variations in the time-varying mass distribution from sub-daily to long-term. These variations are very exciting, because of the potential to study changes in groundwater levels and basin-scale water storage changes (Dickey, 1997). Gravity information may even open a new route towards solving the important issue of basin-scale water storage changes for hydrological and climate modelling. As an example, Goodkind & Young (1991) reported some examples of the interaction between hydrological phenomena and gravity. The first example shows the potential of *in situ* techniques. At two locations with superconducting gravimeters near to volcanoes on Hawaii, the temporal variation in the gravity field is well explained by the temporal storage of rainwater in interconnected aquifers. So, gravity provides very explicit information about local hydrology. The second (airborne) example is the GRACE satellite mission (Gravity Recovery and Climate Experiment) that will accurately map the gravity field at 2–4 week intervals, providing global data on temporal changes in continental water storage. Although the first results are promising, the relative accuracy of the Grace-derived estimates is still influenced by instrument error, atmospheric modelling errors, and the magnitude of the variations. Therefore we are investigating how *in situ* observations of the gravity field, such as provided by the superconducting gravimeters, will allow us to increase the relative accuracy of these GRACE-derived estimates. When this is achieved, then really the step will have been made from *in situ* point-scale river basin water storage change measurements to integrated measurements at a much larger scale using remote sensing techniques.

Precipitation

Another example of making the step from point scale *in situ* measurements to regional information is the development of rainfall estimation using weather radar. Because rainfall constitutes the main source of water for terrestrial hydrological processes, accurate measurement and prediction of the spatial and temporal distribution of rainfall is a basic issue. The group has made important contributions to the parameterization of rainfall microstructure for radar meteorology and hydrology, with a direct impact on hydrological modelling at the catchment scale. In particular, a novel mathematical framework for the description of raindrop size spectra and their properties has been developed (Uijlenhoet, 2001). This framework, which takes the form of a scaling law, unites all previously proposed parameterizations for the microstructure of rainfall. Moreover, it provides a physical interpretation for the parameters of radar reflectivity – rain rate relationships, which are central to rainfall estimation using weather radar.

DATA ASSIMILATION: COUPLING OBSERVATIONS AND MODELS

Despite its promise, distributed modelling of hydrological processes has its limitations. The major problems are over-parameterization and uncertainty. Distributed models require a level of spatial data that only remote sensing can provide. Also, models need to be designed to work with spatial information from spaceborne sensors. Combining and integrating the capabilities of and information from simulation and remote sensing techniques is thus both appealing and necessary for improving our knowledge of fundamental hydrological processes (Troch *et al*., 2003b).

Soil water storage and data assimilation

The ability to predict soil water storage and movement in a heterogeneous landscape is important to managing water resources (Van Loon & Troch, 2002). Many studies have addressed spatial variability of soils and soil water by recognizing the stochastic nature of local variability. The integration of both systematic and stochastic components has partially been achieved by conditioning geo-statistical techniques with secondary data such as topographic indices. However, geo-statistical techniques do not explicitly incorporate the knowledge about system dynamics and cannot easily take advantage of additional conditioning information at various scales, such as catchment discharge or evapotranspiration from different vegetation patches. In summary, we can say that there are two distinct types of soil moisture studies: (a) focusing on the lateral soil moisture distribution and using static models, and (b) considering the vertical distribution of soil moisture while using dynamic models. The first type of study uses mainly field observations of soil moisture in combination with soil and terrain properties, whereas the second type of study almost exclusively uses remote sensing observations. It is the aim of this study to combine elements from both areas, as a first step towards an integration of the two approaches. The key ingredient for this integration is regularization, a new data assimilation techniques recently developed by van Loon & Troch (2002), i.e. the appropriate weighting of both model components in a structured and objective manner.

