A strategy for observing soil moisture by remote sensing in the Murray-Darling basin

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SUMMARY

The article presents a proposal for a strategy for integration of the data from the new environmental satellites, SMOS, HYDROS and ALOS in a system for monitoring soil moisture in the Murray-Darling basin in Australia. The proposal was developed as one of the results of the team project STREAM during the Summer Session Programme 2004 of the International Space University.

KEYWORDS: *Remote sensing, environmental satellites, soil moisture, hydrology, water management.*

INTRODUCTION

This article presents research done in a project STREAM by a group of students participating in the Summer Session Programme of the International Space University, which took part in the summer 2004 in Adelaide, South Australia. STREAM stands for Space Technologies for the Research of Effective wAter Management. The team project explored the use of space technology for a more effective and better water management and focused on the Murray-Darling basin in Australia. One of the results of the research was a proposal for a strategy for improvement of the existing soil moisture observation system in the Murray-Darling basin.

Remote sensing is the process of inferring surface parameters from measurements of the electromagnetic radiation that is either emitted or reflected from the surface of the Earth. Remote sensing methods play an important role in observing the parameters of the global water cycle and consequently in the water management. Airborne and space-based remote sensing systems are used for observation of the various water cycle parameters. More precisely, in hydrology the reflected solar radiation is used for mapping the snow, vegetation, land cover and water quality, the thermal emission in the infrared spectrum for measuring surface temperature and the thermal emission in the microwave range for soil moisture and snow studies. Some of hydrological parameters can also be measured using active sensors, for example radars for measuring precipitation and soil parameters (Annes et al., 2004, Schmugge et al, 2002).

Soil moisture is a key variable in describing the water and energy exchanges at the land surface and atmosphere levels. It influences hydrological processes such as infiltration, runoff, water absorption, transpiration and evaporation. It also characterises droughts: a drought is a condition when the storage of soil moisture falls below a certain level. The amount of soil moisture is influenced by infiltration, soil particle size, chemistry, thickness of the soil layer, layering and local soil composition, vegetation cover, terrain roughness, topography, temperature and rainfall intensity. Soil moisture data is used as input to hydrological models for applications such as crop forecasting, estimating fire risk, flood forecasting and environmental conservations (Houser, 2003, Wigneron et al., 2003).

Soil moisture can be measured by in situ measurements, by remote sensing or estimated by hydrological modelling (Puma et al., 2005).

The most reliable and accurate means of determining soil moisture is to conduct measurements on site. These observations also provide a basis for understanding results from remote sensing techniques. The three methods that are most commonly used for soil water content determinations today are the thermogravimetric method, neutron thermalisation and a group of methods based on soil dielectric properties. The thermogravimetric method estimates the water content in the soil by weighing a sample before and after drying it in the oven. The neutron method uses the ability of hydrogen to slow down fast neutrons more efficiently than other substances. In any soil, most of the hydrogen is present in water molecules and therefore the number of backscattered slow neutrons emitted from a radioactive source and measured by a detector in the probe, directly corresponds to water content in the soil. The dielectric methods are based on the large difference between the dielectric constant of water (80) and of the most dry soils (less than 5). In a mixture of water and dry soil, the resulting dielectric constant is between these two extremes, thus offering a mechanism for detecting the water content in the soil (Gardner et al., 2001). Gravimetric sampling and networks of impedance probes based on dielectric methods are the two most reliable methods of estimating surface soil moisture. But since these methods require a significant effort, technological as well as financial, there are only a few places where such measurement networks exist. Therefore remote sensing soil moisture observations are necessary for global applications. (Puma et al., 2005, Cosh et al., 2005).

Remote sensing methods for measuring the soil moisture are based on either passive measurements in the microwave range of the spectrum or on the backscatter of an active radar sensor. At microwave frequencies there is a large contrast in emissivity between water and land due to the large difference in the dielectric constant of water and soil. By observing the emissivity at microwave frequencies, the water content in the soil can be estimated in a similar way from remotely sensed data as from the data obtained with dielectric in situ methods (Puma et al., 2005). This difference can be sensed using microwave radiometers in the L-band frequency (around 1.4 GHz or with 21cm wavelength), which allows good penetration of the soil up to one fourth of the wavelength, i.e. 0-5cm depth (Schmugge et al, 2002). In conjunction with other information, the moisture in the whole root zone (up to 30cm depth) can be inferred from the surface soil moisture (Wilson et al., 2003). The quality of remotely sensed data depends on the sensor type (active or passive), vegetation cover, topography, surface roughness, surface temperature and soil type (Wigneron et al., 2003). While remote sensing methods can not replace ground based methods for providing high quality point data, their advantage is in mapping soil conditions at regional, continental or global scales on a repetitive basis. Active sensors can provide high-resolution data (of the order of tens of metres) which can be used for detailed local hydrological studies, but they are more sensitive to surface roughness, topography and vegetation than passive sensors, which in turn provide poorer resolution data (tens of kilometres) and are therefore appropriate for meteorological and climate models on a global scale (Schmugge et al., 2002).

