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Soil moisture-runoff relation at the catchment scale as observed with coarse resolution microwave remote sensing

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Abstract

Microwave remote sensing offers emerging capabilities to monitor global hydrological processes. Instruments like the two dedicated soil moisture missions SMOS and HYDROS or the Advanced Scatterometer (ASCAT) onboard METOP will provide a flow of coarse resolution microwave data, suited for macro-scale applications. Only recently, the ERS scatterometer, which is the precursor instrument of ASCAT, has been used successfully to derive soil moisture information at global scale with a spatial resolution of 50 km. Concepts of how to integrate macro-scale soil moisture data in hydrologic models are however still vague. In fact, the coarse resolution of the data provided by microwave radiometers and scatterometers is often considered to impede hydrological applications. Nevertheless, even if most hydrologic models are run at much finer scales, radiometers and scatterometer allow monitoring of atmosphere-induced changes in regional soil moisture patterns. This may prove to be valuable information for modelling hydrological processes in large river basins (>10 000 km^2). In this paper, ERS scatterometer derived soil moisture products are compared to measured runoff of the Zambezi River in south-eastern Africa for several years (1992–2000). This comparison serves as one of the first demonstrations that there is hydrologic relevant information in coarse resolution satellite data. The observed high correlations between basin-averaged soil moisture and runoff time series (R^2>0.85) clearly demonstrate that the seasonal change from low runoff during the dry season to high runoff during the wet season is well captured by the ERS scatterometer. Additionally, differences in runoff from year to year could be to some extend, explained by soil moisture anomalies.

1. Introduction

Soil moisture is widely recognised as a key parameter in environmental processes, including meteorology, hydrology, agriculture and climate change. From a hydrologic viewpoint, soil moisture controls the partitioning of rainfall into runoff and infiltration and therefore has an important effect on the runoff behaviour of catchments (Aubert et al., 2003). Being basic to hydrologic processes an accurate assessment of the spatial and temporal variation of soil moisture may therefore not only be useful for improving the predictive capability of runoff models, it may also be of high value for improving and validating hydrologic process representation at the catchment scale. Unfortunately, in-situ observations are rarely available as area representative measurements are expensive and tedious to collect (Hollinger and Isard, 1994; Rombach and Mauser, 1997). The difficulty of measuring soil moisture on the ground has motivated considerable research in the field of remote sensing to retrieve soil moisture of use for hydrological models (Engman and Chauhan, 1995). Specifically, microwave remote sensing offers the possibility to retrieve soil moisture at various scales due to the sensitivity of microwaves to changes in the dielectric properties of the soil.

Much emphasize has been put on Synthetic Aperture Radars (SAR), the only system which can provide information on smaller scales (<50 m), with some success being achieved using change detection approaches (see e.g. Moran, 2000). However, currently available SAR systems neither provide the data necessary for routine application of these methods nor are they truly optimised for soil moisture retrieval. That is why SAR studies are in general still experimental and progress has been slower than expected. At the same time, significant progress has been made using coarse-resolution microwave radiometers and scatterometers. The advantage of these systems compared to SAR is that they offer multi-dimensional, multi-temporal observation capabilities (multiple frequencies and polarisations in the case of microwave radiometers and multiple-viewing capabilities in the case of scatterometers). These capabilities allow to better account for the confounding effects of vegetation and surface roughness, which are inherent in both active and passive microwave observations. The progress made, has consequently led to the approval of two experimental satellite missions designed to measure soil moisture, ESA's second Earth Explorer Opportunity Mission SMOS and NASA's Earth System Science Pathfinder mission HYDROS. As low microwave frequencies are beneficial for soil moisture retrieval (longer wavelengths better penetrate vegetation) both missions will be operated in L-band. SMOS will use a radiometer to make measurements at a spatial resolution of about 40 km (Kerr et al., 2001). HYDROS will combine a radiometer (40 km) and a scatterometer (3 and 10 km). Foreseen launch dates are 2007 and 2010, respectively. These two missions will perform first-of-a-kind exploratory measurements and aim to measure soil moisture with an accuracy of 0.04 $m^3 m^{-3}$.

Beside these two dedicated soil moisture missions, an operational scatterometer has also been found capable of soil moisture retrieval. Recently, the first global, remotely sensed soil moisture dataset has been derived from ERS-1/2 scatterometer data (Scipal et al., 2002; Scipal, 2002). The data set has a spatial resolution of 50 km and was found to be of comparable quality with state-of-the-art, global soil moisture models (Wagner et al., 2003). The accuracy of the scatterometer based soil moisture product was assessed using over 45 000 measurements worldwide and is around 0.054 $m^3 m^{-3}$ for the 0–1 m layer for temperate and tropical climatic regions (a red-noise filtering approach was used to estimate the water content in the soil profile from the remotely sensed surface soil moisture series). The retrieval algorithm developed for use with the ERS scatterometer will be directly applicable to its successor, the Advanced Scatterometer (ASCAT). This instrument will have a spatial resolution of 25 km and will be flown on a series of METOP satellites, providing data continuity over an initial period of at least 14 years, starting in 2005.

The coarse resolution of the afore mentioned sensors is however often assumed to be insufficient for hydrologic applications, therefore they have so far not been considered by the hydrologic community. Given the impending launch of a series of coarse resolution microwave sensors capable of accurately retrieving soil moisture in the next few years and the unavailability of other data sources, the logic dictates, that it is now necessary to investigate the potential of these techniques to support hydrologic applications. Clearly, substantial research efforts will be needed to develop methods for ingesting such kind of data into hydrologic models. The questions of spatial resolution, irregular sampling intervals, and low penetration depth into the soil surface need to be addressed. Fortunately, the technique of data assimilation has recently gained significant attention and will provide important impetus in the future (e.g. Walker et al., 2001).

Before complex hydrological assimilation schemes are developed to ingest a particular remotely sensed soil moisture product, it is nevertheless advisable to firstly test the quality of the remotely sensed products by means of simple methods to gain a better understanding of the available information. This is the aim of this paper, which compares ERS scatterometer soil moisture with runoff time series from the Zambezi River. The Zambezi River has been chosen for this investigation because of its large catchment area and its pronounced intra- and inter-annual variability in runoff. Before the results of this comparison are presented in Sect. 7, Sect. 2 reviews a number of studies, which investigated the possibility of using soil moisture observations for improving runoff prediction. Soil moisture scaling issues are addressed in Sect. 3 to lay the foundation for assessing the information contained in coarse resolution data. The soil moisture retrieval technique based on ERS scatterometer data is explained in Sect. 4, including a more detailed discussion on the accuracy of the derived soil moisture products in Sect. 5. The available hydrometric data are described in Sect. 6. The discussion of the results aims particularly at identifying the information inherent in the macro-scale soil moisture products.

2. State of the art

In recent years there have been a few studies geared towards combining hydrologic models and space borne data to improve the predictive capability of runoff models, or just to use the data to improve and validate hydrologic process representation at catchment scale.

Classically, soil moisture observations are not used directly to address hydrologic problems such as runoff prediction, drought monitoring or flood forecasting, but are used in assimilation schemes of land surface hydrologic models or to constrain soil vegetation atmosphere transfer models (Aubert et al., 2003; for examples see Houser et al., 1998; Li and Islam, 199; Walker et al., 2001; Walker and Houser, 2001; Reichle et al., 2001). Most of these studies focused on the assimilation technique itself and its influence on the soil water content, but did not examine the effect of the soil moisture assimilation on other modelled fluxes such as discharge and evapotranspiration (Pauwels et al., 2001). This was also noted by Aubert (2003) who states that coupling soil moisture observations with the routing function of hydrological models, in order to improve stream flow simulations and forecasts, has not extensively been studied. However, first experimental studies confirm that assimilation of remotely sensed soil moisture can significantly improve simulation results especially under extreme conditions.

