Hydrological Modelling For Quantification Of Coarse Scale Soil Moisture In Southern Africa

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EXTENDED ABSTRACT

The prediction of hydrological dynamics is an important issue in the scientific community of hydrologists and modellers and essential for integrated water resources decision support. However, the utilization of hydrological models in regions with no or a limited amount of measured data is restricted. Remote sensing techniques provide the means to derive such information, e.g. land cover or soil moisture, over various space and time scales.

The ERS scatterometers on board the European Remote Sensing Satellite (ERS)- 1 and -2 are able to provide large scale soil moisture content in the top layer (<5cm) of soil (Wagner et al. 2003) and in combination with an infiltration model, the Soil Water Index (SWI) can be derived. The temporal resolution of the Scatterometer amounts to 3-4 days depending on conceptual formulation. The SWI can be directly derived without any external data sources from ERS Scatterometer data. However, the disadvantage of this dataset is its spatial resolution of 50x50km because a spatial resolution of this size is only useful for global modelling. However, an application of this data set at a regional scale would be a valuable tool for validation and after further investigation as data source, in particular for ungauged basins.

Therefore, an assessment of these datasets is necessary to estimate its usefulness for regional hydrological modelling, which is the overall objective of the study. To obtain soil moisture information three approaches can be used: First, field measurements achieve soil moisture information as point measurements and are barely able to show spatially variability representatively over an area of 50x50km. Second, remote sensing techniques offer the possibility to acquire soil moisture information over wide areas. However, currently only one global validated data set is available (Scipal et al. 2005) with the disadvantage of 50x50km spatial resolution. Third, hydrological models predict soil moisture as a part of the hydrological cycle whereas the accuracy of these estimates depends on the model structure as well as model input data. As a result of the inability to represent large spatial distributions by finely resolved ground-based measurements and the deficiency of remote sensing techniques to provide fine-scale soil moisture estimates, the evaluation of the coarse-scale data set will be based on the application of a hydrological model to obtain soil moisture values more finely resolved in terms of time and space than the original Scatterometer data.

The applied concept to assess coarse-scale soil moisture data is based on the assumption that the value of one Scatterometer pixel reflects the moisture conditions as an integral response over a representative area and that the remotely measured moisture conditions result from heterogeneous physiographic properties. This spatial variability will be managed by applying the Hydrological Response Units (HRU) approach, which can differentiate the heterogeneity within a grid cell. Additionally two model concepts for soil layer representation are examined: first, the two layer concept dividing the soil layer into horizontal layers and second, the concept of subdividing the soil layer into its pore size storages. Therefore, the Precipitation Runoff Modelling System (PRMS) Model and the J2000 model will be applied in the study area of the Limpopo River in southern Africa.

This paper includes preliminary PRMS model results to achieve fine scale soil moisture estimates, which are later used to assess coarse scale soil moisture. The modelling results show a model performance dependent on weather conditions. Whereas the model predicts poorly under dry conditions, it performs satisfactorily under humid conditions. In a next step the application of the J2000 model will show if this model concept is suitable for semiarid catchments and therefore to predict soil moisture generation more accurately then the PRMS model. After completing the hydrological modelling with J2000, the analysis of temporal and spatial time series will follow that will lead to the evaluation of the coarse-scale soil moisture data set.

1. INTRODUCTION

Hydrological models require a defined data set to predict the rainfall-runoff relationship properly. In regions with a limited amount or even no observed information the application of hydrological models is strongly limited. However, the need to predict hydrological dynamics in ungauged catchments has been discussed widely in the scientific community.

A possible method is the empirical regression approach (Beven 2001) in which empirical models use indices of similar structured catchments. However, every catchment has individual characteristics and model parameters cannot simply be transferred from one basin to another. A better solution would be to look for other data sources such as remote sensing which has been used to derive land use and topographic information as well as for plant physiological parameters. In addition to these parameters, scientists are working on the derivation of soil moisture, an important parameter in many hydrological models. So far, hydrological models do not work with soil moisture as input but simultaneously soil moisture data could be used for validation and after further investigation as an input data set.