Aircraft observations of the microwave emission for soil moisture have been in existence for the last 30 years. Some current examples of measuring soil moisture from airborne sensors include experiments using the Electronically Scanned Thinned Array Radiometer (ESTAR) (Mohanty and Skaggs, 2001, Schmugge et al. 2002), the Scanning Low Frequency Microwave Radiometer (SLFMR) (Uitdewilligen et al., 2003) and an active airborne Synthetic Aperture Radar AirSAR (Western et al., 2004)

From space, soil moisture is primarily measured using passive microwave radiometers. These include the Advanced Microwave Scanning Radiometer (AMSR), which was on the JAXA's Advanced Earth Observing Satellite II (ADEOS – II). The operation of ADEOS-II was abandoned in October 2003 due to technical troubles (JAXA, 2003). Another Advanced Microwave Scanning Radiometer for Earth Observing System (EOS) is placed on NASA's Aqua satellite, which is currently in orbit (Liu et al., 2000) and has been used for several soil moisture experiments (Njoku and Li, 1999, Cosh et al., 2004).

Soil moisture can be also derived from data from active spaceborne sensors. One of them is the Precipitation Radar (PR) on NASA's Tropical Rainfall Measuring Mission (TRMM), which is a radar sensor for rainfall measurement in the tropics. Its frequency is too sensitive to vegetation cover and rainfall to yield a direct measurement of the soil moisture, but since at the time of the TRMM launch in 1997 there were no sensors planned for monitoring the soil moisture, there has been some research on how to derive soil moisture parameters from PR data, usually in combination with passive microwave data from the microwave imager TMI from TRMM (Lee and Anagnostou, 2004). Surface soil moisture can also be estimated from backscatter of another active microwave sensor, Wind scatterometer (WSC) on board the European Remote Sensing satellite ERS-1, which was primarily designed to estimate wind characteristics, speed and direction, over the ocean surfaces (Magagi and Kerr, 2001). The most common alternative of using active microwave sensors for soil moisture is to use radar backscattering data from Synthetic Aperture Radar (SAR) sensors. SAR sensors measure the spatial distribution of surface reflectivity in microwave spectrum. The radar transmits a pulse and then measures the time delay and strength of the reflected echo, where the ratio of scattered and incident microwave energy is termed the radar backscatter. The scattering behaviour of the SAR signal is directly related to the dielectric properties of soil and vegetation. SAR systems have the advantages of cloud penetration, all-weather coverage, high spatial resolution, day/night acquisitions and signal independence of the solar illumination. On the other hand, the backscatter is more sensitive to surface roughness than on changes in dielectric constant and is also highly influenced by topographic features and vegetation density. In spite of this, SAR data obtained from various satellites (European Remote Sensing satellite (ERS-1/2), the Canadian RADARSAT and Japanese Earth Resources Satellite (JERS-1)) have been widely used for monitoring soil moisture, either alone or in combination with other data, for example Shuttle Imaging Radar SIR-C, Wind scatterometer (WSC), Landsat TM and other optical imagery (Paloscia et al., 1999, Moeremans and Dautrebande, 2000, Moran et al., 2000, Moran et al., 2002, Zribi et al., 2003).

Soil moisture can also be derived from a combination of hydrological modelling and remote sensing data. The instantaneous surface soil moisture inferred from remote sensing observations are assimilated into hydrological models in order to estimate the soil moisture in the deeper soil layers (Puma et al., 2005), often in combination with other data, such as ground measurements (Wilson et al., 2003) and relative evaporation, derived from a combination of meteorological data and remote sensing data from the NOAA Advanced Very High Resolution Radiometer AVHRR (Su et al., 2003).

THE CASE STUDY AREA – THE MURRAY-DARLING BASIN

The Murray-Darling basin has been chosen as an example of a large catchment area with an effective system of water management. The Murray-Darling basin covers roughly one seventh of Australia and is home to ten percent of Australia's population. The basin is one of the world's major river systems. It extends over 1.000.000 km^2 and over five Australian states: Queensland, New South Wales, Victoria, South Australia and the Australian Capital Territory. It includes the catchments of the three longest rivers in Australia (fig. 1): the Darling (2740 km), the Murray (2530 km) and the Murrumbidgee (1690 km) (MDBC, 2004).