Pauwels (2001) examined the effect of ERS SAR derived soil moisture assimilation on modelled discharge, concluding that the data assimilation could improve model based discharge estimates. In the study, a lumped hydrologic model was used in combination with two assimilation methods of remotely sensed soil moisture. One assimilation method used the spatial patterns, the other only the statistics (spatial mean and variance) of observed soil moisture. Already the assimilation of the spatial mean and variance significantly improved hydrological model based discharge predictions. These results suggest that the mean value captured by coarse resolution soil moisture is a statistically meaningful descriptor, which may help to improve simulation results regardless of scale differences between model and data.

Francois et al. (2003) and Bach and Mauser (2003) showed that spaceborne observations of soil moisture are especially useful to improve simulation results under extreme flood conditions. Francois et al. (2003) used an extended Kalman filter with a lumped rainfall runoff model, Bach and Mauser (2003) a four dimensional data assimilation method with a flood forecasting model. Similar results were obtained by Aubert et al. (2003) showing that observed soil moisture can be used to improve runoff prediction over a sub-catchment of the Seine River in France. Although not using remotely sensed data, the study elaborates on the use of remotely sensed soil moisture observations and indicates its potential if provided frequently enough (1–3 days). This high temporal sampling requirements can currently only be fulfilled by coarse resolution sensors. Although none of these studies directly used coarse resolution data, they indicate the potential of coarse resolution data and point to possible ways forward in the use of macro scale soil moisture products.

3. Soil moisture scales

To make best use of a certain data set it is essential to define the processes captured by the data set, to understand the processes influencing the observed quantity, the scale at which the variability acts and finally the relation between the process and the observation scale. According to Grayson et al. (2002), scale is one of the key issues in hydrologic applications. It is not only a question how to observe relevant features but also to observe and use them at the appropriate scale. In the ideal case process scale, model scale and the measurement scale are compatible (Blöschl, 1996). The process scale characterizes the typical time and length scales on which a particular natural process predominantly takes place, while the measurement scale refers to the spatial resolution and temporal sampling interval of the measurement device.

Based primarily on in-situ soil moisture data, from both experimental and operational observational networks, scaling properties of the soil moisture field in the spatial and temporal domain have been investigated. It has been found that soil moisture is spatially and temporally highly variable. Several authors showed that the variability is driven by vegetation, soil type and topography and suggested that the spatial scale of soil moisture is on the order of tens of meters (Nielsen et al., 1973; Vieira et al., 1981; Vachaud et al., 1985). The perception was that beyond this distance there is too much variability of soil, vegetation and topographic properties to maintain a correlation of soil moisture. Concurrently it was argued by Kontorschikov (1979), Meshcherskaya et al. (1982) and more recently by Cayan and Georgakakos (1995) that a second factor influences soil moisture variability on a scale of hundreds of kilometres and attributed it to atmospheric forcing effects. Recent studies by Vinnikov et al. (1996) and Entin et al. (2000) support the two scale concept with a small scale component influenced by vegetation, soil type and topography acting on the range of centimetres to hundreds of meters and a large scale component influenced by climatic conditions and atmospheric events such as precipitation and radiation acting on scales of kilometres and larger. Vinnikov et al. (1999) argued that small scale variability does not effect soil moisture above 1 km, and that above this scale the variability in soil moisture for the scale of typical coarse resolution sensors (ranging from 1 km to 100 km resolution) is relatively constant.

Evidence of a two scale concept to describe the soil moisture process can also be found in Ceballos et al. (2003) and Martínez-Fernández and Ceballos (2003). The authors studied characteristics of soil moisture in a semiarid environment based on data from the REMEDHUS network located in the North West of the Iberian Peninsula. The network consists of twenty soil moisture measurement stations spread over a 1200 km^2 large area, characterised by different soil and land use types. The stations are within the same climatological context but are hydrological independent. The analysis of multi-year soil moisture time series indicated clear spatial patterns of persistence. Some stations were noted to be consistently wetter than the average while some were consistently drier, independent of the point in time. Still, observations from all stations followed the same temporal trend and a high correlation in the time series build of data from the twenty different stations could be observed. Differences in absolute soil moisture were explained by differences in soil type, texture and topography.

This leads to the conclusion that observations made with coarse resolution sensors such as scatterometers, which effectively average over the small-scale structure of the observed region, contain information about the large-scale component which refers to meteorological and climatic events such as precipitation and evapotranspiration patterns.

4. Soil moisture from scatterometer data

Soil moisture data used in this study is taken from the Global Soil Moisture Archive 1992–2000 located at http://www.ipf.tuwien.ac.at/radar/ers-scat/home.htm (Scipal et al., 2002). The archive is based on ERS Scatterometer data and comprises global surface soil moisture data and indicators of root zone soil moisture sampled at ten-day intervals.

Scatterometers are active microwave sensors characterised by a coarse spatial but a high temporal resolution. To retrieve soil moisture information, scatterometers onboard of the European Remote Sensing Satellites ERS-1 and ERS-2, operated by the European Space Agency were used. The ERS scatterometer operates at 5.3 GHz (C-band) vertical polarization, collecting backscatter measurements over an incidence angle range from 18° to 57° using three sideways looking antennae. The sensor achieves global coverage within 3 to 4 days where each beam provides measurements of radar backscatter from the sea and land surface for overlapping 50 km resolution cells with a 25 km grid spacing at approximately 10:30 a.m. and 10:30 p.m. for ascending and descending tracks, respectively.

Scatterometry offers capabilities to infer soil moisture due to the strong variation of the dielectric constant of soil with volumetric water content. However, scattering from land surfaces also depends on other factors. Potential retrieval techniques must account for the confounding effects of surface roughness, vegetation, topography and soil texture. Since the 1970's several methods have been developed to retrieve soil moisture from microwave remote sensing data. Possibly the largest potential is held by change detection approaches. Change detection has successfully been used to retrieve soil moisture for active (Wagner et al., 1999; Moran et al., 2000) and passive data (deRidder, 2000). Unlike more complex theoretical or semi empirical approaches often preferred for retrieval purposes, change detection is attractive for global applications because comprehensive pre-knowledge of surface characteristics is not required.

Retrieval of soil moisture for "The Global Soil Moisture Archive" is based on the change detection method developed by Wagner et al. (1999). The method allows the retrieval of surface soil moisture information equivalent to the degree of saturation in relative units (ranging between 0 and 100%). To infer root zone soil moisture a red-noise filtering approach was used, which is controlled by the ratio of the layer depth and the pseudo diffusivity that depends on the soil properties (Wagner et al., 1999; Ceballos et al., 2004). As soil properties are not known quantitatively on a global scale, this parameter was determined empirically and set constant (Wagner et al., 1999). The resulting index is the Soil Water Index *SWI*, a percentile measure of soil moisture between the soil moisture extremes Θ_{min} (dry) and Θ_{max} (wet) which have been shown to correlate well with the wilting level and point midway the field-capacity and total water capacity (Wagner et al., 1999).

