Development of a Validation Tool for Regional Distributed Models using Coarse Scale Soil Moisture Products, Case study: Great Letaba River, South Africa

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EXTENDED ABSTRACT

The majority of river basins in semiarid regions have a poor hydrological infrastructure or are even ungauged. Due to their specific climatic characteristics these catchments are naturally water stressed areas and local water management authorities are under obligation to balance disparities between regions with water surplus and those with water shortage. Water management requires reliable prediction of the hydrological dynamics by means of distributed, physically based models. However, these models are difficult to calibrate and to validate due to the lack of data.

The paper addresses this deficit by presenting research results on the development of an independent validation tool for hydrological models that can be applied to downscale macro-scale soil moisture data derived from the remotely sensed ERS-Scatterometer dataset. The method developed applies the concept of Hydrological Response Units (HRU) to further analyze the spatial variability within one Scatterometer footprint. The HRU are used as model entities in the process- oriented modular modeling system J2000. The study area is the Great Letaba River catchment (approx. 4.700km²), a tributary of the Olifants River in South Africa.

The paper highlights problems of representing the observed runoff by the model. Firstly, the comparison between modelled and simulated runoff showed that some runoff events had been overestimated. Analysis of the runoff data along the river course of the Great Letaba showed that the runoff continuously decreased. This is primarily due to evaporation losses within the river course, water extraction along the river due to transportation of water out of the catchment, irrigation farming and dams which were built for this purpose. Secondly, the modeling results are depended on density of precipitation stations within the catchment. The modeling results showed an under simulation of single events during the rainy season. From the examination of precipitation data it can be argued that the density of stations in this area is not able to measure local precipitation events and leads to the conclusion that the precipitation can be underestimated.

In a next step, the simulated soil moisture data were compared to the remotely sensed ERS-Scatterometer data (Figure 1).

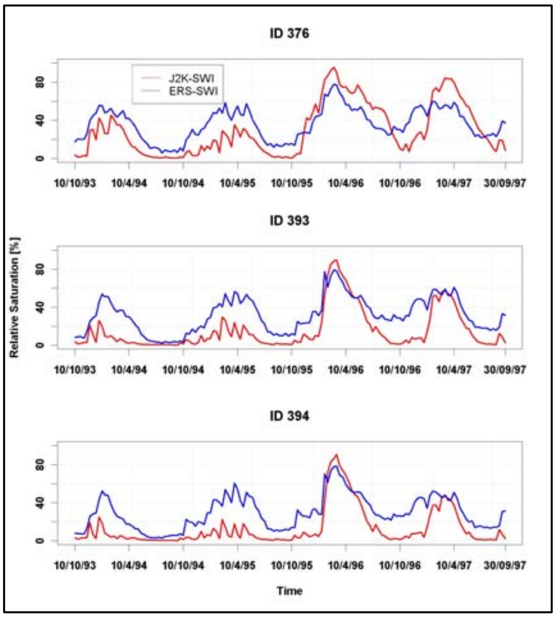

Figure 1. Comparison of the time series of the two Soil Water Indices

Figure 1 shows that similar dynamics were predicted by J2000 as derived from the ERS-Scatterometer. This was also reflected by the correlation analysis, representing coefficients of determination higher then 0.59.

The results of this study show that both data sets (modelled soil moisture time series and soil moisture time series derived from the ERS-Scatterometer) contain information in order to describe soil moisture generation in time and space.

1. INTRODUCTION

Regional Water Management authorities in South Africa are under obligation to ensure the local population access to water (Republic of South Africa 1998). However, most parts of that country belong to the semiarid climate zone. These areas are characterized not only by highly spatial imbalance in water supply between regions, but also in high temporal variability of yearly rainfall. Due to these natural characteristics, water authorities rely on hydrological models to predict the rainfall-runoff relationship properly. Unfortunately, most semiarid catchments lack satisfactory data sets, a basic requirement for hydrological models, so their application is strongly limited. Additionally, due to data errors, the calibration and validation procedures are questionable. Transfer functions such as the empirical regression approach (Beven 2001:86ff) in which models use indices of similar catchments offer a possibility for applying hydrological models in areas with limited data. However, due to the individual characteristics of every catchment the transfer from one catchment to another is difficult. To overcome this problem other sources of information have to be used and other validation tools have to be developed. Here, remote sensing techniques offer a high potential because they operate over wide areas with temporal resolution of several days.