Except for its eastern boundary along the Great Dividing Range, the basin is flat and mostly below 200m above sea level. The gradients are low and the water movement slow: it takes 5 weeks for the water to travel the whole length of the river Murray. Due to its large geographical extent the climatic conditions vary extensively over the basin, from the sub-tropical conditions in the northeast, over the cool humid climate on the eastern uplands supporting areas of rainforest, to the temperate climate in the southeast of the basin. The largest part of the basin consists of the western plains with a semi-arid and arid climate. Another characteristics of the climate in the basin is also the large interannual variability of the rainfall, caused by the impact of the Southern Oscillation on the area.

Southern Oscillation is a global-scale irregular air pressure fluctuation, related to weather anomalies in the southern Pacific ocean. It is measured by the Southern Oscillation Index (SOI), derived from the pressure difference between Tahiti and Darwin. An anomalously low SOI is associated with the El Niño phenomenon, while a strong positive anomaly is called La Niña. The periodicity of the changes in the SOI is estimated to vary between two to ten years, with El Niño events lasting between 18 and 24 months, which has a large impact on the climate in Australia and thus also in the Murray-Darling basin. The occurrence of El Niño is strongly correlated with reduced rainfall over the continent, resulting in extensive droughts in the basin (Sturman and Tapper, 1996).

Figure 1: The location of the Murray-Darling basin in the south-eastern part of Australia

The basin generates between thirty and forty percent of total Australian industrial production and about fifty percent of Australian agricultural production. The development of agriculture in the basin has contributed to a series of environmental problems, some of which are directly related to extensive irrigation. The area under irrigation for crops and pastures extends over 1.5 million hectares and represents seventy-five percent of the total irrigated area in Australia (MDBC, 2004). Because of the large volume of water removed from the rivers, median annual flow to the sea is now only twenty-seven percent of its natural pre-development flow. A century of water diversion and physical regulation by dams and weirs has resulted in less water reaching floodplains and wetlands and changed seasonal flow patterns. These effects have significantly impacted river health, resulting in environmental changes such as extinction of nature fish species, stress of river red gum trees, closing the mouth of the Murray, and deterioration of water quality, which is mainly due to the development of dryland salinity, caused by the modern landuse practices in the basin (Purdie, 2003).

The effective governance of water collection and distribution is essential for the sustainable development of the Murray-Darling basin. Current water management strategies in the basin demonstrate one of the world's best practices in integrated catchment management. The water management in the basin is governed by the Murray-Darling Basin Agreement, an intergovernmental agreement that coordinates planning and management of the water, land and other environmental resources between the five states that are situated in the basin. The executive body that implements nature resources management is the Murray-Darling Basin Commission. Water management strategies in the basin include integrated catchment management, human dimension, monitoring and evaluation, basin salinity management, floodplain wetland management, algal management, native fish and salinity and drainage. The policy of the management is to achieve healthy rivers, ecosystems and catchments by setting targets for water quality, water sharing, ecosystem health and terrestrial biodiversity (MDBC, 2004).

MONITORING SOIL MOISTURE IN AUSTRALIA AND IN THE MURRAY-DARLING BASIN

In spite of its importance for hydrological analysis, soil moisture studies over the major agricultural regions of Australia have been scarce in the past. The soil moisture data consists mostly of point scale data, which are representative only of very small areas. This data was used together with other meteorological data and remotely sensed data in various simulations and studies which have been used to compensate for actual measurements (Munro et al., 1998, Pellenq et al., 2003). Most of the recent soil moisture studies and field experiments in Australia using remotely sensed data have been performed over small catchments which are not situated in the Murray-Darling basin. However, there was one small experiment located inside the basin and one study encompassing the whole basin.

SAR backscatter data from ERS-2 was compared with the predicted backscattering from several widely accepted state-of-the-art backscattering models in order to explore the potential for measuring near-surface soil moisture and evaluate the effect of surface roughness in the backscattering predictions. The experiment was performed in Nerrigundah catchment near Dungog in New South Wales, which is outside the Murray-Darling basin but lies in a similar pasture environment for cattle as a large part of the basin is (Walker, 2004). Another experiment was performed in the Tarrawarra catchment on the Yarra river in Victoria. Again this catchment is located outside the basin but is in the pasture land and therefore similar to a large part of the basin. During this experiment a large dataset of spatial soil moisture over a small catchment was collected, including high resolution spatial patterns, detailed moisture profile data and remotely sensed data from ERS SAR and AirSAR, in order to evaluate the use of remotely sensed data in the prediction of surface soil moisture (Western et al., 1999, Western et al., 2004).