5. Soil moisture quality

To assess the quality of scatterometer derived soil moisture, data from "The Global Soil Moisture Archive 1992–2000" has been compared extensively with soil moisture information from various sources.

Wagner et al. (2003) compared scatterometer derived monthly soil moisture estimates with global gridded precipitation data and global modelled soil moisture of the 0–50 cm layer. The study showed that there is reasonable agreement between the different datasets especially under tropical and temperate climates. Only in extreme climates such as deserts and the arctic, spurious effects have been observed. Given, that the accuracy of the gridded precipitation and the modelled soil moisture is not known it is not possible to draw any quantitative conclusions. Considering that the datasets are independent it is however reasonable to assume that a high agreement indicate regions of good data quality and that in such a case upper limits of the accuracy of the scatterometer derived soil moisture can be inferred. This upper limit has been determined to be in the range of 0.03–0.07 $\mathrm{m}^3\mathrm{m}^{-3}$.

A quantitative assessment of the quality of the soil moisture product was carried out by Scipal (2002) using over 45 000 soil moisture measurements from 372 stations worldwide. Samples were taken at agro-meteorological large-scale measurement networks located in Russia, Ukraine, China, Mongolia and the US, covering a wide range of soil types and climatic regions. For Ukraine, Russia and Illinois soil moisture samples from a depth of 1 m were compared. In India and China, soil moisture samples from a depth of 50 and 60 cm, respectively were used, as samples of deeper layers were not available. Statistical analysis indicated an accuracy of scatterometer derived soil moisture for the 1 m layer between 0.049 m^3m^{-3} and 0.084 m^3m^{-3} depending on the measurement network. The average accuracy was determined to be 0.054 m^3m^{-3}. Even better values have been determined for soil moisture anomalies with an average accuracy of 0.032 m^3m^{-3}.

A more detailed study, was carried out by Ceballos et al. (2003) who compared scatterometer derived soil moisture to field observations from the REMEDHUS network. All stations of the REMEDHUS network are within one scatterometer pixel therefore allowing a more detailed assessment of soil moisture conditions of the covered region. For the comparison, data from twenty stations were averaged. The resulting time series compared well with scatterometer derived soil moisture. The coefficient of estimation R^2 for the average soil moisture profile (0–100 cm) reached a value of 0.74 and the mean square error (RMS error) was 0.022 m^3m^{-3}.

6. Hydrometric data

Hydrometric data is available for the Zambezi River. The basin of the Zambezi River is one of the largest of the African continent covering approximately 1.35 million km^2 or 5 % of the continent. The Zambezi River runs through six countries: Zambia, Angola, Zimbabwe, Namibia, Botswana and Mozambique, from the centre of Africa to the Indian Ocean. The source of the Zambezi River is situated at Kalenehills in the northwestern part of Zambia. At the frontier to Zimbabwe, the Zambezi reaches a largest width of 1,7 km before it reaches the Victoria falls. The entire river amounts 3000 km from source to estuary (Zambezi River Authority, 2002). Along the Zambezi River two major dams (Lake Kariba and Cabora Bassa) have been built that are mainly used for generation of energy.

The climate of the Zambezi catchment generally underlies the movement of the Intertropical Convergence zone ITC, resulting in distinct dry and wet seasons during the year in the southern part of the catchment. Consequently, the flow of the Zambezi River is seasonal in nature with the lowest flows occurring during the dry months, from June to November and the higher flows occurring during the wetter parts of the year, December to May. The study period, ranging from 1992–2000, was characterized by a wet period from 1992 to 1994, followed by a rather dry period from 1995 to September 1997. The end of the study period was characterized by extreme wet conditions with disastrous floods in the years 1997 and 2000.

The Zambezi River Authority in Zambia provided hydrometric parameters from a network of eleven stations where water levels are monitored daily (Fig. 1). Data of the station Kasambamezi has not been provided. At seven of these stations, additional flow measurements are carried out which allows calculation of runoff. The observations cover the years 1992 to 2000. Only stations above Lake Kariba have been used, which are Chavuma, Watopa, Lukulu, Kalabo, Matongo, Senanga, Sesheke, Nana's Farm and Victoria Falls (Table 1). Records of the stations Gwayi and Sanyati are incomplete and have therefore not been used in this study. For the station Sesheke unrealistic low water level values have been recorded for the period March 1997 to October 1998 which clearly do not fit with the other measurements. Therefore these records have been removed prior to the analysis.

7. Results

Studying the relationship between soil moisture and hydrometric parameters is not a straightforward task. Principally it can be expected that both parameters are related. When soils are close to saturation runoff will be much higher compared to the situation when soils are dry. However given the different nature of the parameters it can be expected that no linear relationship exists but that a more complex interaction between the processes has to be considered. Soil moisture will, for example, show higher sensitivity to changes under dry conditions compared to runoff. Under prolonged wet conditions soil moisture will saturate and will be insensitive to additional rainfall. Runoff, conversely, is theoretically not bound to an upper limit and will be highest under such conditions. Additionally, it has to be considered that runoff is a point measure integrating information on the hydrologic status of an entire catchment. To get a representative indicator, *SWI* data has therefore been integrated over all grid points of the respective sub basins according to Eq. (1) to derive a "Basin Water Index" *BWI*:

$$BWI = \frac{\sum_{i=1}^{N} SWI_i}{N}. \tag{1}$$

In this simplistic approach the position of each sample point with respect to the hydrometric gauging station is not accounted for. Principally it can be expected that each point shows a distinct relation to the hydrometric gauging station characterised by the response time which should be longer for points farther away from the gauging station. This will specifically be the case for large catchments. Equation (1) also assumes that all points in the catchment are equally relevant for the generation of runoff. For the sake of simplicity of this explanatory analysis more realistic schemes were set aside. To retrieve temporal matching data sets daily hydrometric parameters have been averaged over ten day periods.

To compare samples from hydrometric gauging stations with scatterometer derived soil moisture, time series have been visually analysed for all stations in a first step. It was examined whether similar temporal trends can be observed and if the climatic conditions observed throughout the study period are reflected in both datasets. Figure 2 shows discharge and *BWI* time series for the station Victoria Falls for the years 1994, 1997 and 2000. The year 1994 is characteristic for wet conditions, the year 1997 for dry conditions whereas the year 2000 was an extreme wet year with disastrous floods. These climatic differences are well reflected in both time series. However, the extreme conditions of the year 2000 are better visible in the discharge time series than in the *BWI* time series. Generally, it can be observed that the *BWI* shows less variability between the sampled years than the hydrometric data. However, annual variations in the *BWI* are clearly evident for all stations.

In Fig. 2 it can also be observed that the highest discharge lags some time behind the highest of the *BWI*. For the station Victoria Falls the highest runoff is recorded between April and May, whereas the *BWI* maximum is already observed between February and March. The time difference in the observed maxima is most likely explained with the delay time of the discharge system. It can be expected that runoff measured at a gauging station shows a much slower response to precipitation events than soil moisture which will immediately respond. This is also in agreement with the observation that the magnitude of the delay time increases with the basin size. Despite of this difference in the two data sets, differences in the annual cycle observed during the observation period are clearly visible and correlate well between both data sets.

Principally, these temporal patterns can be observed in time series from all stations, which closely follow the climatic conditions experience during the study period. Only for the station Kalabo situated at the Luanginga River a different behaviour is observed (Fig. 3). At Kalabo, hydrometric data indicates only little runoff during the entire observation period. Elevated runoff measurements, which significantly exceeded samples taken at previous years were reported only in the year 2002. This extreme pattern is not evident in the *BWI*.