One main current research focus in remote sensing is the quantification of soil moisture from space. Researchers have been focused on the derivation of soil moisture from microwave data (e.g. Jackson et al. 1999, Zribi et al. 2002) because the microwave signals are independent of cloud cover and can penetrate into the soil column up to a few centimeters depending on wavelength. However, the interpretation of these data is very complex because of the dependency of the backscattering on soil texture, surface roughness, vegetation, and geometry effects (Lewis & Henderson 1998).

The global remotely sensed soil moisture data set (Scipal et al. 2005) based on microwaves was derived from the European Remote Sensing Satellite (ERS) Scatterometer (Wagner et al. 1999) This data set contains two information layers: the surface soil moisture information (ms) and the Soil Water Index (SWI) an indicator for root zone soil moisture (Wagner et al. 1999). The later data set is available with a weekly to monthly temporal resolution. However, the spatial resolution of these data sets is 50km. This is problematic for hydrological purposes because models generally require more highly resolved data. However, the assumption of this study is that coarsely resolved data contains valuable information to bridge the scale related gap between local in-situ measurements and spatial data demands for hydrological model validation and parameterization. Therefore, the coarse scale soil water product was compared to modeled soil moisture time series. The evaluation and utilization of spatially low resolution scatterometer data should give a better understanding of the weaknesses and strengths of both the hydrological model and the remotely sensed data products.

2. SITE DESCRIPTION AND SYSTEM-ANALYSIS

The Great Letaba River catchment is located in the north eastern part of South Africa. The catchment size is approximately 4700km² at the river gauge Letaba Ranch (23°39’29.0’’S, 31°03’00.0’’E) (Department of Water Affairs and Forestry 2007). The basin of the Great Letaba River is characterized by high elevation differences (between 330 and 2120m (USGS 2003), Figure 2) on which the vegetation is adapted (CSIR & ARC 2005).

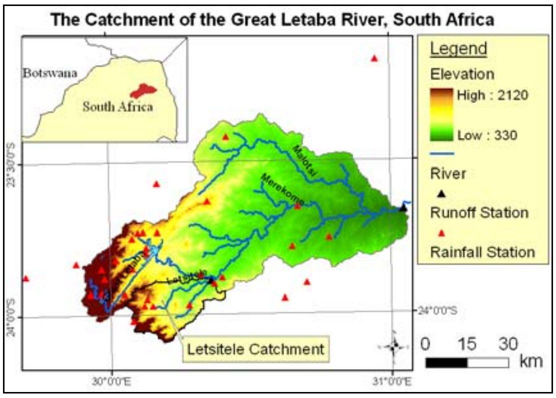

Figure 2. Location of the Great Letaba catchment

The high elevated (> 650m NN) areas are dominated by forests, especially monoculture of eucalyptus, pine and acacia. The lower elevations are characterized by savanna vegetation (bush- and woodland) which are interspersed by agriculture mainly along the river course. The intensive agriculture, however, leads to the problem of extensive soil exposure. Thus, in combination with the climatic conditions, these areas are affected by soil erosion.

