Root Zone Soil Moisture Retrieval Using Streamflow and Surface Moisture Data Assimilation in Nested Catchments

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EXTENDED ABSTRACT

Correct knowledge of soil moisture is important for improving the prediction of coupled land surface - atmosphere interactions. This is due to the control that soil moisture exerts on the latent and sensible heat flux transfer between the land surface and atmosphere. Because of this strong dependence on moisture availability, improved atmospheric prediction requires correct initialisation of soil moisture states within the hydrological model.

Satellite remote sensing and ground point measurements present two techniques for obtaining soil moisture observations. While point measurements allow for the collection of high resolution data through the soil profile, it is limited to a local or at most regional scale due to instrument and logistical constraints. On the other hand, satellite remote sensing is limited to the top few centimetres but yields good spatial information over large areas. However surface soil moisture remote sensing is limited to regions of low-to-moderate vegetation cover, as dense vegetation masks the soil moisture signal. This makes remote sensing of surface soil moisture impossible for heavily vegetated regions such as the Amazon or south-east Asia; regions which have been shown to have the most potential for improved predictability of precipitation when knowledge of soil moisture values is improved. Hence, an alternate approach for soil moisture information is required.

Recent work by the authors has shown the potential for assimilating streamflow measurements to retrieve soil moisture in a small single catchment. In those studies a variational-type data assimilation approach was used to account for the fact that observed streamflow is the result of rainfall and soil moisture conditions at some time in the past. While this approach was able to retrieve the root zone soil moisture well, the surface soil moisture was not well retrieved. It is thus suggested to combine the two approaches to utilise their individual strengths, particularly in regions of mixed vegetation conditions. In this paper we report on use of the variational data assimilation approach to assimilate streamflow observations and/or surface soil moisture observations

This synthetic study is undertaken on three nested catchments within the Goulburn River experimental catchment in south-eastern Australia to demonstrate the approach. Three scenarios are presented: i) only streamflow observations are available for the outlet of the lowest catchment, ii) there are no streamflow observations and surface soil moisture observations are only available for the lowest catchment under the assumption that the upper and middle catchments are too densely vegetated and iii) streamflow observations are available for the lower catchment and surface soil moisture observations for the middle catchment. This synthetic study identifies the potential of using different observations, where and when available, for the retrieval of soil moisture initial states.

Results are shown for soil moisture and runoff retrieval and the subsequent changes in surface heat fluxes. The assessment is based on a comparison between assimilated, truth and non-assimilated (control) simulations. It was found that the assimilation of streamflow has a significant improvement in the retrieval of profile and root zone soil moisture in all three catchments, but displays limitations in retrieving the surface soil moisture state. In contrast, the assimilation of surface soil moisture in the lower catchment alone does not have any effect on the upstream catchments, as there is no feedback between the downstream and upstream soil moisture and respective runoff. Finally, the joint assimilation of both streamflow and surface soil moisture observations leads to a further improvement from the streamflow assimilation alone.

1. INTRODUCTION

Koster et al. (2000a) show that knowledge of soil moisture should result in improved predictability of precipitation with coupled land-ocean-atmosphere models. At mid latitude regions over land, this improvement is at least as great as that from knowledge of sea surface temperatures. However, accurate root zone soil moisture knowledge is not typically available.

While a number of complementary techniques exist for obtaining soil moisture knowledge, they each have limitations. For example, land surface models are able to resolve the space-time variation in soil moisture globally. However, these kind of models suffer from errors in the model conceptualisation, their input parameters, the atmospheric forcing and their initial conditions. Hence different models may generate a wide range of soil moisture estimates even when using the same input parameters, atmospheric forcing and initial conditions. This contrasts with point measurements that yield highly accurate root zone soil moisture knowledge but only on a local or regional scale, due to logistical problems and high spatial variability of soil moisture. Remote sensing on the other hand gives good spatial and temporal coverage but is limited to an estimate for the top few centimetres at most. To overcome the individual weaknesses of the different approaches, remote sensing observations of surface soil moisture have been assimilated into land surface models to constrain those errors.

