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THE DEVELOPMENT OF AN INNOVATIVE COMPUTER-BASED INTEGRATED WATER RESOURCES MANAGEMENT SYSTEM FOR WATER RESOURCES ANALYSES

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The European IWRMS (Integrated Water Resources Management System) project is dedicated to developing a toolset for a sustainable use and distribution of water resources in southern African countries. This system integrates various scientific components: remote sensing, information systems, database management, and hydrological modelling. This paper is mainly related to the remote sensing contribution of the project. Two points are discussed: land cover classification and the spatio-temporal processing of remote sensing data to extract hydrological parameters.

Keywords: water resources management, evapotranspiration, land cover classification, remote sensing.

1 Introduction

The lack and the irregularity of water resources in semi-arid countries are at the origin of a great deal of research focusing on hydrological phenomena. Understanding the water balance budget is crucial to the success of the decision process for an efficient and sustainable use of the available water resources. This is a challenge taken up by the IWRMS project which aims to develop an integrated information management system for water resources in southern African countries. It is investigating a toolset to assist local and regional water authorities to validate and improve their present water resources management and flood protection strategies. IWRMS is a multidisciplinary project involving various scientific domains and specialist skills such as: remote sensing, GIS, hydrological modelling, information system management.

This paper deals with the remote sensing contribution of the project. After a presentation of IWRMS principles and objectives in section 2, two major subjects are presented: land cover classification in section 3 and the spatio-temporal processing of satellite data for hydrological parameters estimation and characterization in section 4.

2 Integrated water resources management

Over the past decade, water resources management has faced a multiple paradigm shift: from supply to demand management, from an engineering to an environmental perspective, from a top-down to a participatory management. There is a broad consensus for the need to achieve a better balance between economic efficiency and environmental quality regarding the sustainable development of natural resources. Such an integrated water resources management approach can be supported by analyzing water quantity and quality together with their temporal and spatial distribution within a river catchment based on its physical and socio-economic conditions, integrated with water demand and utilization analysis. In this context, Decision Support Systems can assist in turning a multidisciplinary management using separate tools into an integrated, interdisciplinary framework system.

2.1 The IWRMS Decision Support System: key concepts

Important characteristics of a Decision Support System (DSS) for sustainable water resources management include flexibility for tackling various 'what-if?' scenarios, the assistance in problem identification and solving by means of analytical tools which enable the end-user to manage, analyze and present information, and interaction and ease of use so as to involve the stakeholders in the management process themselves. Using GIS and traditional DSS in an integrated way leads to an extended concept of the Spatial Decision Support System (SDSS), incorporating the capabilities of both GIS, which accounts for the spatial dimension of water resources management and makes use of powerful visualization techniques, and DSS, which brings user assistance, models, a database, scenario-building and a generic framework into the system. The IWRMS project is following these principles. Among others it comprises the following specific aspects [7]:

- Classifying and investigating land use, degraded areas and settlements by means of remote sensing techniques, interpretation of aerial photography and linkage with GIS to develop methods for gaining aerial input and validation data for hydrological models in southern Africa.

- Simulating hydrological and erosion dynamics using the deterministic, physically based hydrological model ACRU.
- Developing a GIS-based management decision support system to identify competing stakeholders' water demands and to address water allocation conflicts with respect to socio-economic issues.

The aspect of water allocation modelling and optimization using hydrological model scenarios and water use scenarios in a GIS network model environment can be obtained from [2]. An overview on the impact of object orientation on hydrological modelling and some technical aspects of the modelling core of the framework system OMS (Object Modelling System) used for IWRMS is given in [1]. The acquisition of input and validation data using remote sensing data is discussed in [7]. This data, namely land use, elevation, rural settlements, vegetation and meteorological parameters such as leaf area index, land surface temperature and evapotranspiration, is used for two major purposes, both serving as input for the hydrological catchment model. On the one hand, static areal data like land use and elevation can be used to derive spatial model entities (WRRUs, Water Resources Response Units), generated by GIS overlay analysis. On the basis of each of these WRRUs, the hydrological processes can be modelled in a distributed manner. This takes into account need for changing specific land segments according to future scenario simulation. On the other hand, the data generated by remote sensing is used to parameterize the process algorithms. An algorithm e.g. calculating rainfall interception in the canopy layer needs information about the leaf area index as a measure for the canopy storage capacity. Besides model parameterization, remote sensing data can be very valuable for validating models performance by comparing the real world scenario results with remotely sensed data.

The final product, the prototype Integrated Water Resources Management System (IWRMS) is a toolset of validated data, documents, applications and computer based procedures, integrated into a database-centred SDSS that is able to optimize equitable water allocation among competing stakeholders. To validate IWRMS methods and models, three test catchments were selected due to different scale and water usage conflicts: the Mkomazi river basin in Kwazulu-Natal (South Africa), the Mbuluzi catchment in Swaziland and the Mupfure catchment in Zimbabwe. These study areas are described in [7].

