Application of Remote Sensing and GIS for Integrated Water Resources Management in Southern Africa

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SUMMARY

Optical and microwave remote sensing data has been evaluated for land cover classification, classification of land degradation as well as settlement detection to provide areal and actual contributions to water resources management in Southern Africa. Apart from the development of a GIS-based Decision Support System to account for competing stakeholders' water demands and to address water allocation conflicts with respect to socio-economic aspects, the focus was also on simulating hydrological and erosion dynamics using deterministic, physically-based models with remote sensing input. The result, an integrated water resources management system, is a computer based toolset designed as an assembly of tested, validated and well documented procedures comprising the above outlined key technologies.

ZUSAMMENFASSUNG

Fernerkundungsdaten aus dem optischen und dem Mikrowellenbereich wurden hinsichtlich der Klassifizierung von Landnutzung und –degradation sowie der Siedlungserkennung ausgewertet, um damit einen flächenhaften und aktuellen Beitrag zu wasserwirtschaftlichen Problemen im südlichen Afrika zu leisten. Neben der Entwicklung eines GIS-basierten Decision Support Systems unter Berücksichtigung von Wasserangebot, -qualität, -bedarf und -zuteilung der unterschiedlichen Nutzergruppen stand dabei die Simulation von Wasser- und Stoffflüssen unter Verwendung von physikalisch basierten Modellen mit Fernerkundungsinput im Vordergrund. Das Resultat, ein integriertes System zur nachhaltigen Wasser-bewirtschaftung, ist ein innovatives computerbasiertes System, bestehend aus getesteten, validierten und dokumentierten Prozeduren, die die oben genannten Technologien umfassen.

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1. INTRODUCTION

1.1 *Integrated water resources management in semi-arid areas*

In 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 of the need to achieve a better balance between economic efficiency and environmental quality in the sense of sustainable development of natural resources (REITSMA 1996). Such an integrated water resources management can be supported by analysing water quantity and quality and their temporal and spatial distribution within a river catchment. This should be based on its physiographic and socio-economic conditions, and integrated with water demand and utilisation analysis. In this context, Decision Support Systems can assist in turning a multidisciplinary management using separate tools into an integrated, interdisciplinary framework system.

1.2 *The role of Remote Sensing, GIS and Process Modelling within an Integrated Water Resources Management System*

The development of integrated information and management systems (see Fig. 1) for water resources in Southern Africa requires the extensive application of remote sensing techniques. The reasons are mainly the missing availability of area-wide data and the inaccessibility of many areas in the region. There are many hydrologically relevant parameters that can be determined by using remote sensing data (HOCHSCHILD et al. 2000). Remote sensing can supply input and validation data for hydrological models and concentrate on water balance and water demand. One of the key points in the remote sensing applications is the use of different image sources for improving the results. By fusion of data of different spectral, temporal and spatial information as well as with ground measurements, it is possible to combine the various advantages of the different sources.