While there have been encouraging results from the assimilation of remotely sensed surface soil moisture data into land surface models, it is unlikely that this approach will satisfactorily address the predictability problem. The reasons for this are that: i) current remote sensing of surface soil moisture is limited to regions of low-to-moderate vegetation (Jackson et al. 1982), ii) land surface models typically show the greatest uncertainty in regions of high vegetation, and iii) the regions where soil moisture knowledge is expected to have the greatest impact on precipitation prediction are also largely located in regions of high vegetation (Koster et al. 2000a). This means that alternate approaches for soil moisture estimation must be sought if improvements in precipitation prediction are to be realised.

To overcome these limitations, the possibility of constraining land surface model soil moisture prediction through assimilation of widely available streamflow observations has been studied (Rüdiger et al. 2004). The basis of this approach is that streamflow is dependent upon the lumped soil moisture conditions in the upstream catchment(s) in response to rainfall events hours to weeks in the past. Hence, initial soil moisture states are assumed to be retrievable from the given downstream information, subsequently leading to an improved prediction of soil moisture throughout the assimilation window. While this approach was shown to work well for a single catchment, surface soil moisture was not well estimated when applied to a multi-catchment simulation with streamflow observed only at the outlet of the lowest catchment (Fig. 1a,b) of a nested catchment configuration (Fig. 2).

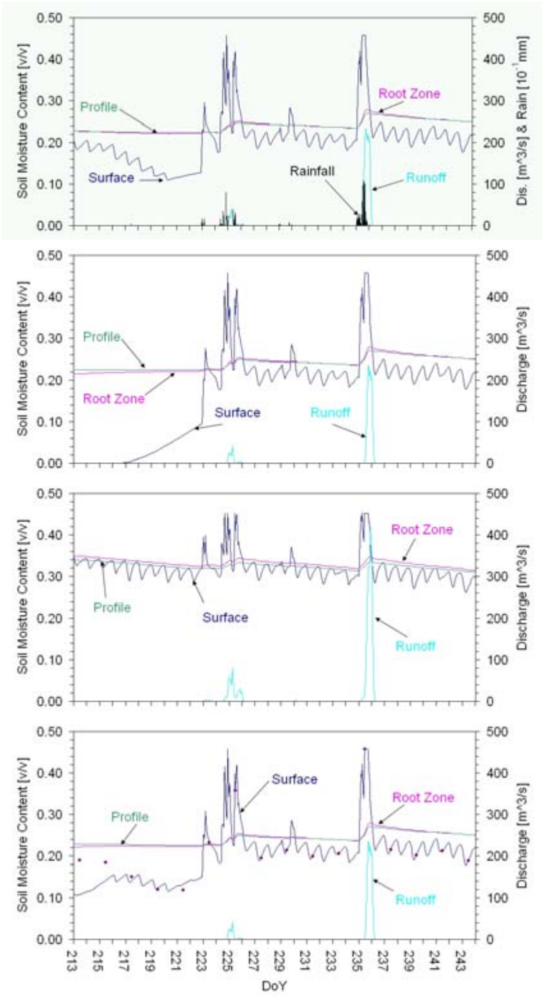
When patches of low-to-moderate vegetation are scattered throughout heavily forested regions, it may be possible to further constrain the soil moisture retrieval through a combined streamflow and surface soil moisture assimilation approach. A reason for this is that the surface soil moisture observations will help constrain the partitioning between surface and baseflow and hence surface and root zone soil moisture content for areas where both types of observations are available.

This approach is demonstrated for three nested sub-catchments in a synthetic study. Three scenarios for observation availability were considered: i) streamflow observations only for the lower catchment, ii) soil moisture observations only for the lower catchment, and iii) streamflow observations available for the lower catchment and surface soil moisture observations for the middle catchment. The study inter-compares and identifies the potential of using i) streamflow to constrain soil moisture in gauged catchments, ii) remotely sensed soil moisture to constrain soil moisture in ungauged low-to-moderately vegetated catchments, and iii) joint use of streamflow and surface soil moisture to constrain soil moisture in gauged low-to-moderate vegetated catchments.