Based on the time series analysis, the relation between the hydrometric parameters and the *BWI* has been assessed quantitatively in a second step. For this purpose hydrometric samples have been plotted against the *BWI* for all stations. As the extreme temporal pattern observed at the Kalabo station made a quantitative analysis difficult, data for the station Kalabo was not further considered.

To account for the difference in the response time observed in the time series, hydrometric data was shifted back such that the observed maxima corresponded. Figures 4 and 5 show the plots between the *BWI* and the shifted runoff and water level data, respectively. The best fit and hence the magnitude of the applied shift was determined using a simple regression model. The models used to determine the relation between the *BWI* and the hydrometric parameters (runoff and water level) has been set up empirically based on a visual analysis of the scatterplots. The regression models are given in Eqs. (2) and (3) were the first is used for discharge measurements and the second is used for water level measurements. Although both models are mathematically identical they have been defined separately to allow a correct interpretation of the fitted parameters. In Eq. (2) the discharge Q at time t is determined by the "baseflow" Q_0, the highest observed Basin Water Index $BWI_{\max}$, a hydrometric scaling factor χ_Q and the delay time of the system Δt:

$$Q(t) = Q_0 + \chi_Q \ln \frac{BWI_{\max}}{BWI_{\max} - BWI(t - \Delta t)}. \tag{2}$$

Similarly, in Eq. (3) the water level h at time t is determined by the lowest water level h_0, by the highest observed Basin Water Index $BWI_{\max}$, a hydrometric scaling factor χ_h and the delay time of the system Δt:

$$h(t) = h_0 + \chi_h \ln \frac{BWI_{\max}}{BWI_{\max} - BWI(t - \Delta t)}. \tag{3}$$

The models were designed in such a way that its parameters can be related to physical quantities. The baseflow Q_0 and the lowest water level h_0 relate to the waterflow when soils are completely dry. The highest observed *BWI* relates to the threshold where the soils are close to saturation and any additional water available on a certain area will directly result in runoff. The hydrometric scaling factor is necessary to determine the shape of the logarithmic model, such influencing the soil moisture runoff/water level behaviour. The delay time Δt determines the difference observed in the temporal response of the two parameters to precipitation events.

The fit of the regression model expressed in Eqs. (2) and (3) is excellent as can be observed in Figs. 4 and 5. The estimated correlations are well above R^2=0.8 for all stations (Tables 2 and 3). Evidentially, the parameters Q_0, h_0 and $BWI_{\max}$ give realistic numbers. It is also interesting to note that the delay time Δt shows a dependency on the catchment size. For upstream gauging stations a delay time of 30 days is estimated, for downstream stations this value increases to 60 days (Fig. 6). Also the hydrometric scaling factor increases with basin size, but more knowledge would be needed to appropriately interpret these observations.

Although the results are favourable they need to be considered carefully. It can be expected that the pronounced inter-annual cycle observed in the discharge behaviour of the Zambezi with a very dry period and a wet period predetermines the high correlations observed. To check if the *BWI* is not only sensitive to annual variations, anomalies have been compared. Anomalies were calculated by subtracting the mean annual cycle from the samples (both from the *BWI* and the hydrometric series). If measurement series were incomplete, care was taken that the calculation of the mean hydrometric parameter and scatterometer soil moisture were based on the same data range. Mean values were only calculated if at least two measurements per sample interval were available, otherwise the respective sample was removed from the data set. Figures 7 and 8 show scatterplots of the anomalies. To ease interpretation both quantities have been scaled between −1 and +1. The trend observed in all plots is positive which indicates that differences in runoff/waterlevel from year to year can to some extent be explained by soil moisture anomalies. However under dry conditions the *BWI* anomalies show much more variability than the hydrometric anomalies. This is not surprising as especially under dry conditions variations caused by different precipitation/evapotranspiration rates will only be experienced by the soils. But given the lack of appropriate ground truth information about these quantities distinct conclusions are speculative and should be clarified in further studies.

8. Conclusions

In this paper a novel data set “The Global Soil Moisture Archive 1992–2000” has been presented. Although being not optimum for hydrologic applications due to the coarse resolution it was shown that the soil moisture products contain valuable information about large scale atmospheric induced variations of the soil moisture field. Contrary to the availability of this soil moisture data, a review of state of the art research led to the impression that concepts of how to make best use of this data and how to integrate coarse resolution products in current hydrological modelling are still vague. The quality of the soil moisture data set, and first result of soil moisture assimilation studies however gave rise to the argumentation that coarse resolution soil moisture can successfully be used in hydrologic applications if scaling issues are considered carefully.

To assess the usefulness of coarse resolution soil moisture data for catchment scale modelling, scatterometer derived soil moisture data was compared to hydrometric measurements (runoff and water level) taken at eight gauging stations of the Zambezi River in Africa. For this purpose the “Basin Water Index” *BWI* has been introduced which integrates scatterometer derived soil moisture over the respective sub-basins. Visual analysis showed a reasonable agreement between the *BWI* and the hydrometric time series. Aside a shift between the observed maxima of the two datasets climatic conditions and multi-annual variations are clearly visible. The observed shift could be explained with differences in the response time to precipitation events. For a quantitative comparison between the *BWI* with hydrometric measurements a simple logarithmic regression model has further been developed. Using this model considerable agreement has been found between the absolute measures of the datasets with coefficients of correlation well above R^2=0.8. Also for anomalies a positive trend was observed which led to the feeling that differences in runoff/waterlevel from year to year can to some extent be explained by soil moisture anomalies.

These observations are especially encouraging given the approaching launch of a number of coarse resolution microwave sensors which will provide a flow of operational, global, high quality soil moisture data. Especially in ungauged basins these datasets might turn out as invaluable source of information to improve the predictive capability of runoff models, or just to use the data to improve and validate hydrologic process representation at catchment scale.

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References

Aubert, D., Loumagne, C., and Oudin, L.: Sequential assimilation of soil moisture and streamflow data in a conceptual rainfall-runoff model, J. Hydrol., 280, 145–161, 2003.

Bach, H. and Mauser, W.: Methods and Examples for Remote Sensing Data Assimilation in Land Surface Process Modelling, IEEE Geosci., 41, 1629–1637, 2003.

Blöschl, G. and Sivapalan, M.: Scale issues in hydrological modelling: A Review, Hydrol. Proc., 9, 251–290, 1995.

Blöschl, G.: Scale and scaling in hydrology, Wiener Mitteilungen, Wasser Abwasser Gewässer, Band 132, Insitut für Hydraulik, Gewässerkunde und Wasserwirtschaft, Technische Universität Wien, 1996.

Cayan, D. R. and Georgakakos, K. P.: Hydroclimatology of continental watersheds: II spatial analyses, Water Res. R., 31, 677–697, 1995.

Ceballos, A., Martinéz-Fernández, J., Santos, F., and Alonso, P.: Soil Water Behaviour of sandy soils under semi-arid conditions in the Duero Basin (Spain), J. Arid Env., 51, 501–519, 2002.

Ceballos, A., Scipal, K., Wagner, W., and Martínez-Fernández, J.: Validation of ERS Scatterometer-Derived Soil Moisture Data in the Central Part of the Duero Basin, Spain, Hydrol. Proc., in press, 2004.