Global remotely sensed soil moisture data sets were derived recently from the European Remote Sensing Satellite (ERS) Scatterometer that is an active microwave sensor with a coarse spatial resolution and a high temporal resolution. By applying a change detection method (Wagner et al 1999) surface soil moisture information and the Soil Moisture Index (SWI) an indicator for root zone soil moisture were retrieved with a temporal resolution of weekly to monthly depending on the conceptual formulation. According to Scipal et al. (2005) the surface soil moisture is described as a degree of saturation in relative units and the SWI represents the percentile measurement of soil moisture between soil moisture extremes dry and wet which have been shown to correlate well with the wilting level and the point central to the field-capacity were compared to the total water capacity.

However, the drawback of this data set is its coarse spatial resolution of 50x50km. This resolution is problematic because hydrological models generally require more highly resolved data. For the purposed application of this data as validation tool and as data source for hydrological models, the gap between scales has to be mitigated by developing a downscaling approach under consideration of scale issues. The evaluation and utilization of spatially low resolution Scatterometer data for hydrological modelling is the main objective of the current research project. The project is based on the assumption 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. The objective is the development of an exact scientific and generic disaggregation scheme for SWI data set based on the assumption that a remotely sensed pixel value provides an average value over a certain area (Western et al. 1999).

The value of coarse soil moisture data was investigated in a few studies such as Reichle et al. (2001), Pellenq et al. (2003) and Kim et al. (2001) who dealt with the feasibility of disaggregating low resolution soil moisture to a finer scale. For example, Reichle et al. (2001) investigated the possibility of achieving fine resolution soil moisture data from passive lower resolution microwave measurements using data assimilation techniques. The downscaling method was based on finer resolved micrometeorological data, soil texture and land cover inputs. Other studies examined the downscaling potential of large scale images in order to determine the temporal and spatial variability of soil moisture (Bindlish et al. 2002 and Kim et al. 2001). The key finding was that soil moisture variability is strongly related to soil texture and vegetation water content. Based on this result the soil moisture information was successfully disaggregated from 10km to 1km with a fractal interpolation scheme. In general, the experiments demonstrated that fine-scale soil moisture could be estimated from low-resolution data. However, the applied downscaling approaches are based on individual relationships, which are dependent on local constraints. For an exact scientific development of a downscaling concept a combination of parameters driving the spatial and temporal soil moisture variability, such as evapotranspiration, soil texture, geology, topography, precipitation and temperature, is recommended. Additionally the distribution concept of response units which is more process oriented than raster based concepts used in most studies could help in the development of a more generic downscaling method which is less dependent on local constraints of test sites.

2. PROPOSED METHOD TO QUALIFY COARSE SCALE SOIL MOISTURE

To develop a downscaling method, finer scale data are required. So far, soil moisture information can be obtained from three sources: First, ground-based measurements provide soil moisture information as a point measurement but at spatial distributions that are limited over a large

50x50km. Second, remote sensing techniques offer the possibility to obtain soil moisture information over various space and time scale. However, only coarse – scale remote sensing techniques succeed in derivation of soil moisture information for routine application. Third, rainfall-runoff models estimate soil moisture as an element of their hydrological cycle whereas the accuracy of soil moisture generation depends on model structure and model input data. As a result of the locally restricted availability of ground-based measurements and the inability of remote sensing to achieve fine-scale soil moisture, hydrological modelling offers the only possibility to obtain soil moisture information at finer scale over an area of 50x50km.

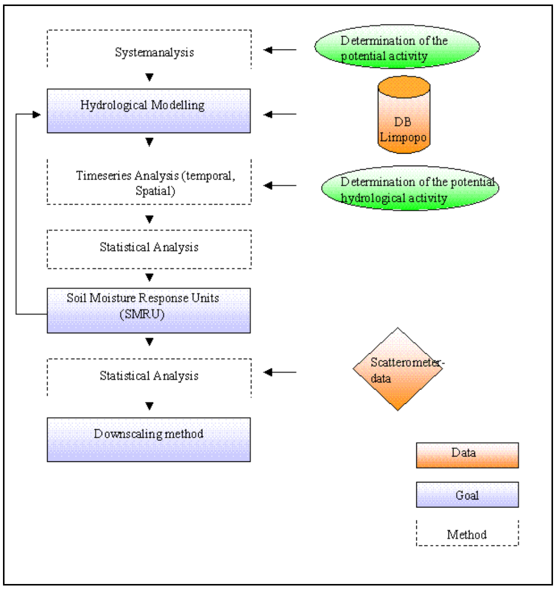

Figure 1: Flowchart of the working processes

The resultant assessment method (Fig. 1) is a combination of large scale measurements and fine scale model outputs and is based on the following assumptions:

(i) The satellite information of each grid cell is driven by physiographic properties within the grid cell.