Assimilating latent heat flux estimates within distributed models

Schuurmans *et al*. (2002) address the question of whether remotely sensed latent heat flux estimates over a catchment can be used to improve distributed hydrological model water balance computations by the process of data assimilation. The data used is a series of NOAA-AVHRR satellite images for the Drentse Aa catchment in The Netherlands for the year 1995. These 1 × 1 km resolution images are converted into latent heat flux estimates using SEBAL (Surface Energy Balance Algorithm for Land). The physically-based distributed model SIMGRO (SIMulation of GROundwater flow and surface water levels) was used to compute the water balance of the Drentse Aa catchment for that same year. Comparison between model-derived and remotely sensed area-averaged evapotranspiration estimates show good agreement (Fig. 4), but spatial analysis of the model latent heat flux estimates indicate systematic under

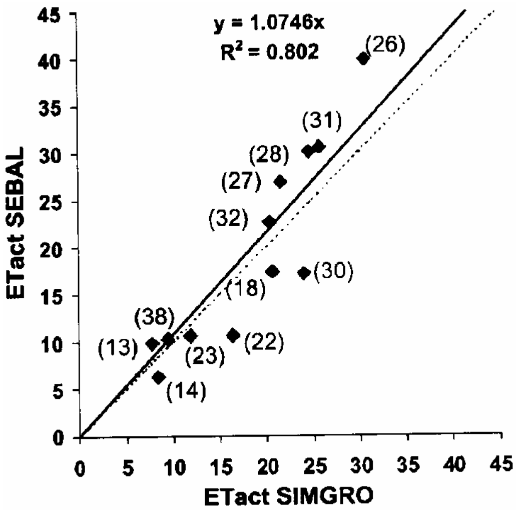

Fig. 4 Scatter plot of the area-averaged actual evapotranspiration over one week calculated by SIMGRO and SEBAL (mm). The week numbers of 1995 are given between parentheses. The dotted line represents the 1 to 1 line, the solid line the relationship between the data points (Schuurmans *et al.*, 2002).

estimation in areas with higher elevation. A constant gain Kalman filter data assimilation algorithm is used to correct the internal state variables of the distributed model whenever remotely sensed latent heat flux estimates are available. It was found that the spatial distribution of model latent heat flux estimates in areas with higher elevation (left edge of catchment) were improved through data assimilation (Fig. 5).

Data assimilation for regional water balance studies in arid and semi-arid areas (Ghana)

The objective of this research is to improve the methods for estimating the regional water balance in arid and semi-arid regions of Africa. For this, the synergetic use of remotely sensed land surface and lower atmosphere characteristics, *in situ* observations, distributed modelling of water and energy balances, and data assimilation procedures are chosen. The expected results are: (a) improved water and energy balance models to compute catchment-scale fluxes, and (b) innovative river basin management tools based on data assimilation. For a selected region in Africa (Volta basin), a distributed water balance modelling strategy will allow computation of the partitioning of net rainfall into surface runoff and infiltration components. The model is formulated in a distributed way, by incorporating information on topography and soil variability. Data needed for the application of this model are basin discharge, daily precipitation and evapotranspiration rates. Both the water and the energy balance models can rely on input data provided by the MSG satellite system. In addition to the MSG derived surface parameters and driving forces of the water and energy balance, information from SAR sensors will be employed to further parameterize the distributed models, including soil moisture status, canopy characteristics and vegetation moisture status. Furthermore, the model-derived and remotely sensed state variables and parameters of the water and energy balance need to be combined in a computationally efficient way.