Crow, W. T. and Wood, E. F.: The assimilation of remotely sensed soil brightness temperature into a land surface model using Ensemble Kalman filtering: A case study based on ESTAR measurements during SGP97, Adv. Water R., 26, 137–149, 2002.

De Ridder, K.: Quantitative estimate of skin soil moisture with the Special Sensor Microwave/Imager, Bound-Lay. M., 96, 421–432, 2000.

Engman, E. T. and Chauhan, N.: Status of microwave soil moisture measurements with remote sensing, Remot. Sen. E., 51, 189–198, 1995.

Entekhabi, D., Asrar, G. R., Betts, A. K., Beven, K. J., Bras, R. L., Duffy, C. J., Dunne, T., Koster, R. D., Lettenmaier, D. P., McLaughlin, D. B., Shuttleworth, W. J., van Genuchten, M. T., Wei, M., and Wood E. F.: An Agenda for Land- Surface Hydrology Research and a call for the Second International Hydrological Decade, B. Am. Meteor., 80, 2043–2058, 1999.

Entin, J. K., Robock, A., Vinnikov, K. Y., Hollinger, S. E., Liu, S., and Namkhai A.: Temporal and spatial scales of observed soil moisture variations in the extratropics, J. Geo. Res-A., 105, 11 865–11 877, 2000.

Francois, C., Quesney, A., and Ottle C.: Sequential assimilation of ERS–1 SAR data into a coupled land surface hydrological model using an extended Kalman filter, J. Hydromete., 4, 473–487, 2003.

Grayson, R. B., Blöschl, G., Western, A., and McMahon, T. A.: Advances in the use of observed spatial patterns of catchment hydrological response, Adv. Water R., 25, 1313–1334, 2002.

Hollinger, S. E. and Isard, S. A.: A Soil Moisture Climatology of Illinois, J. Climate, 7, 822–833, 1994.

Houser, P. R., Shuttleworth, W. J., Famiglietti, J. S., Gupta, H. V., Syed, K. R., Goodrich, D. C.: Integration of soil moisture remote sensing and hydrologic modelling using data assimilation, Water Res. R., 34, 3405–3420, 1998.

Kerr, Y. H., Waldteufel, P., Wigneron, J.-P., Martuzzi, J.-M., Font, J., and Berger, M.: Soil moisture retrieval from space: The Soil Moisture and Ocean Salinity (SMOS) mission, IEEE Geosci, 39, 1729–1735, 2001.

Kontorschikov, V. I.: Statistical structure of the soil moisture in Ukraine, (in Russian), 1979.

Koster, R. D., Houser, P. R., Engman E. T., Kustas W. P.: Remote Sensing May Provide Unprecedented Hydrological Data, http://www.agu.org/eos_elec/97035e.html, 1999.

Li, J. and Islam, S.: On the estimation of soil moisture profile and surface fluxes partitioning from sequential assimilation of surface layer soil moisture, J. Hydrol., 220, 86–103, 1999.

Martinéz-Fernández, J. and Ceballos A.: Temporal stability of Soil Moisture in a Large-Field Experiment in Spain, Soil Sci. So., 67 1647–1656, 2003.

Meshcherskaya, A. V., Boldyreva, N. A., and Shapaeva N. D.: District Average Plant available soil water storage and the depth of snow cover, statistical analysis and its usage (some examples), Gidrometeoizdat, Leningrad, USSR, 243, (in Russian), 1982.

Moran, M. S., Hymer, D. C., Qi, J., and Sano, E. E.: Soil Moisture Evaluation Using Multi-

Temporal Synthetic Aperture Radar (SAR) in Semiarid Rangeland, Agr. For. Met., 105, 69–80, 2000.

Pauwels, V. R. N., Hoeben, R., Verhoest, N. E. C., and DeTroch, F. P.: The importance of the spatial patterns of remotely sensed soil moisture in the improvement of discharge predictions for small scale basins through data assimilation, J. Hydrol., 251, 88–102, 2001.

Reichle, R. H., Mc Laughlin, D. B., and Entekhabi, D.: Variational data assimilation of microwave radiobrightness observations for land surface hydrology applications, IEEE Geosci, 39, 1708–1718, 2001.

Robock, A., Vinnikov, K. Y., Srinivasan, G., Entin, J. K., Hollinger, S. E., Speranskaya, N. A., Liu, S., and Namkhai, A.: The Global Soil Moisture Data Bank, B. Am. Meteor., 81, 1281–1299, 2000.

Rombach, M. and Mauser, W.: Multi-annual analysis of ERS surface soil moisture measurements of different land uses, 3rd ERS Symposium on Space at the service of our Environment, Florence, Italy, 14–21 March, European Space Agency, SP-414, 27–34, 1997.

Scipal, K.: Global Soil Moisture Monitoring using ERS Scatterometer Data, Dissertation an der Technisch Naturwissenschaftlichen Fakultät, Technische Universität Wien, Juni, 2002.

Scipal, K., Wagner, W., Trommler, M., and Naumann, K.: The Global Soil Moisture Archive 1992–2000 from ERS Scatterometer Data: First Results, in Proc. IGARRS'2002, Toronto, Canada, 24–28 June, 2002.

Vachaud, G., Passerat de Silans, A., Balabanis, P., and Vauclin M.: Temporal stability of spatially soil water probability density functions, Soil Sci. So., 45, 1040–1048, 1985.

Vieria, S. R., Nielsen, D. R., and Biggar J. W.: Spatial variability of field meassured infiltration rate, Soil Sci. So., 67, 1647–1656, 1981.

Vinnikov, K. Y., Robock, A., Qiu, S., Entin, J. K., Owe, M., Choudhsury, B. J., Hollinger, S. E., and Njoku, E. G.: Satellite remote sensing of soil moisture in Illinois, USA, J. Geo. Res-A., 105, 4145–4168, 1999.

Wagner, W., Lemoine, G., and Rott, H.: A Method for Estimating Soil Moisture from ERS Scatterometer and Soil Data, Remot. Sen. E., 70, 191–207, 1999.

Wagner W., Scipal, K., Pathe, C., Gerten, D., Lucht, W., and Rudolf B.: Evaluation of the agreement between the first global remotely sensed soil moisture data with model and precipitation data, J. Geo. Res-A., 108, 4611–4626, 2003.

Walker, J. P. and Houser, P. R.: A methodology for initializing soil moisture in a global climate model: assimilation of near-surface soil moisture observations, J. Geo. Res-A., 106, 11 761–

11 774, 2001.

Walker, J. P., Willgoose, G. R., and Kalma, J. D.: One-dimensional soil moisture profile retrieval by assimilation of near-surface observations: A comparison of retrieval algorithms, Adv. Water R., 24, 631–650, 2001.

Zambezi River Authority: http://www.zaraho.org.zm, 2002.

Table 1. Gauging stations on the Zambezi River used in this study.

Gauging station	River	Location	Catchment size	Measurement
Kalabo	Luanginga	14°58′ S–22°41′ E	28 500 km^2	Discharge
Watopa_Pontoon	Kabompo	14°02′ S–23°37′30″ E	66 750 km^2	Discharge
Chavuma mission	Zambezi	13°05′ S–22°41′ E	76 000 km^2	Discharge
Victoria Falls	Zambezi	17°55′ S–25°50′ E	507 200 km^2	Discharge
Nanas Farm	Zambezi	17°50′ S–25°39′ E	524 000 km^2	Discharge
Lukulu	Zambezi	14°23′ S–23°14′ E	212 450 km^2	Water level
Matongo	Zambezi	15°16′ S–23°03′30″ E	245 000 km^2	Water level
Senanga	Zambezi	16°07′ S–23°23′15″ E	290 572 km^2	Water level
Sesheke	Zambezi	17°25′ S–2°12′ E	322 500 km^2	Water level

Table 2. Parameters of the logarithmic model given in Eq. (2) after optimising the fit between the model and the parameters for all stations, and coefficient of correlation R.