A small field experiment in the Murray-Darling basin was undertaken near Wagga Wagga on the Murrumbidgee river in New South Wales using AirSAR data for mapping the soil moisture. Only a poor relationship was found between the in situ measurements of the soil moisture and the AirSAR-derived dielectric constant, due to the changes in salinity effecting the dielectric constant. This is one of the limitations for remotely measuring soil moisture in Australia, that soil texture and soil salinity data are both needed to incorporate in the model using remote sensing data in order to provide a good estimate of soil moisture. Such data can only be gathered for small catchments with the required accuracy and does not exist for the entire Australian continent (McVicar and Jupp, 1998).

Over the whole Murray-Darling basin, the moisture availability has been estimated using the remotely sensed data from the Advanced Very High Resolution Radiometer (AVHRR) and meteorological data. The AVHRR data is integrated with the interpolated meteorological data into the Normalised Difference Temperature Index (NDTI), which provides a measure of the surface moisture availability, the ratio of actual to potential evapotranspiration (McVicar and Jupp, 2002). This study integrates data with very different spatial and temporal scales. The AVHRR data are spatially dense but temporally sparse (depending on satellite repeat characteristics and cloud coverage) while meteorological data are spatially sparse and temporally dense. The meteorological stations are sparsely distributed over the Murray-Darling basin: there are 80 meteorological stations recording data since the 1980s, out of which only 63 have complete data series, while the other miss numerous periods. The meteorological data from long-term, large area networks are usually daily integrals (totals of rainfall) or daily extremes (maximum and minimum temperature) acquired regularly over long periods of time. Such data has to be interpolated both spatially and temporally, to fit with the exact time and place of the remotely sensed data acquisition (McVicar and Jupp, 1999). McVicar and Jupp (2002) present an approach of estimating the NDTI by using three covariates derived from AVHRR data (surface temperature minus air temperature, percent vegetation cover and net radiation) over the network of meteorological stations. This approach maps changes in moisture availability over the Murray-Darling basin and thus provides useful information about regional hydroecological processes.

THE STREAM PROPOSAL FOR THE SOIL MOISTURE MANAGEMENT STRATEGY FOR THE MURRAY-DARLING BASIN COMMISSION

The outcome of the STREAM team project at the Summer Session Programme 2004 of the International Space University is a proposal for a five year Soil moisture management strategy for the Murray-Darling Basin Commission, which builds on the existing studies described above. The strategy consists of two parts:

- developing a hybrid system for soil moisture monitoring in the Murray-Darling basin, based on the existing studies, by using the new environmental satellites SMOS, HYDROS and ALOS and adding a network of ground sensors at selected sites to supplement the existing remotely sensed and ground data and
- to establish a central library for data in order to support the water management decision making.

In the near future there are three major satellite missions planned which will include sensors for measuring soil moisture: SMOS mission by ESA, HYDROS mission by NASA and ALOS mission by JAXA. The Soil Moisture and Ocean Salinity (SMOS) satellite by ESA will be launched in 2007. It will monitor soil moisture, ocean salinity, the water content in vegetation and the snow and ice cover by using a passive microwave interferometer MIRAS – Microwave Imaging Radiometer using Aperture Synthesis. MIRAS will operate in the L-band, where the sensitivity to soil moisture is very high whereas the sensitivity to atmospheric disturbances and surface roughness is minimal (ESA, 2005). In 2010 NASA will launch the Hydrosphere State satellite (HYDROS), which will monitor soil moisture and freeze-thaw cycles and provide the data for weather and climate prediction, hydrospheric modelling and water resource availability prediction. The instrumentation will utilize both active and passive microwave radiometers in L-band to measure the dielectric characteristics of soil and vegetation (NASA, 2005). A Phased Array type L-band Synthetic Aperture Radar (PALSAR) is one of the three land observing sensors placed on the Advanced Land Observing Satellite (ALOS), which will be launched in the September 2005 by JAXA (JAXA, 2004).

The data from SMOS, HYDROS and ALOS should be supplemented with the data obtained from new automatic ground probes. These should be distributed in a network at critical points all over the basin and should provide data on the soil moisture at multiple depth levels and in real-time. The probes would be positioned at selected sites of interest, for example where a long-term study of areas adjacent to wetlands might be required. As an example, Measurement Engineering Australia supports automatic remote monitoring of soil moisture using a network of radio base stations. Up to thirty-two field stations with four soil moisture sensors per station can be connected to a single radio base station in a radius of 1km around the base station (MEA, 2005). The system is primarily meant for local agricultural users and monitoring of the soil moisture on local basis, but has a potential to be implemented over the whole basin and contribute to the central collection of soil moisture data.