2. STUDY CHARACTERISTICS

2.1. Catchment

This study uses three nested catchments within the Goulburn River study catchment (Rüdiger et al. 2003) in south-eastern Australia (Fig. 2). These three catchments form the catchment of the Krui River, a tributary of the Goulburn River. The individual sizes and elevation ranges of the three study subcatchments are presented in Table 1.



Soil properties were derived from the Atlas of Australian Soils and were taken to be constant throughout the individual catchments, using the dominant soil types. Vegetation cover was obtained from GSWP-2 (Global Soil Wetness Project)

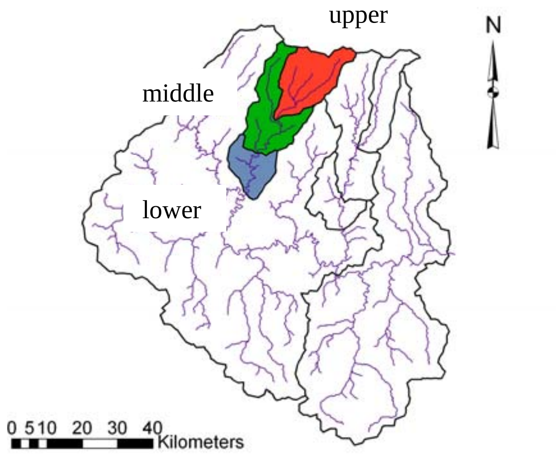


Figure 2. Sub-catchment layout of the Goulburn River study catchment, with the three focus catchments highlighted.

vegetation maps, within the Global Energy and Water Cycle Experiment (GEWEX).

2.2. Land surface and routing models

This study used the Catchment Land Surface Model (CLSM; Koster et al. 2000b) to demonstrate the feasibility of the proposed streamflow data assimilation scheme. CLSM is a lumped land surface model in which subgrid soil moisture variability and its effects on runoff and evaporation are treated explicitly using topographic information from a DEM. Three prognostic variables describe implicitly the water contents of three soil stores: i) the catchment deficit represents the amount of water needed to saturate the entire soil column for a given watertable depth and equilibrium profile; ii) the root zone excess represents any short term variation in root zone water storage from an equilibrium profile; and iii) the surface excess similarly represents any additional short term changes in the near-surface soil layer, which is assumed to be 5cm. Transpiration only takes place when the soil moisture is above the wilting point, whereas bare soil evaporation is possible down to the residual soil moisture content in the surface soil layer. Different rates of evaporation and transpiration are calculated for the saturated,

Table 1. Site characteristics of study catchments.

Catchment	Size [km^2]	Elevation range [m]	Avg. Slope	Vegetation	Soil type
Upper	217	359 - 1239	12.48	Grassland	Clay
Middle	227	316 - 1226	9.52	Grassland and shrubs	Clay
Lower	118	268 - 574	4.07	Shrubs and Forests	Loam

water-unstressed and stressed fractions of the catchment.

Runoff is generated as both baseflow and surface flow in response to precipitation and soil moisture conditions. However, there is no routing mechanism within the CLSM so a simple three-parameter (surface, stream and subsurface runoff) linear routing scheme was introduced, derived from Manning's equation

$$v = (5/3) c_r S^{1/2}, \qquad (1)$$

where v is velocity; c_r is a routing parameter for each flow condition; and S is slope. The parameters for this model were determined from calibration of model runoff with field observations.

2.3. Bayesian data assimilation

The assimilation scheme used in this study is a "brute force" application of the variational approach, with a Bayesian nonlinear regression scheme (NLFIT; Kuzcera 1983) used to minimise the objective function. NLFIT alters the initial soil moisture states until the predicted streamflow and/or surface soil moisture best matches the observations. No-flow observations are filtered out as they dominate the streamflow record in the semi-arid catchment used here. Moreover, they would also have dominated the objective function evaluation and do not carry sufficient information of the upstream soil moisture states.

2.4. Forcing Data

Forcing data used by CLSM are temperature, wind speed, precipitation, specific humidity, and longwave and shortwave downward radiation. Except for the radiation data, which was obtained from the Global Data Acquisition System (GDAS), the forcing data has been obtained from real observations at weather stations within the catchment and comprises data from April 2003 to February 2004. Forcing data has been assumed homogeneous throughout all three subcatchments in this synthetic study. The study demonstrates this approach for a one-month period with two streamflow producing rain events.