Gauging station	Q_0	χ_Q	$BWI_{\max}$	Δ_t	R
Watopa_Pontoon	32.78	93.08	82.4	30	0.94
Chavuma Mission	8.55	151.28	75.1	40	0.96
Victoria Falls	19.87	711.637	74.7	60	0.95
Nana's Farm	56.69	630.29	73.3	60	0.96

Table 3. Parameters of the logarithmic model given in Eq. (3) after optimising the fit between the model and the parameters for all stations, and coefficient of correlation R.

Gauging station	h_0	χ_h	$BWI_{\max}$	Δ_t	R
Lukulu	1.52	0.88	82.6	30	0.92
Matongo	1.48	1.93	84.1	50	0.96
Senanga	0.15	1.671	83.6	60	0.96
Sesheke	4.77	1.52	78.9	60	0.96

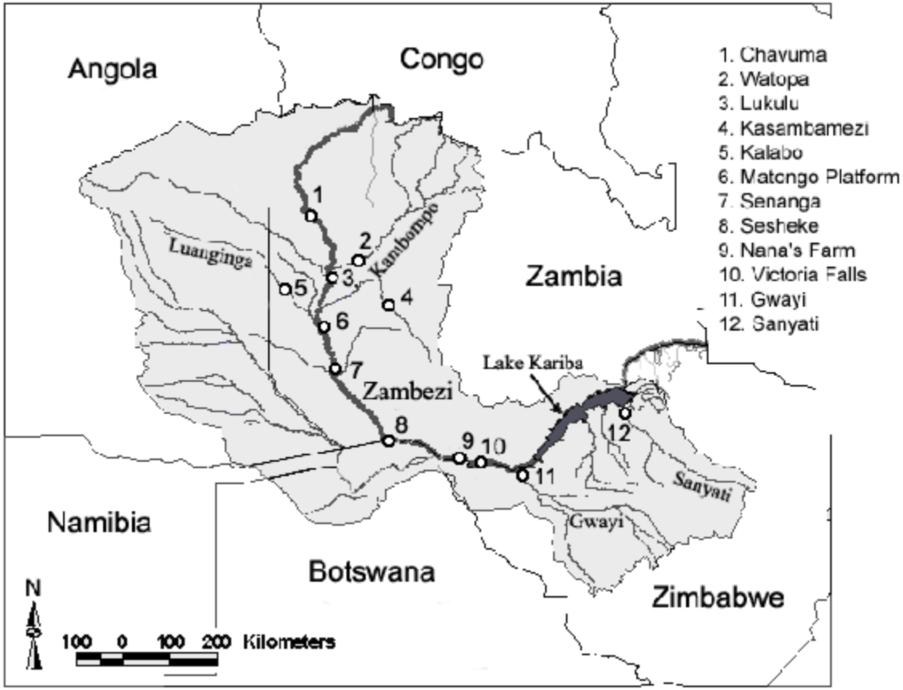

Fig. 1. The catchment of the Zambezi River with the location of the twelve gauging stations operated by the Zambezi River Authority.

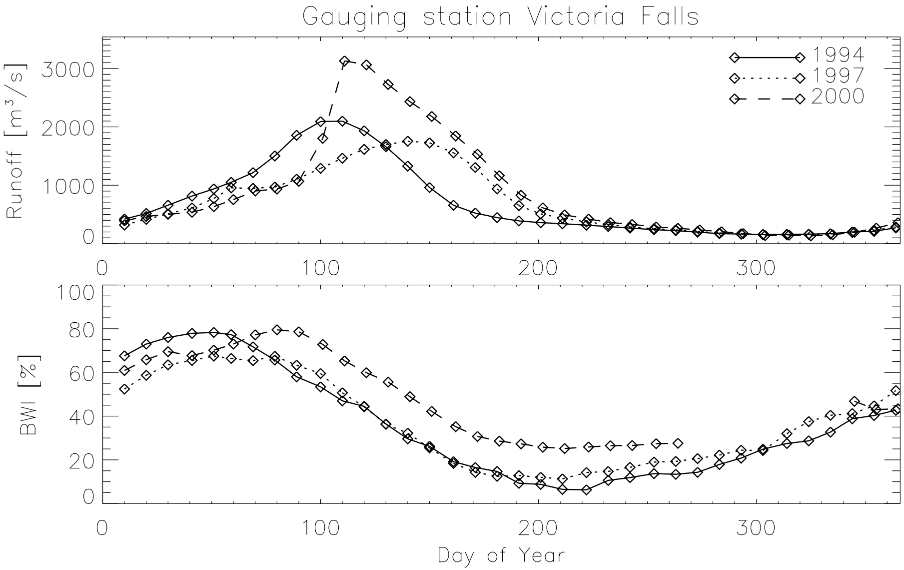

Fig. 2. Runoff and Basin Water Index series for the station Victoria Falls situated on the Zambezi River for the years 1994, 1997 and 2000.

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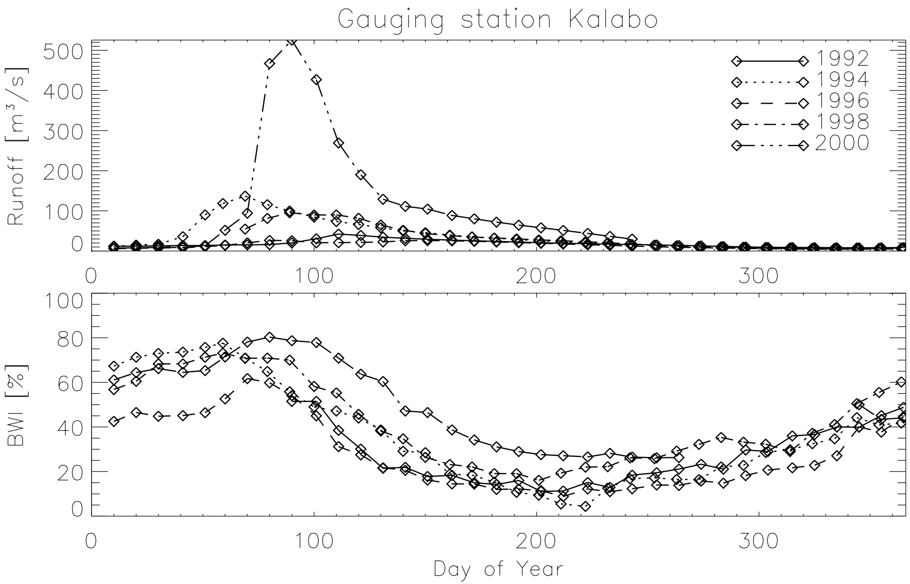

Fig. 3. Runoff and Basin Water Index series for the station Kalabo situated at the Luanginga River for the years 1992, 1994, 1996, 1998 and 2000.