(ii) To develop a disaggregation scheme, a differentiation of the physiographic heterogeneity is necessary.

(iii) Fine scale soil moisture information can be provided by hydrological modelling.

The value of each Scatterometer grid cell represents an aggregation of single signals of different sources resulting from heterogeneous physiographic properties. To cope with the distinction of heterogeneous physiographic properties the hydrological modelling will be based on Hydrological Response Units (HRU). HRUs are described as distributed, heterogeneously structured entities characterized by a common climate, land use, and underlying pedo-topo-geological association controlling their hydrological transport dynamics (Flügel 1995) which are delineated and parameterized by generally available data (Becker et al 1999). Distributions based on the HRU concept result in a more natural subdivision of a catchment compared to raster cells. These will provide an estimate of the fine scale distribution of soil moisture. Because the HRU concept has been developed for hydrological modelling, it has to be adapted according to the factors governing soil moisture generation. The analysis of temporal and spatial patterns of soil moisture together with their driving physiographic factors, such as soil properties, evapotranspiration, topography, land use, as well as climate will provide the knowledge base for the delineation of the Soil Moisture Response Units (SMRU). Modelling the hydrological cycle based on the SMRUs will simulate the fine scale distribution of soil moisture. Error estimation and sensitivity analysis of the parameter used in the model will help to minimize the modelling error and so to determine the fault tolerance of the downscaling method. The received temporal and spatial finer resolved soil moisture information of the SMRUs will be generalized and normalized by means of statistical analyses to provide a generic basis for the disaggregation of the gridded Scatterometer data. As mentioned before, the disaggregation will be based on all parameters driving the temporal and spatial variability of soil moisture.

Finally, as a proof of the concept, the results will be validated by modeling with time series not used for the development of the methodology described above and the comparison of spatial disaggregated remotely sensed soil moisture data. The timeframe of the study is between 1992 and 2000 whereas the years from 1992 to 1995 represent the calibration period and the years from 1996 to 2000 the validation period. The validation will show if the developed SMRU concept can be used as a disaggregation scheme for remotely sensed soil moisture.

3. SITE DESCRIPTION AND DATA

Based on the data structure and the algorithm used to derive soil moisture the study area had to meet two demands: First, due to the spatial resolution of 50x50km the basin area should cover a few thousands of square kilometers so that at least ten Scatterometer grid cells could be analyzed. Second, a study area in subtropical or temperate climates had to be chosen because the soil moisture algorithm used cannot be applied in snow covered areas or in tropical areas with high vegetation density.

The catchment area of the Limpopo River in southern Africa with an area of about 412.000 km² matches the requirements. Within the Limpopo River catchment, five subbasins were selected. Figure 2 shows the location of these five basins and Table 1 summarizes the size and the main rivers of these subbasins.

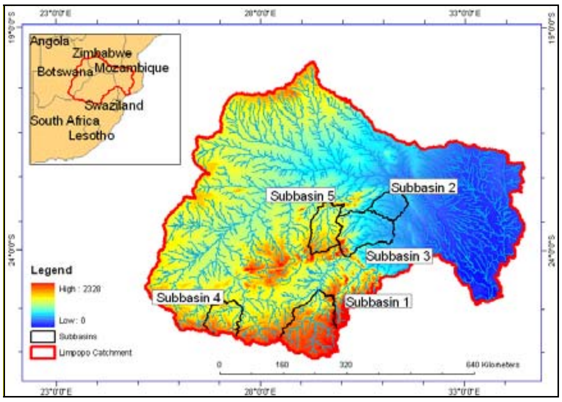

Figure 2: Location and elevation of the Limpopo catchment

Table 1: Subbasins and their size

	River	*Size*
Subbasin 1	Olifants	16531 km²
Subbasin 2	Shingwidzi	4792 km²
Subbasin 3	Letaba	10684 km²
Subbasin 4	Elands/ Hex	6091 km²
Subbasin 5	Sand	7718 km²

The catchment area of the Limpopo River is very heterogeneous. The topography varies from flat surfaces of only a few hundred meters in the east to the South African highveld forms with a height of more than 2000 meters in the south. The climate varies from semiarid to arid conditions with a mean annual precipitation of 520 mm (Abdullah 2003). Most rain falls from November to March. The vegetation is mainly a shrub-savanna or grassland, and pockets of deciduous forest pockets can be found in the highlands. The main soil types, according to FAO classification are Arenosols, Regosols, Luvisols and Acrisols. To establish the hydrological models the following data sets have been used (Table 2).