Finally, a central data library should be established, which would collect or link the ground measurements from the new system of soil moisture probes, the meteorological data from the existing meteorological stations, the existing remotely sensed data (AVHRR) and the soil moisture data from the three future satellites. The task of the library would be to process the data for further use, either in environmental modelling on a scientific level and/or for other end users that need to have information about water management (primarily water-dependent users, such as farmers, irrigators, water-dependent industries, etc.). The conceptual arrangement of the suggested data processing system is illustrated in fig 2. It is suggested that the central library might be undertaken as a function of CSIRO, Australia's Commonwealth Scientific and Industrial Research Organisation. The central library function is a concept for the overall management of historical and future data sets. Even though the data may continue to residue in separate physical locations, the library gives a possibility to the users to understand what is available and to access the necessary data. Another necessary factor for supporting the long-term studies of soil moisture in the MDB apart from the establishment of a central library functional concept is the development of hydrological models for soil moisture.

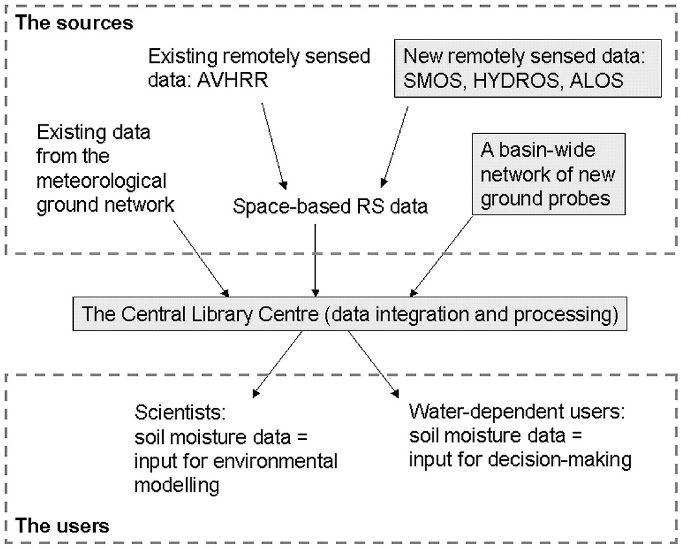

Figure 2: The conceptual arrangement of the soil moisture measurement strategy for the Murray-Darling basin. The STREAM proposed components of the system are presented in the grey boxes.

The STREAM project also suggested to the Murray-Darling Basin Commission a 5-year management strategy for implementation of the conceptual solution for monitoring soil moisture presented above. The basic steps of this strategy include: a feasibility study to confirm/reject/improve the proposed solution (in 2005), establishment of the ground network over smaller regions in the basin every year for a period of five years (2005-2009), development of hydrological models using the SMOS/HYDROS/ALOS data (2006-2010) and implementation of the central library functions, such as cataloguing, data matching, storage and distribution (2006-2010). A tentative cost analysis for the strategy was also performed, including costs for build-up of the sensor network, preparations for handling the new remotely sensed data and for on-going operating costs. According to the STREAM suggestion, a budget of 250000 USD per year would be required in order to successfully implement the 5 year strategy. However, this number should be regarded only as a rough estimate, since due to limited project time the STREAM authors were not able to research the detailed requirements and existing technological solutions.

CONCLUSIONS

One of the results of the STREAM project was to identify the observation of soil moisture, an important factor in water management, as an example of how remote sensing technology can bring significant benefits to water management. Currently ground data about soil moisture is difficult and expensive to collect and the existing space-based remote sensing methods on gathering soil moisture were not primarily meant for monitoring soil moisture and their measurements depend on many other factors apart from the moisture, such as topography, surface roughness and vegetation. This will change in the near future with the new planned environmental satellite missions that will be specifically equipped for monitoring soil moisture. The data from these future missions should be integrated with other data sources into a system that can provide information about this important hydrological parameter to scientists as well as the water-dependent users in the Murray-Darling basin. The concept could be extrapolated to water management in other areas around the world with the similar hydrological and climatological conditions, i.e. arid and semi-arid areas with a high level of human regulation of the river systems, where droughts are the main concern. Such areas include for example the Yangtze-Haihe-Huaihe basin in China, river systems in the Middle East (Tigris, Euphrates), Amu Darya and Indus river systems, the river systems in the midwestern USA, the Rio Grande system in Mexico, etc.

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