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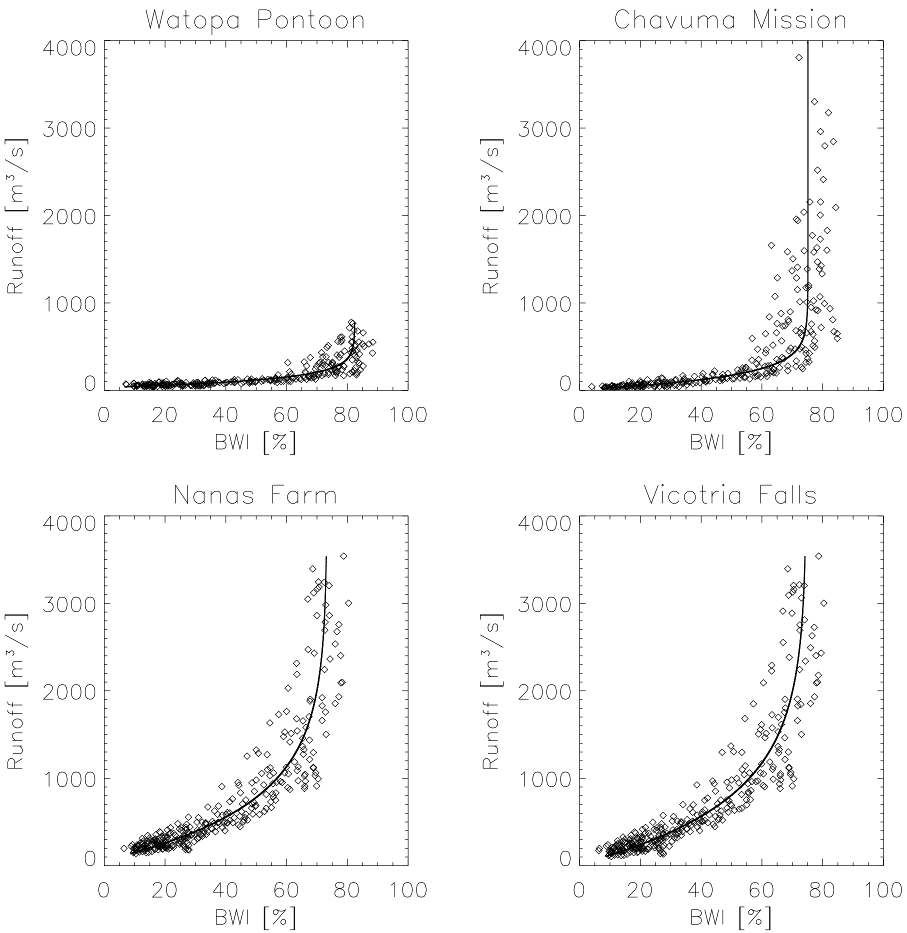

Fig. 4. Scatterplot of Basin Water Index and runoff at four gauging stations of the Zambezi River. Runoff data has been shifted back such that the observed maxima corresponded. The fitted model of Eq. (2) is also shown.

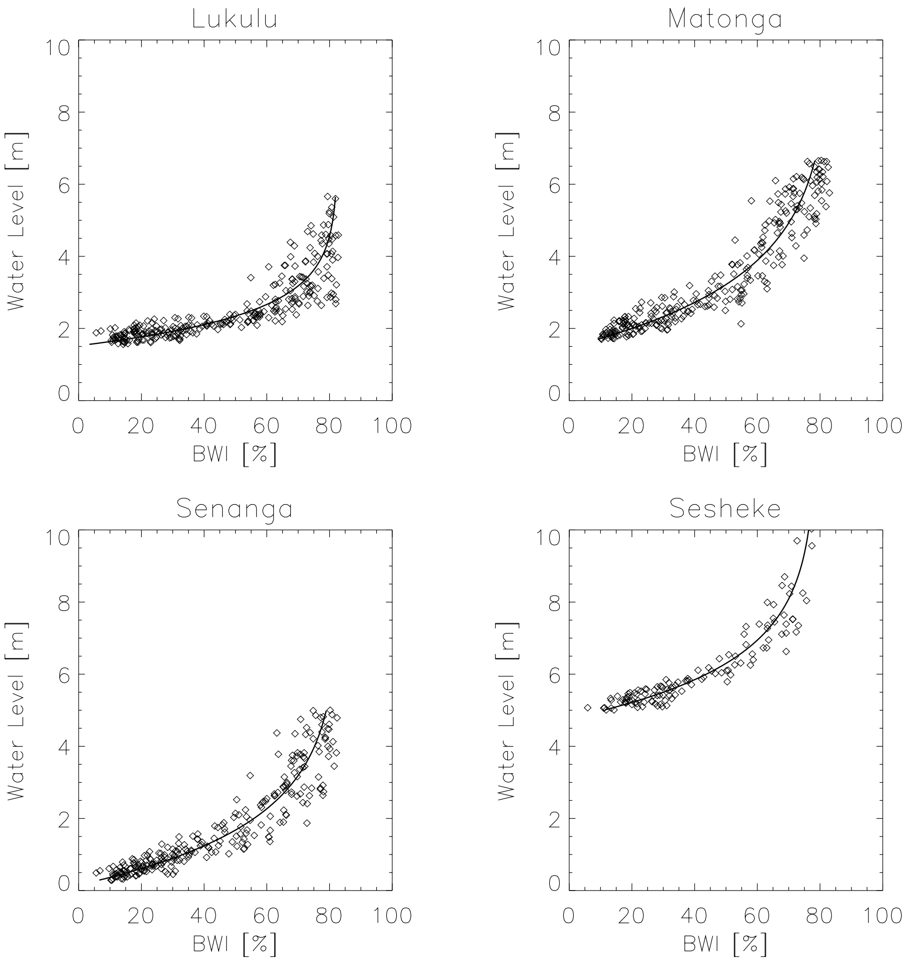

Fig. 5. Scatterplot of Basin Water Index and water level at four gauging stations of the Zambezi River. Water level data has been shifted back such that the observed maxima corresponded. The fitted model of Eq. (3) is also shown.