Table 2: Datasets

Parameter	*Data set*	*Resolution (Spatial/ temporal*
Topographic Information (Elevation, Aspect, Slope etc.)	USGS Digital Elevation Model	1km
Geology	Map of Geological Survey South Africa	1:1000000
Landcover	MODIS Landcoverdata	1km
Hydrometric data	Department for Forestry and Water Affairs, South Africa	Daily
Climatological parameters	University of Kwazulu-Natal, South Africa	Daily
Soil Information	FAO SOTER Database	1:2.000.000

4. HYDROLOGICAL MODELS

Hydrological models are developed to analyse a determined problem, which is reflected in its model structure. To select the appropriate model, different concepts with a particular consideration of the soil module were analyzed.

The comparison of different concepts to describe soil moisture generation showed the following concepts (Krause 2001):

K1: Modelling of the soil as a single storage

K2: Vertical distinction of the soil layer into two or more soil layers and modelling of the compartments as consecutively operating storages

K3: Distinction of the soil layer on the basis of specific pore storages, modelled as parallel operating storages

These concepts have been analyzed in regard to the coarse scale soil moisture data set. The Soil Water Index (SWI) is derived by applying a simple infiltration model (Wagner et al. 2003), which is based on a two-layer model: the first layer represents the satellite measured layer from where the water infiltrates into the underlying layer. This concept corresponds to the distinction of the soil into two vertical layers (K2). The third concept (K3) takes physical soil parameters into consideration and represents therefore a more realistic generation of soil moisture whereas an application of the first concept (K1) constricts the analysis of the coarse scale data. Concluding, the best soil concepts for the proposed task are K2 and K3. In regard to these two concepts two models were selected.

The Precipitation Runoff Modelling System (PRMS) Model developed by the United States Geological Survey (USGS) (Leavesley et al. 1983) is the first model. PRMS was successfully applied in various climates and at different catchment sizes, for instance the Sierra Nevada (Jeton and Smith 1993), the Rocky Mountains (Flügel and Lüllwitz 1993) as well as in South Africa (Staudenrausch 1996). The soil water balance in PRMS is calculated based on a simple water balance equation whereby the active soil column is divided into two soil layers: in the first soil layer the water losses occur due to transpiration and evapotranspiration and the second layer loses water only due to transpiration.

The complex model system J2000 developed at the Forschungszentrum Jülich and afterwards in cooperation with the Friedrich-Schiller University Jena (Krause 2001) is the second selected model. The model was successfully applied in various catchments of sizes ranging from 2 to 6000 km². The soil module separates the soil layer into middle pore storage and large pore storage. Depending on the 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 surface runoff and groundwater generation.

PRMS and J2000 represent two different concepts of modelling soil moisture that will be evaluated on their representation of soil moisture generation. This comparison will give a more detailed inside view on model performance in semiarid catchments and supports a better understanding of model behaviour in semiarid climates.

5. PRELIMINARY MODELLING RESULTS

As a first working step for the assessment of coarse scale soil moisture the hydrological model PRMS was applied to retrieve fine soil moisture estimates. The first studied subbasin was the Letaba basin with an area of 10684km². Therefore, 159 HRUs with a size ranging between 300 and 1800km² have been delineated in regard of landcover, soil type, slope, aspect, elevation as well as geology shown in Figure 3.

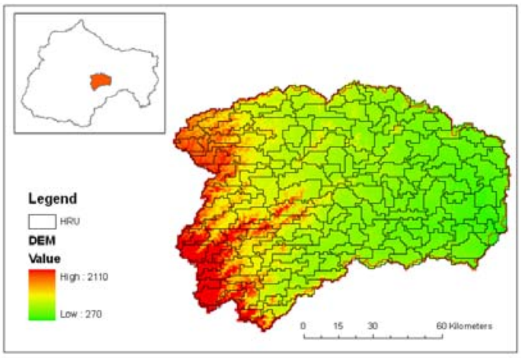

Figure 3: Hydrological Response Units of the Letaba basin

Based on the HRUs the runoff was modelled in the timeframe from 1992 to 1995. As an example Figure 4 shows the comparison of the observed and simulated runoff for the years 1994 and 1995 in which the red line represents the observed runoff and the black line the modelled runoff.