3. NUMERICAL EXPERIMENTS

3.1. Truth simulation and observations

The truth data and observations were obtained by repeatedly running CLSM over the one year until dynamic equilibrium conditions were reached. The derived initial conditions from the model spin up were then used to run the model to obtain a set of truth soil moisture streamflow and land surface fluxes in 1 hour time intervals.

3.2. Degraded simulation

The first guess of initial soil moisture states used in the optimisation is the average value of wilting point and saturation. These average values were chosen to represent poor knowledge of initial soil moisture conditions. To obtain control results, soil moisture values in the spun up model were replaced with these values and a simulation performed.

In this study the average moisture content was higher than the true soil moisture observations and consequently led to increased runoff, transpiration and evaporation under the same environmental conditions as the true simulation (Fig. 3 and 4). The main differences are displayed i) in the second runoff event, where runoff is overestimated by a factor of 2; and ii) in the increased latent heat flux over the first ten days of the simulation, compared to the almost nonexistent fluxes in the true simulation.

3.3. Streamflow assimilation

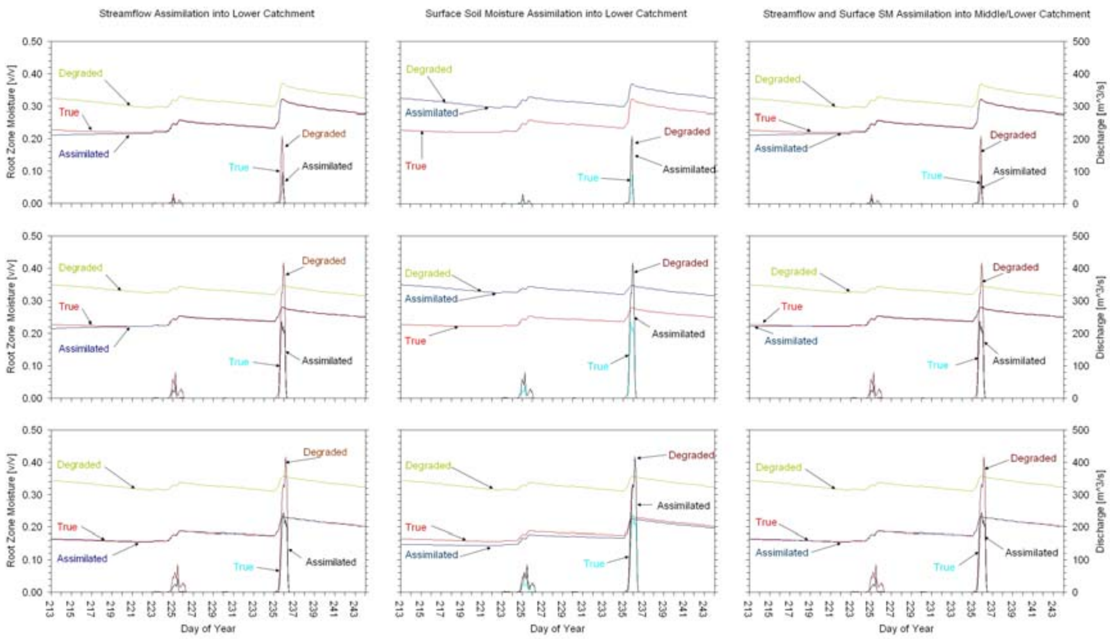
Assimilation scenario 1 assumed that only streamflow observations for the lower catchment were available. Such a scenario simulates the possibility of catchments having forested upstream conditions from the stream gauge and allows assessment of the impact of streamflow assimilation into downstream catchments and the resulting soil moisture states in the upstream catchments.

3.4. Surface soil moisture assimilation

Assimilation scenario 2 assumed that no streamflow observations were available and that remotely sensed surface soil moisture observations are available only for the lower catchment. This simulates remote ungauged streams, where the only observations are remotely sensed soil moisture data in one of the subcatchments.