The climate of the catchment is semiarid which is characterized by seven to nine months in which evapotranspiration exceeds precipitation (Lauer & Frankenberg 1987). This also indicated by the calculated runoff-rainfall coefficient of 0.05. The analysis of the available rain-fall data (1980-1999) was carried out using 35 stations located within and around the catchment. The calculated mean annual precipitation (MAP) was 760mm showing high spatial differences in over the catchment. The amount of MAP ranges from 1750mm in the mountainous area in the western part down to approximately 420mm in the eastern part of the catchment. Figure 2 also depicts the availability and distribution of rainfall stations in the catchment. The high elevated area is relative well instrumented whereas in the eastern part only a limited number of rainfall stations are present. Along the Malotsi River course in the north east of the catchment no rainfall stations exist. A similar situation is shown downstream of the Great Letaba River. Another problem is the type of rainfall, which mostly falls as convective rainfall (Typson 1987:6), it is very likely that the overall amount is underestimated by the measurement network.

According to the FAO (2003) the soil is distributed as follows: In the headwater, as well as in the north eastern part of the catchment, soils with high clay content (>25%) such as lixisole, acrisole, nitisole and luvisole are dominant. In the center and the south east part of the catchment medium clay content (between 10 to 25%) soils such as leptosols and regosols are characteristic. Close to the outlet, in the south western part of the catchment, arenosols can be found, which are high in sand content. The catchment of the Great Letaba River is mainly characterized by precambrian granites, gneisses and granitoids (Vegter 2003:i).

3. DATA BASE[1]

For rainfall-runoff-modeling of the Great Letaba River catchment the following daily hydro-meteorological time series have been used as input data sets (Table 1).

Table 1. Hydro-meteorological datasets

Data Set	Stations	Period	Source
Precipitation	35	1980-1999	Lynch (2004)
Temperature	9	1992-2004	SAWS
Relative Humidity	3	1993-2004	SAWS
Sunshine duration	2	1993-2004	SAWS
Wind speed	1	1993-2004	SAWS
Runoff	1	1959-2006	DWAF
Remotely Sensed Soil Water Index	3	1992-2000	IPF (TU Vienna)

SAWS = South African Weather Service, South Africa, DWAF = Department of Water Affairs and Forestry, South Africa, IPF = Institute for Photogrammetry and Remote Sensing (TU Vienna)

The rainfall network density amounts to approximately seven stations per 1000km². Only nine temperature stations are located within the catchment and the surrounding area. The relative humidity was measured on three of these stations. Two stations recorded sunshine duration and only one station was available for wind speed measurements. The time series showed data gaps which were filled.

The modeling system applied uses distributed model entities for spatial system representation. These entities are based on the concept of the Hydrological Response Units (HRUs) (Flügel 1995). The requirement for the delineation of the HRUs is an integrated system analysis which is based on the evaluation and assessment of hydrological relevant system characteristics such as topography, soil, geology and vegetation as well as the analysis of hydro-meteorological time series (Table 1) (Flügel 1995).

Table 2. GIS-Datasets for the HRU-Delineation

Data Set	Description	Source
Topography	Shuttle Radar Topography Mission (SRTM)	USGS (2003)
Geology	Hydrogeol. Maps (Messina, Polokwane, Phalaborwa)	DWAF (2002, 2003)
Soil	Soil and Terrain Database for Southern Africa	FAO (2003)
Land cover	National Land cover (NLC) South Africa 2000	CSIR & ARC (2005)

USGS = U.S. Geological Survey, FAO = Food and Agriculture Organization of the United Nations, CSIR = Council for Scientific & Industrial Research, South Africa, ARC = Agricultural Research Council, South Africa

In order to derive the HRUs the GIS-Data sets (Table 2) were reclassified, overlaid and aggregated according to the landscape characteristics. For the Great Letaba 6996 HRUs have been delineated and were used as model entities in J2000 (Krause 2001).

4. THE HYDROLOGICAL MODEL J2000[2]

The background of the proposed study is the evaluation of the coarse scale soil moisture product. Therefore, all parameters influencing the spatial and temporal distribution of soil moisture are needed. This demand can be met by the delineation of process oriented model entities in distributed hydrological models. However, hydrological models are developed to analyze problems at a determined scale and for a determined task that is reflected by the model structure (Singh 1995).