A GIS is coupled with the system and serves as a geodata management and

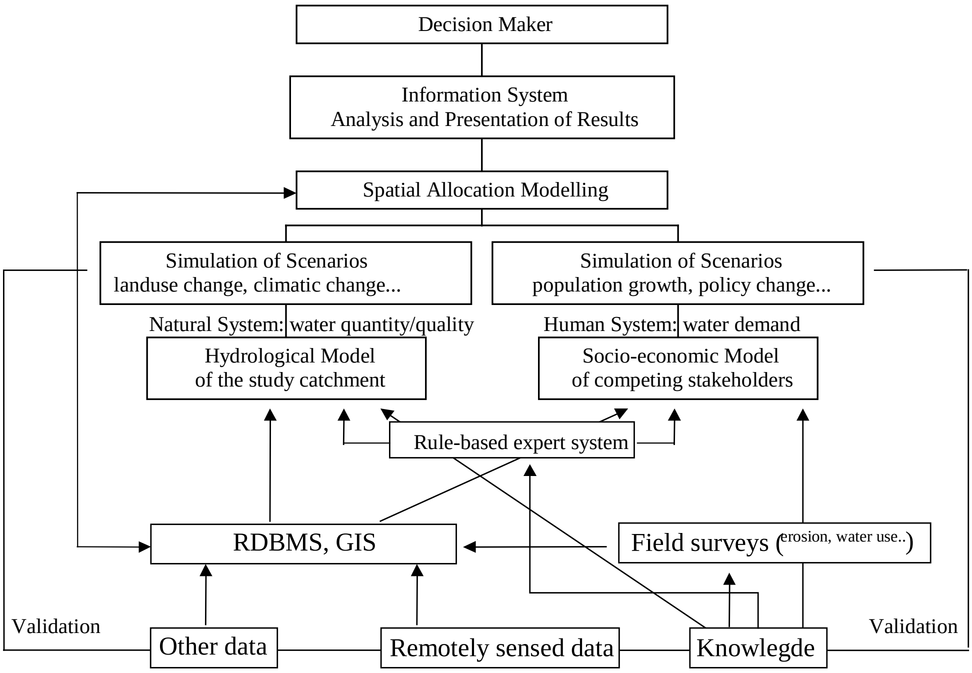


Fig. 1: Concepts and components of an Integrated Water Resources Management System.

preprocessing unit for the hydrological process model. GIS is also used as a post processing component, integrating the various model results and visualizing them.

The core of the system is made up of a physically-based distributed hydrological model, the ACRU system (SMITHERS & SCHULZE 1995), which is used in the IWRMS project (STAUDENRAUSCH et al. 1999), that accounts for the natural water cycle and is capable to simulate "What-if?" scenarios like climate or land use change. A model dealing with socio-economic processes resides on the other side. This component analyses impacts of economic or social changes in the management area. Fig. 1 gives an overview of the components and their inter-relationships involved in such an Integrated Water Resources Management system.

2. STUDY AREAS

2.1 *Physiographic properties*

The development, management and planning of water resources is greatly influenced by the physiographic properties of the region. The study catchments in Southern Africa (Fig. 2) are dominated by east coast climate conditions, enjoying hot and wet summers with rainfall during December and January. Winter half years are dry, cold at night and sunny and warm during the day. However, the study areas are characterised by a high annual variability of rainfall ranging from 300 – 1500 mm, leading periodically to severe droughts as well as floods.

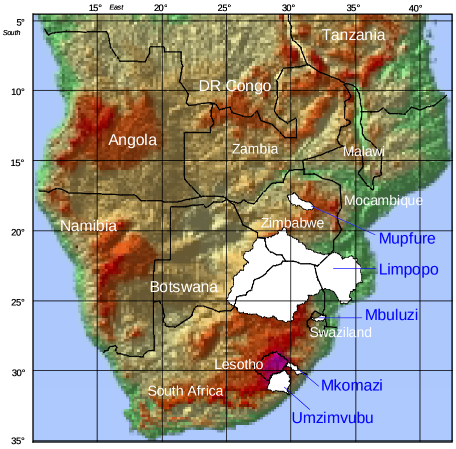


Fig. 2: Locations of the study areas in Southern Africa.

The Mkomazi catchment, situated in the semi-arid upland region of KwaZulu/Natal, South Africa comprises approx. 4400 km², stretching from the Great Escarpment of the Drakensberg (3000 m a.s.l.) to sea level at its mouth at the Indian Ocean. The mean annual precipitation (MAP) varies between 500 - 1200 mm. Water use conflicts are caused by large scale afforestation with demanding alien species like eucalypt as well as a population growth making the rural water supply difficult in terms of water availability, water allocation and water quality. A proposed reservoir in the upper catchment is an additional demanding challenge to investigate.

The Umzimvubu catchment is situated further south in North Eastern Cape Province, South Africa (former Transkei area). The basin's area is approx. 20 000 km^2 in size. Severe environmental problems induced by lacking land use management schemes over years are characteristic. Extensive stock farming and annual burning led to the degradation of the natural grassveld. Large-scale afforestation since the establishment of forest industries in 1989 leads to significant changes of the hydrological response of the catchment.