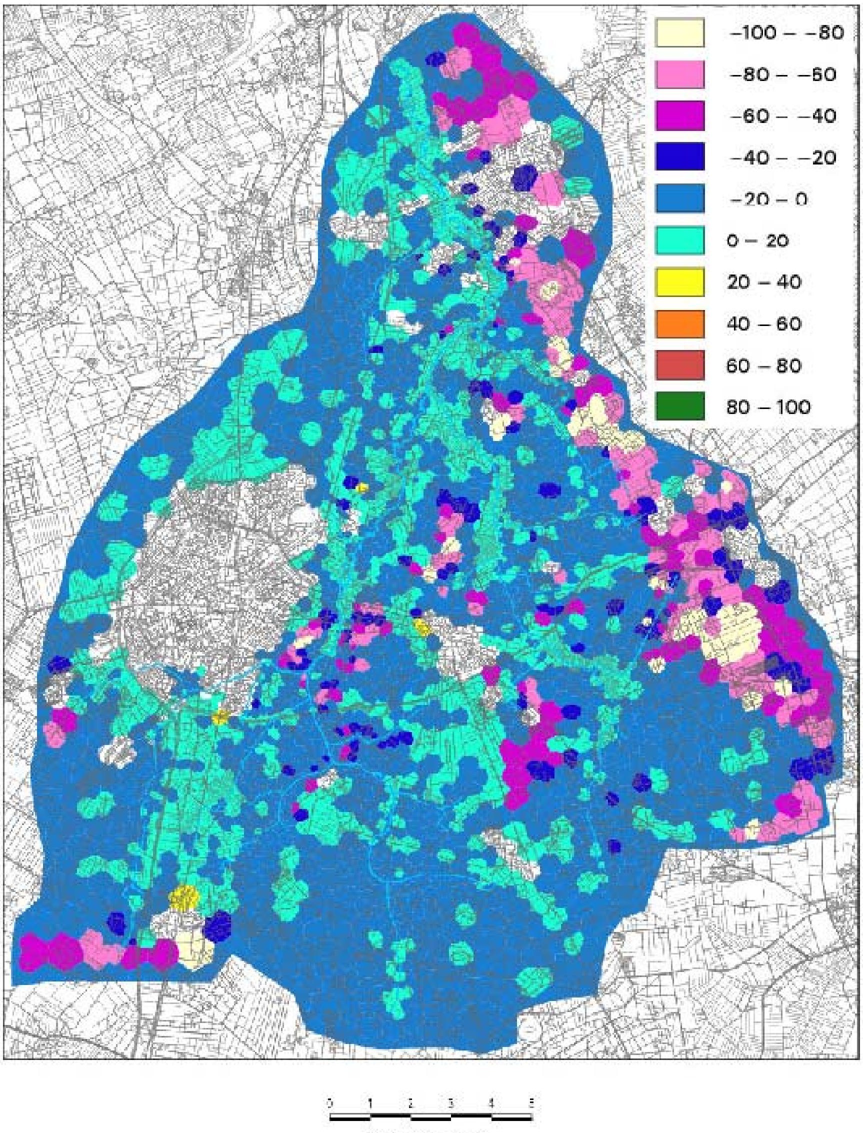

Fig. 5 Spatially distributed difference in yearly latent heat flux [mm] as calculated by the SIMGRO model without and with data assimilation. Negative values mean that the actual evapotranspiration calculated by the model with data assimilation is higher than the actual evapotranspiration calculated without data assimilation.

Three different data assimilation strategies are applied (direct insertion, nudging and statistical interpolation) in order to investigate the efficiency of these procedures to improve the regional water balance. The accurate estimation of the current day water balance of the Volta River is crucial to predict trends in water availability.

Data assimilation of remotely sensed spatial patterns for model structure identification

The complexity of the groundwater–surface runoff interaction forms a major challenge in catchment modelling. Due to the fact that the hydrological system is heterogeneous and distributed, its identification is ill-posed. In this situation progress can be made by supplementing *in situ* observation with remotely sensed soil moisture and evapotranspiration observations. By concentrating on the assimilation of remote sensing data, in its broadest interpretation, with the new strategy in catchment-scale hydrological modelling, this research aims at resolving the long-standing ungauged catchment problem. We propose a novel approach to data assimilation where spatio-temporal patterns of hydrological state variables and fluxes will serve as a means to identify catchment model structure. The method will be based on the recently developed cross-validation filter of van Loon & Troch (2002).

CONCLUDING REMARKS

The IAHS Decade on Predictions in Ungauged Basins (PUB) is a very interesting initiative to bring the hydrological science to the next level. Within all four themes identified, the Hydrology and Quantitative Water Management group from Wageningen University can play a significant role. However, its main focal point lies within the theme "Advanced Data Collection Technologies". Examples of this research are the activities on data-assimilation, on the use of remotely sensed data, on the improvement of techniques and procedures to accurately measure and/or derive precipitation, soil moisture, discharge and evapotranspiration, and on the up-scaling and down-scaling techniques.

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