3.5. Joint assimilation

Scenario 3 considered the joint assimilation of remotely sensed surface soil moisture observations for the middle catchment and streamflow observations for the lower catchment. This c)



combination of observations is used to further constrain the assimilation results of scenario 1, assuming that some of the upstream catchments can additionally have surface soil moisture observations available.

4. RESULTS

The results from the true, control and assimilation runs are shown in Figs 1b-d for all soil layers, Fig. 3 for the root zone, and Fig. 4 for latent heat flux.

4.1. Streamflow assimilation

The assimilation of streamflow observations into the lower catchment leads to a good retrieval of the initial soil moisture states in all three catchments (Fig. 3). The comparison between the results from the degraded and the assimilation runs show a good improvement of the overestimated soil moisture and runoff values.

The best performance is observed for the lower catchment, with slight inaccuracies for the two upstream catchments. The main difference between the truth observations and the assimilation run is the retrieval of the surface soil moisture content, which is underestimated (Fig. 3). This is due to the initial surface soil moisture content not having a significant impact on the runoff and hence the objective function, when the profile moisture is well retrieved. While the infiltration capacity excess mechanism is still the main process contributing to runoff (runoff is only produced when saturation of the surface soil moisture is achieved, see Fig. 1a-d), there is no runoff occurring in the first 10 days of the assimilation window, so that changes to the initial soil moisture states cannot generate runoff events. The precipitation events causing runoff occur over a short period, but during these events sufficient water is introduced into the catchment to wet up the surface layer so far as to allow runoff to be produced. Hence, all subsequent soil moisture values are close to the true observations, and therefore the initial value of the surface soil moisture is irrelevant. The described effect is visible when comparing Fig. 1a and b, where the initial surface soil moisture states are significantly different. However, this is a special case.

Similarly, the heat fluxes are well modelled (Fig. 4). Since the root zone soil moisture is already restricting the latent heat fluxes to low values, the impact on the latent heat flux from the inaccuracies

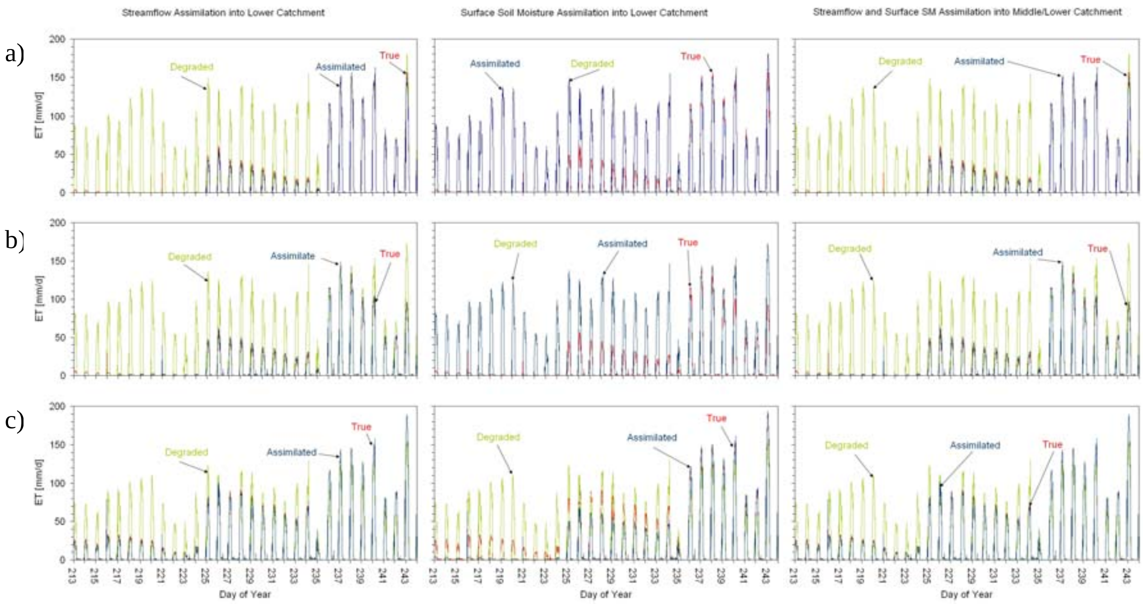


Figure 4. Assimilation results for latent heat fluxes. Individual catchments are shown in rows (a – upper, b – middle, c – lower catchments). Vertical arrangements show the three different assimilation approaches (streamflow, soil moisture and joint assimilation). True observations are shown in red, control simulation in green and assimilated results in blue.

of the surface soil moisture are insignificant, as the latent heat fluxes are dominated by transpiration rather than bare soil evaporation.