The Mbuluzi catchment in northern Swaziland (Area 3000 km², MAP = 800 - 1200 mm) is suffering to similar problems as the South African test areas, but has additionally extensive irrigated sugar cane plantations as major water users. Furthermore, Swaziland has to share the discharge with Mozambique. Its capital Maputo is situated at the mouth of the Mbuluzi river and is depending very much on its waters. The Mupfure catchment (Area 12 000 km², MAP = 750 mm) is much flatter with a lower elevation range. Here, water balance problems occur due to extensive water demand for irrigation purposes; water quality is affected by non point source pollution from agriculture.

The Limpopo basin (approx. 450 000 km²) is shared by South Africa, Botswana, Zimbabwe and Mozambique and hence subject to a number of political implications of water resources management. Different user sectors compete for water; furthermore, nature conservation plays an important role in the light of the transnational parks projected here. During disastrous floods only recently, the Limpopo also showed clearly, that semi-arid catchment management has to deal not only with drought, but also with flood mitigation strategies.

2.2 *Socio-economic conditions*

To appriciate the local management of access to natural resources such as water and land, it is necessary to assess the land tenure system in the study basins. They resemble the subcontinent's uneven distribution of resources and the population in general. Most of the major land use classes of Southern Africa are represented by the study catchments: communal lands (mainly subsistence farming, densely populated, underdeveloped), large scale commercial farming and forestry areas (major water users, sparsely populated, economically important) and small scale commercial farming and resettlement areas (positioned between the communal and commercial land uses, strong potential for development, but little access to resources). Besides agricultural and forestry, the other user sectors are of varying importance in terms of demand amount. Urban centres, mining activities and paper industries, however, can play a considerable role as water users.

3. REMOTE SENSING METHODS

3.1 *Digital Terrain Models*

Due to their importance for the hydrological system dynamics, the integration of Digital Elevation Models (DEM) is prerequisite for improved regional hydrological model applications (FLÜGEL 1996). There has been a noticeable trend to obtain such information from remote sensing data using digital photogrammetry over the last few years (BROCKELBANK & TAM 1991, CONNORS-SASOWSKI et al. 1992, AL-ROUSAN ET AL. 1997, HELMSCHROT 2000).

Because of the limited availability of high-resolution digital elevation data in South Africa, a DEM for the Mooi river subcatchment has been digitally extracted from two pairs of panchromatic SPOT data. The stereoscopic analysis of the images has been carried out with a photogrammetric image processing software, the final accuracy assessment has been done using a GIS.

After the preprocessing a triangulation process was performed, i.e. both the interior and exterior orientation have been calculated from the available ephemeris data and the reference points. Therefore the data were georeferenced using GPS-derived ground control points that are available for each stereo pair. As next step, the stereo pairs that have been resampled to an epipolar orientation were computed from the overlapping imagery. Based on these processed stereo pairs two DEM's of the Mooi river catchment could be calculated. Finally the gap between both DEM's (see Fig. 3) has been closed by digitising contour lines from topographical maps (scale 1:50 000).