[1] This section was taken from Scheffler et al. (2007)

[2] Parts of this section have been taken from Scheffler et al. (2007)

The model used for this study was the distributed, process oriented, modeling system J2000 (Krause 2001). The structure of the model is shown in Figure 3. The modeling system has been successfully applied in catchments between 2 and 6000km² in Europe (Krause 2001). Additionally the model was applied in the semiarid catchments of the Tsitsa River (Bäse et al. 2006) as well as the Great Letaba (Scheffler et al. 2007) in South Africa.

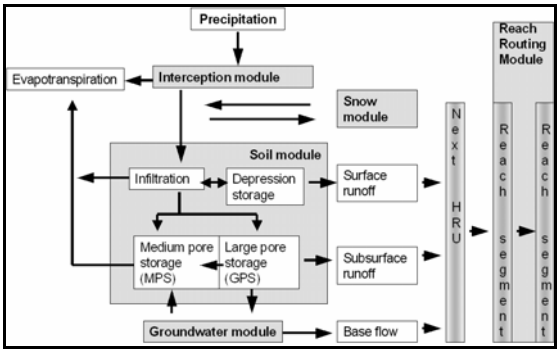

Figure 3. The modeling system J2000 (modified from Krause 2001:74 & 89, modified from Bäse 2005: 25)

As shown in the figure, the modeling system is divided into the process modules such as interception module, snow module, soil water module, ground water module as well as the reach routing module. For every model entity (HRU) the runoff components surface runoff and interflow are calculated in the soil module and the fast and slow base flow components are calculated in the groundwater module. Afterwards, the simulated values of all the runoff components are routed to the adjacent underlying HRU and added to the respective storages. This repeats until a reach segment is reached. Within the reach segment the water is transported to the catchments outlet.

One aspect of this study has been the comparison of the SWI-data set with simulated soil moisture time series at finer scale. To select an appropriate model, different concepts with a particular consideration of the soil module were analyzed. According to Krause (2001: 87) the following concepts exist: a) the soil column is represented as a single storage, b) the soil column is divided into vertical soil layers c) the soil column is separated on the basis of specific pore storages, modelled as parallel operating storages. Concept c) has been applied in this study. As discussed in Scheffler et al. (2005) this concept represents "a realistic generation of soil moisture" (Scheffler 2005: 4) because of its enhanced consideration of physical soil parameters. The soil module separates the soil layer into medium pore and large pore storage. Depending on the empirically calculated infiltration rate the water infiltrates into the soil storages or is routed to the depression storage. The middle pore storage loses water due to evapotranspiration whereas the large pore storage depletes by subsurface runoff and groundwater generation.

5. RESULTS

5.1. Modelling Results[3]

Semiarid areas are characterized by a strong seasonal rainfall accompanied with high evapotranspiration rates. Especially during the dry season, the soil moisture content can drop tremendously. Archer et al. (2002) studied a field site in south–eastern Spain where they found that the soil moisture was dropping down to wilting point during the dry season. Therefore, based on the modeling results in Scheffler et al. (2007), the model parameters of the soil module and groundwater module have been adjusted to deplete the medium pore storage and to have a better representation of the soil water generation.

The runoff-precipitation simulation of the Great Letaba has been carried out for the time frame between 1993 and 1999 in which 02/1993 to 09/1997 was used as calibration period and 10/1997 to 12/1999 as validation period. The simulation results are presented in Figure 4.

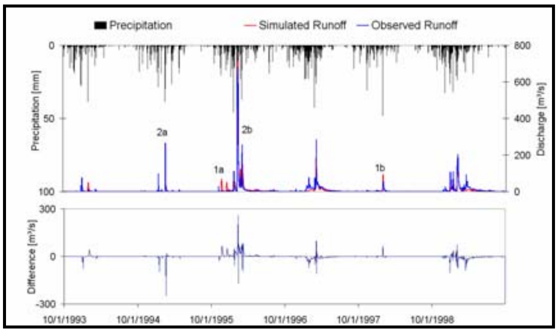

Figure 4. Simulated hydrological dynamics with the distributed model J2000, Great Letaba catchment