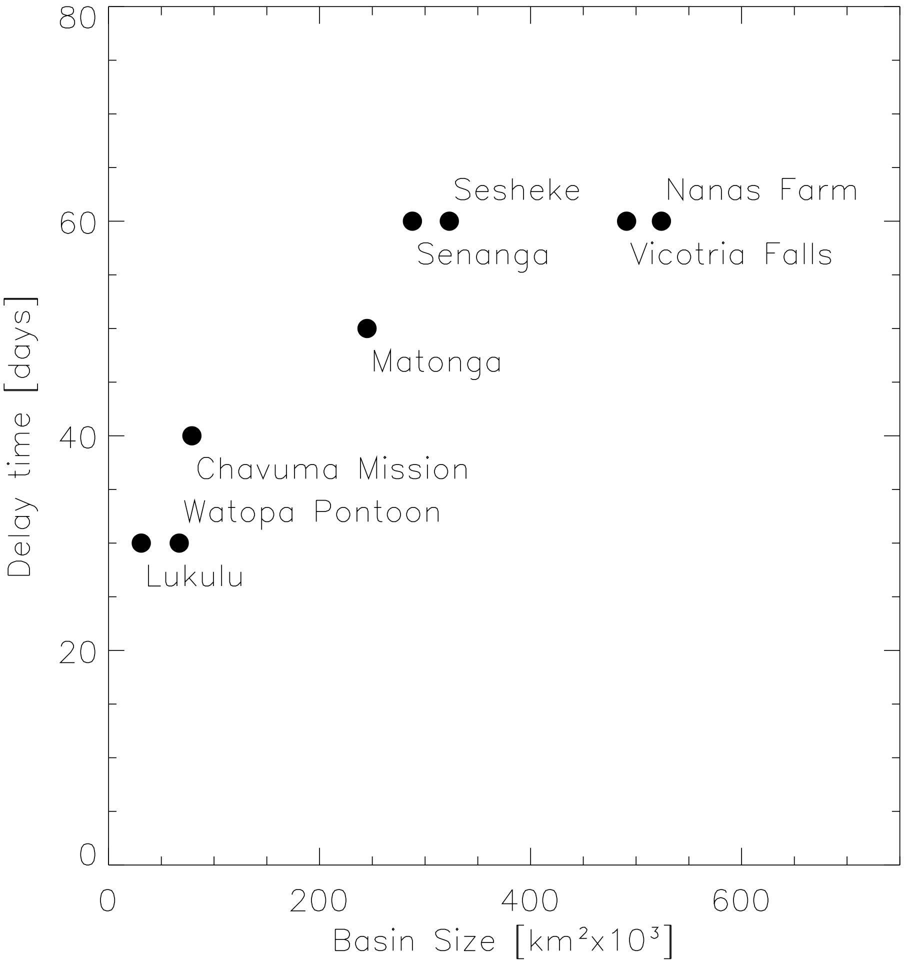

Fig. 6. Relation between basin-size and delay time of the discharge system.

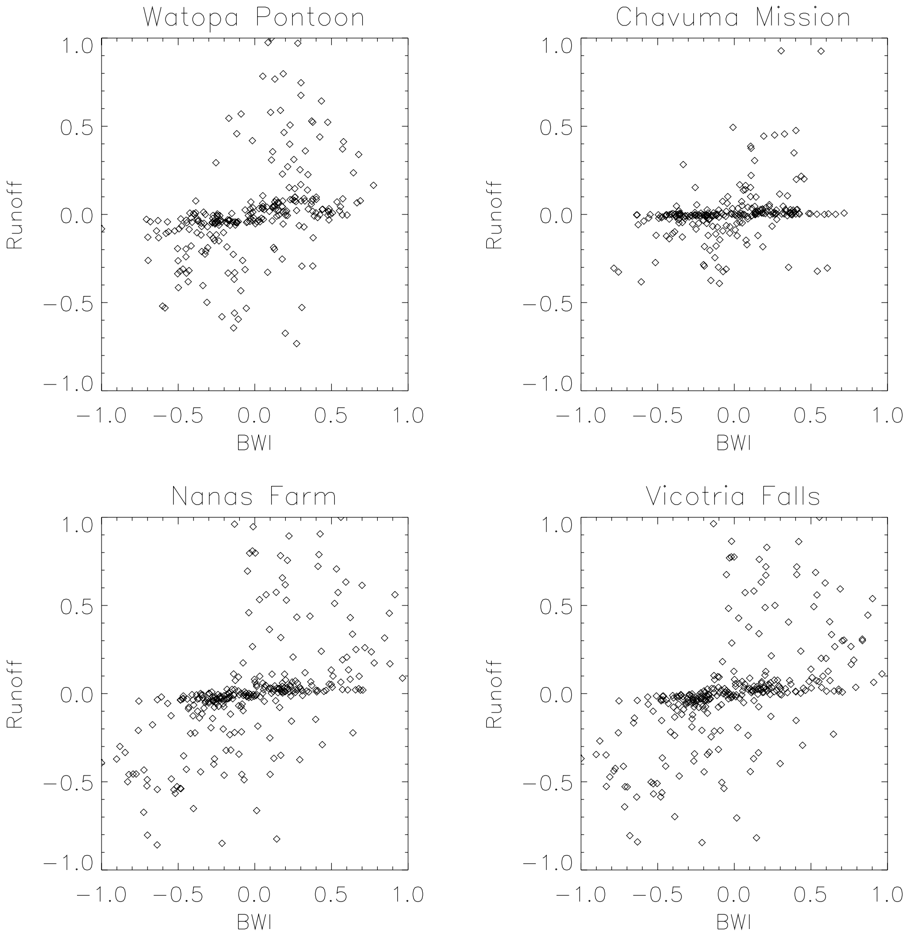

Fig. 7. Scatterplot of Basin Water Index and discharge anomalies at four gauging stations of the Zambezi River. Anomalies have been scaled between −1 and +1.

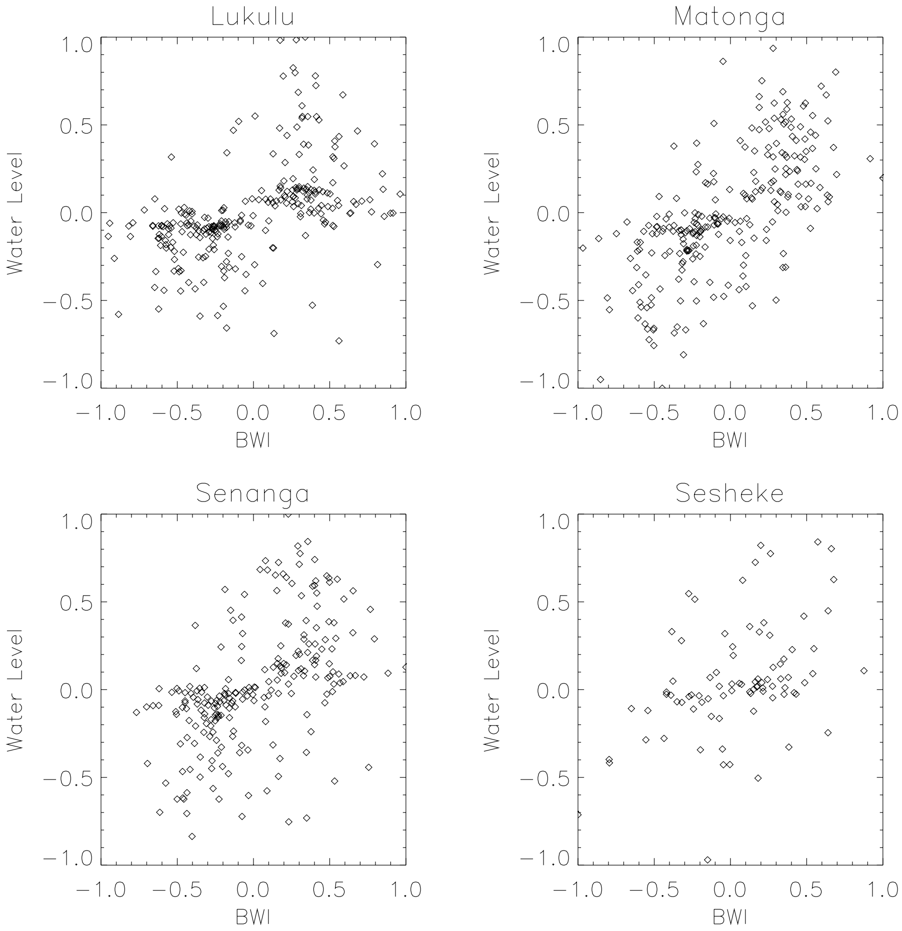

Fig. 8. Scatterplot of Basin Water Index and water level anomalies at four gauging stations of the Zambezi River. Anomalies have been scaled between −1 and +1.