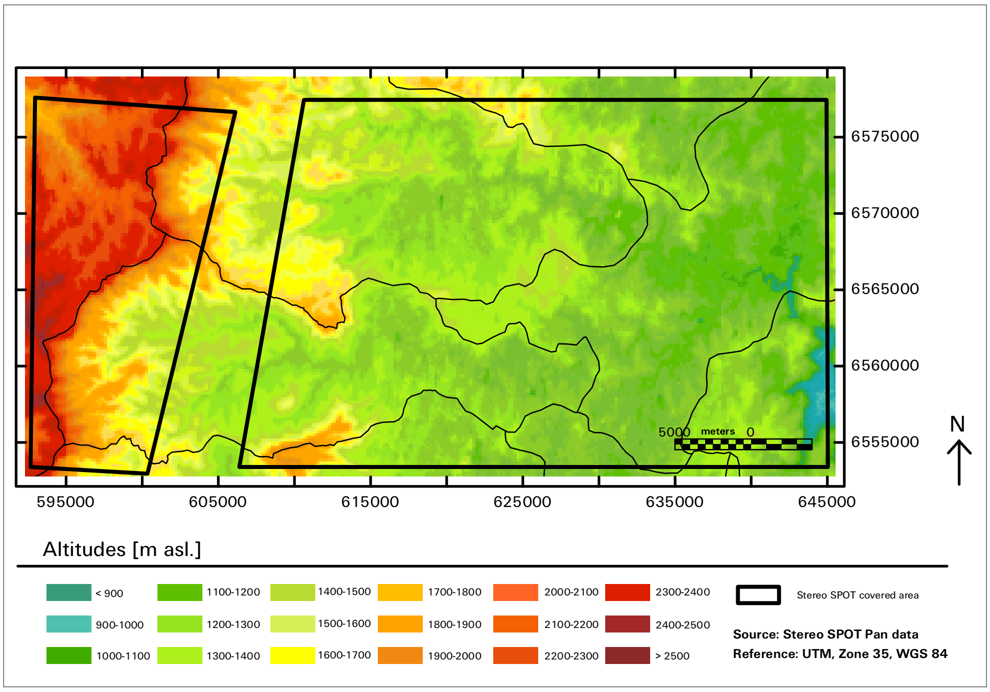


Fig. 3: Digital Elevation Model derived from Spot stereo data.

As a result of the photogrammetric processing, a high resolution DEM (10 m x 10 m cell size) was digitally generated from stereoscopic SPOT PAN data. The analysis and validation against reference points, taken from both topographical maps and from GPS measurements, have shown that the developed DEM achieves a mean horizontal accuracy of approx. 9 m and a mean height accuracy of approx. 13 m. Additionally for validation purposes, all relief contours from topographic maps were compared to the contours automatically computed from the SPOT based DEM. The comparison showed a relatively good accordance (r = 0.92) between the two datasets.

Due to the merging of the different elevation data sets, the overall height accuracy decreased to about 23 m, mainly caused by filtering the edge areas. Fig. 3 shows a subset of the developed DEM.

Finally the DEM could be used successfully to extract hydrologically relevant information such as altitude, slope, aspect, curvature, drainage network, etc., which are important to improve distributed hydrological model applications (FLÜGEL 1996).

3.2 *Land Cover Classifications*

The datasets used for the land cover classifications were recent Landsat TM scenes from 1996 to 1998 together with panchromatic SPOT data for improvement of the spatial resolution. This was extended with several ERS-2 .PRI images acquired during vegetation season to enhance the classification results by combining optical and microwave sensors. The microwave data also serves as additional input for multitemporal evaluations providing data from flood situations during rainy seasons.

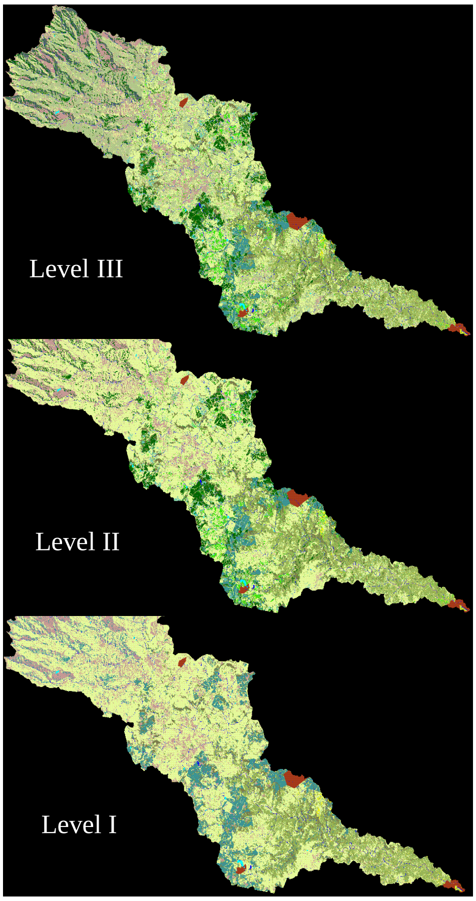


Fig. 4: 3-level IWRMS land cover classification.