4.2. Surface soil moisture assimilation

In scenario 2 the initial soil moisture states in the lower catchment are improved when compared to the control simulation. Hence, heat fluxes are well estimated, but there is no apparent improvement observed in the two upstream catchments. This is because soil moisture estimates for the three subcatchments are uncoupled in the simulation model. As the soil moisture conditions in the upstream catchments remain unchanged, so are the latent heat flux and streamflow.

Following the improvement of soil moisture states in the lower catchment, an improvement of the streamflow is observed at the outlet of the lower catchment. This is due to the improved runoff processes in the lower catchment, as the upstream catchments do not display such an improvement.

4.3. Joint assimilation

In scenario 3 the retrieved root zone soil moisture content for the middle catchment (the catchment with surface soil moisture observations) is slightly improved from that of streamflow assimilation alone. Similarly, the performance of the heat flux estimates shows some improvements. Moreover the surface soil moisture values, while initially still slightly underestimated, are significantly improved before the first major precipitation event (Fig. 1). This is due to the water equilibrium within the soil allowing moisture to be transferred into the surface layer, which was not possible in the previous results as the root zone excess was negative.

5. DISCUSSION

The results show the potential of joint streamflow and surface soil moisture assimilation in a multi-catchment modelling approach. It is shown that streamflow data assimilation alone can improve the retrieval of profile soil moisture, but that the surface soil moisture estimates may be poor. The good retrieval of soil moisture in all three catchments is due to the streamflow being a lumped observation of the routed flow contributions from all three catchments. In contrast, the assimilation of soil moisture alone only impacts on the corresponding catchment as there is no feedback to the upstream catchments. The streamflow assimilation results are improved when surface soil moisture observations are assimilated in addition to streamflow observations. While there is some improvement in the root zone soil moisture content, the most noticeable improvement is in the surface soil moisture content.

The small inaccuracies in soil moisture retrieval from streamflow assimilation alone are due to the degrees of freedom (nine initial values and only one observation field). This is somewhat reduced when additionally assimilating surface soil moisture observations as three initial values are then constrained by the new observation fields.

These results have implications for the modelling of ungauged basins. Given that catchments can be disaggregated into smaller modelling units, according to their available observations, it is possible to obtain good information about the soil moisture states within catchments, even if only surface soil moisture or no observations at all are available for some of the catchments. In particular, it is shown that the assimilation of streamflow data into lower catchments produces an upstream feedback, which is not the case when only surface soil moisture is assimilated.

Previous work (Rüdiger et al. 2004) has shown that the assimilation of streamflow data for soil moisture retrieval under biased forcing data can lead to significant problems in the retrieval of the initial soil moisture states. As only perfect forcing data was used in the present study the impact of observational errors will be investigated in future work. Moreover, the present study was undertaken with data from a semi-arid region experiencing abnormally dry conditions. To fully understand the capabilities and limitations of this approach it will be necessary to study the impact of this approach in humid catchments. In particular, it will be necessary to understand the implications of imposed model thresholds, such as the wilting point and porosity. Finally, this study was undertaken for a small catchment. As this technique for soil moisture retrieval would typically be applied in remote areas with significantly larger catchment areas, it will be extended to such larger catchments.

6. CONCLUSIONS

It has been shown that streamflow data assimilation can be used to retrieve soil moisture in nested catchments from limited observational data. It was also found that streamflow observations have a further reaching impact than surface soil moisture observations on soil moisture retrieval when assimilated into a land surface model with multiple catchments. Additionally a strong dependence of the water profile within the soil on the surface soil moisture was found when assimilating soil moisture. However, surface soil moisture can not be equally well inferred when retrieving soil moisture by assimilating streamflow observations.

7. ACKNOWLEDGMENTS

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