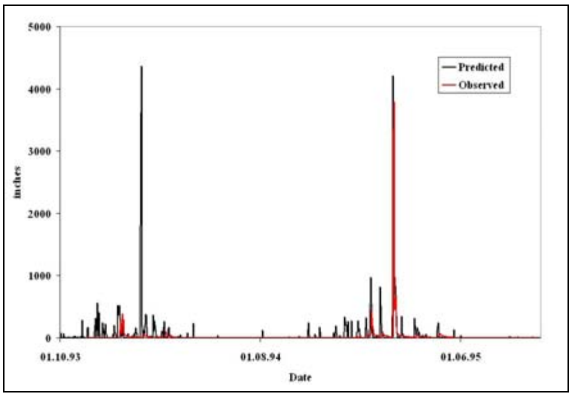

Figure 4: modelled runoff (black) and observed (red) runoff in Letaba catchment

The preliminary results display an overestimation of runoff by PRMS. Additionally, the representation of seasonal dynamics varies in regard to weather conditions: the summer 1993/1994 was very dry whereas the following summer showed more humid conditions. The PRMS model predicts the humid summer quite well whereas the dynamics in the dry summer are underpredicted.

In detail, the model predicts the observed runoff peaks quite well in both displayed summers but the modelled peak lags two days before the observed. Furthermore, the model oversimulates runoff dynamic during the summer. It predicts to nearly every precipitation event a runoff peak that do not occur in the observed data, e.g. in summer 1993/94, whereby the model overestimates the total runoff. In conclusion, the surface runoff occurs too quickly after the rainfall event.

6. CONCLUSION AND OUTLOOK

The PRMS model results are unsatisfying in regard to the representation of the predicted runoff particularly under dry summer conditions which leads to the conclusion that the modelled soil moisture values are not satisfactory either.

The unsatisfying model performance might be caused due to irrigation that is not considered in the model structure. Also, the non-existence of the capillary ascension might be a drawback in representation of a semiarid catchment. Additionally, the unspecified connection between the HRUs in conjunction with the size of the analyzed catchment can cause difficulties in modelling the runoff satisfactorily.

The next step will be to apply the J2000 model and to compare the model results with PRMS to achieve the best representation of the soil moisture generation and to delineate the SMRUs, which will provide the basis for the disaggregation of the gridded Scatterometer data. After completing the hydrological modelling with J2000 and PRMS on the basis of SMRUs, the comparison of temporal and spatial time series to the coarse-scale soil moisture indicators will follow. Figure 5 shows the location of the grid cells within the Limpopo catchment.

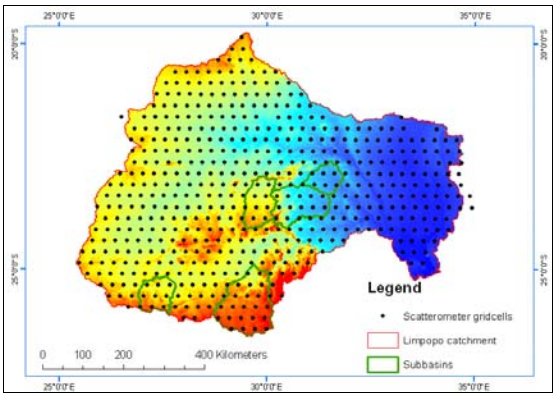

Figure 5: SWI grid cell location in the Limpopo catchment

The proposed disaggregation scheme will help in the quantification of the potential and quality of the Scatterometer soil moisture data and will therefore contribute to the question of whether such data can be used as an input parameter for large scale hydrological models. This study and its methodology developed will provide an important contribution utilization of data for hydrological modelling from new coarse-scale satellites like the Advanced Scatterometer (ASCAT) onboard the MetOp Satellite, which will be launched in 2006 by the European Space Agency (ESA). Similar to the ERS Scatterometer this Scatterometer will have a spatial resolution of 50km (ESA 2003).

7. ACKNOWLEGDEMENT

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