Tab. 1: IWRMS legend according to the degree of detail. Level 3 is unique for each testsite

LEVEL I	LEVEL II	LEVEL III Zimbabwe	LEVEL III South Africa	LEVEL III Swaziland
Grassland	Unimproved Improved	Turpentin grass Not used slopes Feed corn Red gras Irrigated pasture	Not used slopes Feed gras Red gras	Not used slopes Rye gras
Barren lands	Bare rock/soil Degraded land Clear cuts	Fallow land	Bare soil Clear cuts	Granite outcrops Granite/Bush Fallow land Strong erosion
Thicket/Bushland	Thicket Bushland	Wattle/Bushland		Shrubs/Bushland
Forest/Woodland	Forest Woodland Wooded Grasland	Natural Miombo	Natural	Natural/Riverine
Forest Plantations	Pine species Eucalypth spec. Wattle species	Old Young	Pinus patula Old Young Wattle	Pinus patula Old Young
Water bodies	Water	Clear water Sediment loaden	Water	Water
Urban	Residental Commercial Industrial	Low density High density		Residental
Cultivated land	Permanent crops Temporary crops	Sugar cane Maize Recently ploughed	Sugar cane Maize Recently ploughed	Sugar cane Maize Recently ploughed Cotton

The classifications followed the Standard Land Cover Classification Scheme for Remote Sensing Applications in South Africa (THOMPSON 1996) 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 distiguish settlements according to their imperviousness instead of classes of income or to assess agricultural areas according to their site preparation and their above surface layers (litter, mulch, etc., SCHULZE & HOHLS 1993). The multispectral land cover classification was preceeded by extended preprocessing procedures including atmospheric correction, terrain correction, contrast streching and filtering in order to avoid misclassifications due to illumination and relief effects. Afterwards a supervised Maximum-Likelihood-Classifier was applied to the Landsat TM data using 6 bands in the visible, infrared and short wave infrared spectrum. The selection of the training areas was based on ground check campaigns carried out in February/March 1998 (South Africa, Swaziland) and March 1999 (Zimbabwe). For the Mkomazi catchment a second scene from 05.10.98 (first one from 22.04.96) was used to carry out a multitemporal (interseasonal and interannual) classification, which enhanced the result significantly.

To improve the land cover classification results furthermore sensor combinations with ERS data from the microwave range were applied as well as 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 is the IWRMS legend (Tab. 1), consisting of 3 levels of land cover classes (level 1: 8 classes, level 2: 20 classes, level 3 Zimbabwe: 17 classes, level 3 South Africa: 14 classes, level 3 Swaziland: 17 classes). So for each testsite 3 land cover classifications are available (level 1, level 2 and level 3), following the above mentioned Standard Land Cover Classification Scheme (Thompson, 1996), which could be applied for model input according to the requirements of the model. Fig. 4 gives an example of a level III classification from South Africa based on sophisticated GPS-ground truthing from the Mkomazi catchment south of Durban, where the upper part is dominated by grassland, in the middle part intensive farming and afforestations took place meanwhile bushland is the major land cover type in the lower part.