3 Mesoscale land cover classification

Land cover classification is a fundamental input for hydrological models. The classification method follows the Standard Land Cover Classification Scheme for Remote Sensing Applications in South Africa [8] with three hierarchical levels (a fourth level could be enclosed by aerial photo interpretation and field mapping). This scheme, however, is being improved in hydrological terms i.e. to distinguish between planted alien and indigenous forests, to distinguish settlements according to their imperviousness rather than classes of income and to assess agricultural areas according to their site preparation and their surface covers (litter, mulch, etc., [6]).

Classification is first preceded by extended preprocessing procedures including atmospheric correction, terrain correction, contrast stretching and filtering in order to avoid misclassifications due to illumination and relief effects. Then supervised Maximum-Likelihood-Classifier is applied to the Landsat TM data (22.04.96) using 6 bands in the visible, infrared and short wave infrared spectrum. The selection of the training areas is based on ground check campaigns carried out in February/March 1998 (South Africa, Swaziland) and March 1999 (Zimbabwe). For the Mkomazi catchment in South Africa a second scene from 05.10.98 was used to carry out a multitemporal (inter-seasonal and inter-annual) classification, which enhanced the result significantly. To further improve the land cover classification results furthermore sensor combinations with ERS data from the microwave range were applied together with rationing operations (NDVI and LAI) to derive small scale vegetation information. Finally optical sensor merges (SPOT pan with Landsat TM) were carried out for presentation purposes.

The final result consists of a classification with 3 levels: level 1: 8 classes; level 2: 20 classes; level 3 for Zimbabwe: 17 classes; level 3 for South Africa: 14 classes; level 3 for Swaziland: 17 classes due to some local specificities. For each site the 3 levels are available and they follow the above mentioned Standard Land Cover Classification Scheme [8], which can be applied for model input according to the requirements of the model. Figure 1 gives an example of a level III classification from Zimbabwe based on sophisticated GPS-ground truthing from the Mupfure catchment west of Harare, where intensive farming took place around a geological dyke, covered by natural forest.

4 Spatio-temporal processing for characterizing hydrological parameters

Models used to simulate changes in water levels and their effects on vegetation need to accurately simulate all components of the water cycle. One of the most important is evapotranspiration (ET) expressed in mm/unit of time (day,week, ...). ET is the transfer of water from the earth into the atmosphere by evaporation from water and soil surfaces and transpiration from vegetation. In some southern African areas, about 90% of precipitation is sometimes lost by evapotranspiration. Characterizing and monitoring this parameter is therefore necessary to improve water resources management. The estimation of ET at a good temporal and spatial resolution over a river catchment by processing remote sensing data is a fundamental task of the IWRMS project. The estimated parameters are then used to generate maps in order to monitor parameter evolution and detect variations. They also serve as input for hydrological models.

4.1 Estimation of evapotranspiration

ET can be computed as a gradient between air (T^{air}) and soil (T^{surf}) temperatures [3]:

$$ET = A + B \times (T^{surf} - T^{air}) \tag{1}$$

A, B are empirical coefficients, T^{surf} can be estimated from data given by satellite thermal channels, and T^{air} can only be obtained with meteorological stations.

Since we aim to compute ET from satellite imagery, we propose a linear relation model (eq 2) between $\Delta T = (T^{surf} - T^{air})$ and T^{surf}:

$$\Delta T = \alpha T^{surf} + \beta \tag{2}$$

where α and β are empirical constants computed using a set of field measurements:

$$\Delta T = 0.34 \times T^{surf} - 7.22$$

with a correlation coefficient of 0.867

Moreover, parameters of the equation (1) are computed using field measurements from the IWRMS database, and the following relation is obtained with a correlation coefficient of 0.977:

$$ET = 0.964 \times \Delta T + 3.081$$

Lastly, replacing ΔT gives equation (3)

$$ET = 0.33 \times T^{surf} - 3.88 \tag{3}$$

Using this relationship, ET can be estimated given T^{surf} values from satellite images.

4.1.1 Derivation of Land Surface Temperature

At a coarse scale (1.1km) land surface temperature (T^{surf}) is directly obtained from the NOAA/AVHRR thermal channels (channels 4 and 5) using a split window method [5]:

$$T^{surf} = T^4 + a \times (T^4 - T^5) + b \tag{4}$$

Parameters a and b are adapted to the studied region using field measurements collected in Zimbabwe:

$$T^{surf} = T^4 - 5.23 \times (T^4 - T^5) + 30.73 \tag{5}$$

Equations (3) and (5) allow the computation of ET, and the generation of maps given NOAA acquisitions. Nevertheless, due to the coarse resolution of this sensor (1.1 km), it is not possible to characterize ET behavior according to land cover. In fact, each pixel contains more than one land cover type. So individual ET temporal profiles, for the different land cover types, have to be computed. This can be obtained by applying equation (3) for each date t and each land cover type j:

$$ET_j(t) = 0.33 \times T_j^{surf}(t) - 3.88 \tag{6}$$

where $T_j^{surf}(t)$ is the individual surface temperature for land cover j at date t. To access the individual temperature temporal profiles $T_j^{surf}(t)$, we define a learning process. It simultaneously uses the classification of the Landsat image (spatial resolution: 30 meters, see section 3) and the thermal NOAA-AVHRR data. This process considers a physical based mixture model of temperature detailed in [4] and its results are the temporal curves $T_j^{surf}(t)$ for each land cover type j and each date t.