The figure shows that the J2000 model is able to predict the runoff dynamics of the Great Letaba River. In comparison to the modeling results in Scheffler et al. (2007) the Nash-Sutcliffe-Efficiency (NSE) (Nash & Sutcliffe 1970) improved from 0.76 to 0.78 in the calibration period and from 0.53 to 0.71 during the validation period. Also, the calculation of the logarithmic Nash-

[3] Paragraphs 3 to 5 of this section were taken from Scheffler et al. (2007)

Sutcliffe efficiency (log NSE) (Krause et al. 2005) had been adjusted. In the current formulation of log NSE it is a perfect fit if both prediction and observation runoff values are zero. In case either prediction or validation is zero, that pair will be excluded from the calculation due to conceptual reasons. Due to this calculation the log NSE value (log NSE = 0.36) shows a moderate model fit. As discussed in Scheffler et al. (2007) the first half of the calibration period (1993 to 1995) was below long term MAP. This period was characterized by seasonal dry periods up to seven months in which no runoff was measured. This seasonality of the river runoff was not simulated by the model. The validation period instead shows a very good value of the log NSE (log NSE = 0.67). During this period, however, the river never runs dry; this is mainly caused by higher precipitation, also expressed in a higher mean annual rainfall.

However, regardless of better model efficiencies some overall modeling problems remain. First, the representation of single events such as the over-prediction of the observed runoff at the beginning of the summer 1995/96 (flag 1a, Figure 4) is deficient. Analysis of the precipitation data showed that a precipitation event in the headwater of the Letsitele River (Figure 2), a tributary of the Great Letaba River, was the main cause of the runoff event. This was also confirmed through runoff measurements at the Letsitele gauge station. The data examination of the runoff data along the river course of the Great Letaba showed that the runoff continuously decreased because of evaporation losses (McKenzie & Craig 1999) and water extraction, both not considered in J2000 yet. The hydrological dynamics of the Great Letaba is influenced by transportation of water out of the catchment, irrigation farming and dams which were built for this purpose. Due to the low precipitation that characterized the 1993 to 1995 time period it can be assumed that the dams along the river course contained only a limited amount of water at this time. The runoff reduction at the beginning of the rainy season 1995/96 can be explained partially through filling of the dams. Flag (1b) in Figure 4 indicates a similar situation for which it is assumed that the runoff reduction has been caused by water extraction along the river course.

Second, the modeling results showed an under simulation of single events during the rainy season e.g. in the year 1994/95 (flag 2a, Figure 4). In order to clarify that under simulation, data from runoff stations along the river have been analyzed. The analysis of these data showed that the runoff has its source in the area between the Letsitele river station and the catchment outlet. Also, a comparison of the six stations in this 3000km² expanse showed that precipitation had been recorded in this area but the total amount of these events can not explain the observed runoff. Therefore, it can be argued that the density of precipitation stations in this area is not able to measure local precipitation events and leads to the conclusion that the precipitation can be underestimated. Flag 2b (Figure 4) refers to similar situations for which an underestimation of the precipitation might cause the under prediction of the runoff by the model.

5.2. Comparison of the simulated soil moisture to remotely sensed time series

In order to compare the soil moisture time series to the SWI-data set the area within the respective footprints was first determined.

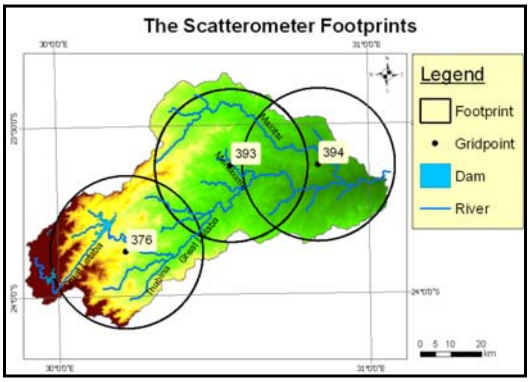

Figure 5. Location of the scatterometer – footprints in the Great Letaba catchment

To obtain the area within one scatterometer footprint a circle of 25km radius was used. As shown in Figure 5 the Great Letaba River catchment is mainly covered by three scatterometer-footprints. For a comparison of the soil moisture time series achieved by the J2000 hydrological model, the time series had to be normalized using the following equation:

$$sw = sw_{FPS} + sw_{MPS} + sw_{GPS}$$
$$\text{J2K-SWI} = \frac{sw - sw_{min}}{sw_{max} - sw_{min}} \qquad (1)$$

First, the water content of the entire soil column was calculated by summing the water content of the three storages: fine pore storage (sw_{FPS}), medium pore storage (sw_{MPS}) and coarse pore storage (sw_{GPS}) up. The fine pore storage acts as a constant, derived from the soil parameters of the FAO (2003). In the second step, the highest (sw_{max}) and lowest (sw_{min}) value of the entire time series (sw) were determined. Additionally, only every 10th day has been extracted from the time series of the

J2K-Soil Water Index (J2K-SWI) because of the 10 day temporal resolution of the ERS- Soil Water Index (ERS-SWI). After this data preparation, the mean area weighted average of the J2K-SWI was calculated over all soil moisture time series of the HRUs lying in the respective footprint. Figure 1 depicts the comparison between the J2K-SWI and ERS-SWI time series. The figure shows that similar dynamics were predicted by J2000 as derived from the ERS-Scatterometer. This is also reflected by the coefficients of determination (ID 376: R^2 = 0.59, ID 393: R^2 = 0.63, ID 394: R^2 = 0.60) for the three scatterometer footprints. The correlation analysis shows that footprint 393 has a slightly higher coefficient than the other footprints. Footprint 376 is mainly characterized by forest, bushland and agriculture. The land cover of the footprint 393 changes to savanna vegetation and agriculture along the river course. In the eastern part of the catchment (footprint 394) the portion of the woodland vegetation increases. Due to the fact that the scatterometer can not penetrate a dense vegetation cover (Lewis & Henderson 1998) the higher R^2 might be explained to some extent by the variability in land cover.

Additionally, Figure 1 shows that the J2K-SWI mostly predicts lower values than the ERS-SWI. Here, the formulation of the ERS-SWI might be the reason. The calculation of the ERS-SWI only depends on the water content of the surface soil moisture layer: Interactions with the surrounding environment, process such as transpiration, groundwater recharge, lateral flow as well as upward fluxes are neglected (Wagner 1998) whereas the model J2000 takes these processes into account. Figure 1 also depicts seasonal deviations especially during the transition periods between wet to dry and dry to wet period. Here, a further investigation has to be carried out.

6. CONCLUSION AND OUTLOOK

The application of a distributed model in the semi-arid catchment of the Great Letaba produced reasonable modeling results. However, the calibration of the model was influenced by two major factors. First, irrigation farming as well as water extraction were not taken into account in the actual version of the hydrological model. Second, the analysis of the precipitation and runoff data showed that the available density of rainfall stations is not high enough for a detailed representation of the precipitation distribution. Therefore, it can be assumed that local rainfall events are not measured and therefore cannot be modeled with J2000.

However, the comparison between the simulated and remotely sensed soil water time series showed significant similarities despite the fact that the datasets are based on different concepts. The modeled soil moisture time series were produced using a process oriented hydrological model whereas the remotely sensed soil water time series were achieved using indirect measurements of the surface moisture content. Following the results of this study, both data sets contain information in order to describe soil moisture generation in time and space. The remote data set can be a valuable source in order to better understand the model's behavior in a temporal as well as in spatial context. However, from this point the following main research tasks arise: 1) Analysis of the differences in the transition periods from summer to winter and vice versa 2) Examination of soil moisture distribution at small scale using the HRUs 3) Derivation of strategies for model improvement as well as improvement for remotely sensed data sets.

7. ACKNOWLEGDEMENT

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