4.2 Results and map generation

Temporal profiles of evapotranspiration are computed using equation (6). These daily individual values are then mapped on the land cover classification (at Landsat spatial resolution) to obtain daily maps at a resolution of 30 meters (see figure 2). These data can then be used as input for the ACRU hydrological model. Comparison of ACRU results using this actual evapotranspiration with those obtained using simulated ET is still under investigation.

5 Conclusion

The work presented in this paper is related to land cover classification and hydrological monitoring using satellite imagery. It is a part of the European IWRMS project dedicated to developing an innovative computer based Integrated Water Resources Management System in semi-arid catchments of Southern Africa. We have shown that remote sensing techniques can offer valuable input data to this project which aims to optimize the use of water resources.

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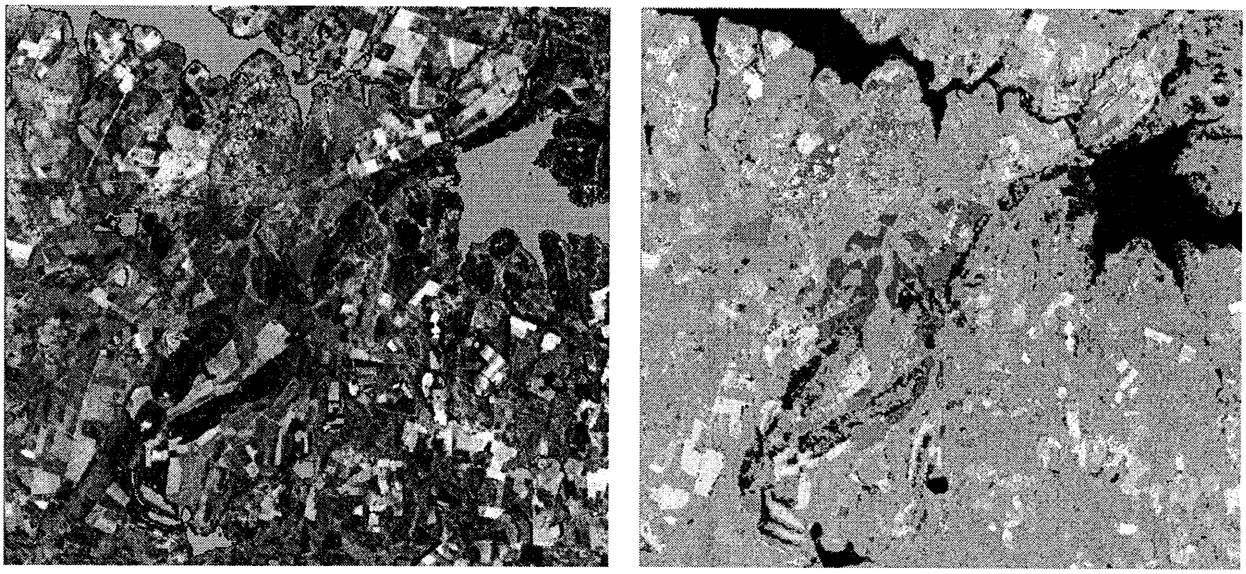

Figure 1: Landsat TM image of 26.04.98 (4,5,3 - right) from Mupfure catchment (Zimbabwe) and the respective level III land cover classification (right). The land cover classes are water, grassland , natural forest, young eucalypthus , old eucalypthus, irrigation farming, bare soil and residential.

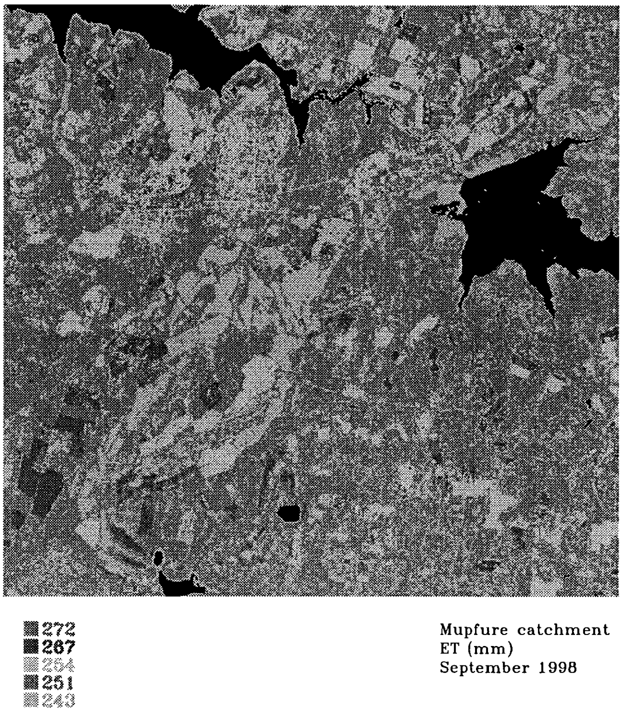

Figure 2: Monthly map of evapotranspiration obtained over the Mupfure river catchment.