3.3 *Vegetation parameters*

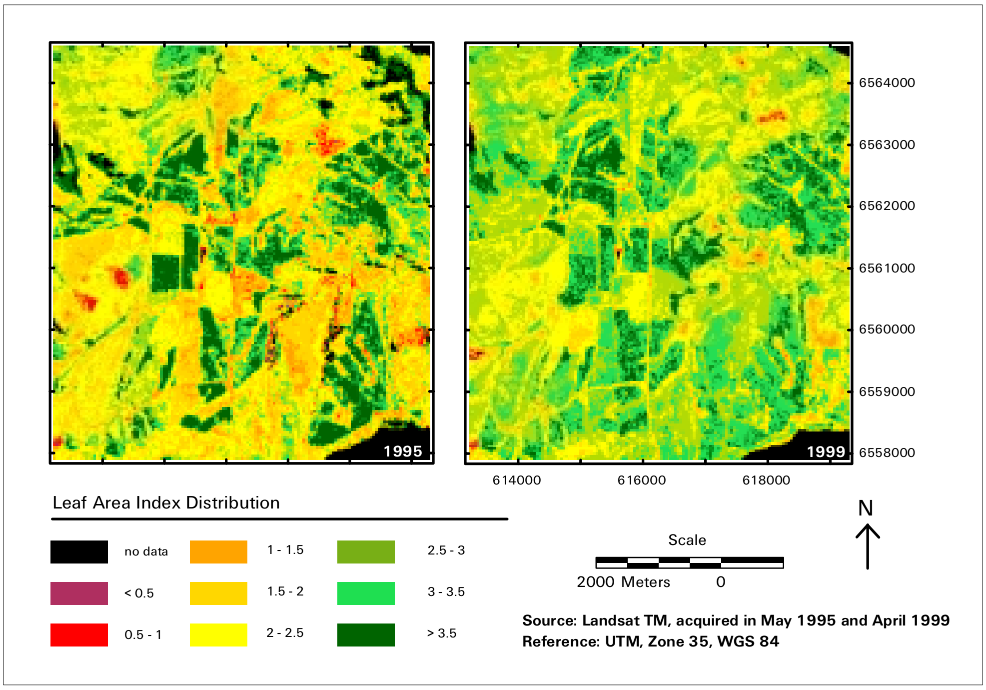
Vegetation is an important and dynamic component of the catchment water cycle, that affects hydrologic processes such as interception, evapotranspiration, and soil water content directly. In the Umzimvubu catchment, South Africa, where large scale afforestation with alien pine and eucalypt species took place since 1989, the influence of those changes on runoff is widely unknown. Hence, there is a need to evaluate suitable parameters for determining the exchange of energy and water between the vegetation canopy and the atmosphere as well as the earth surface. The vegetation parameter usually used in distributed hydrological models is the Leaf Area Index (LAI), which is defined as the ratio of total leaf area to its covered ground area.

In the presented study the LAI distribution and their changes over 4 years period have been evaluated for afforested areas in the Mooi river subcatchment using Landsat TM data from May 1995 and April 1999. The used approach is based on the transformation of the Normalized Difference Vegetation Index (NDVI) derived from preprocessed Landsat TM data to LAI. The following empiric equation presented by SELLERS (1987) has been utilised:

$$LAI = 4.147 * NDVI - 0.276$$

For validation purposes the computed LAI values have been compared to LAI measurements derived from field based data (HELMSCHROT 2000). The high correlation between both data sets (r = 0.86) confirms the general applicability of this method.

For multitemporal analyses, the transformation procedure has been applied for each of both TM scenes. Fig. 5 shows two subsets of the Mooi river subcatchment illustrating the distribution of the computed LAI's. There are significant differences in



Source: Landsat TM, acquired in May 1995 and April 1999
Reference: UTM, Zone 35, WGS 84

Fig. 5: **TM-based LAI distribution in the Mooi river catchment compared between May 1995 and April 1999.**

LAI related to afforestation practices between 1995 and 1999. For example an increasing of the LAI values is evident in areas which have been changed from grassland (yellowish, LAI = 1 – 2) to forest areas planted with pine trees (*Pinus patula*) in the last 4 years (greenish, LAI = > 2.5). On the other hand, a decreasing of LAI within forest stands can be detected accurately. These changes are mainly caused by several forest techniques such as thinning or pruning.

These results show that the applied method can be used to estimate the LAI for different vegetation covers. Moreover the study demonstrated, that there is a potential value of optical remote sensing data to investigate and to quantify the changes within forest canopies.

3.4 *Reservoir mapping and allocation modelling*

Surface water reservoirs are a major component in water resources management in southern Africa, determined by the need to store runoff for the dry season due to the semi-arid climate of the region. A monitoring of the reservoir status can be supported by means of Remote Sensing and GIS. By classifying water surface areas from actual satellite data and overlaying them with a detailed DEM which has been created from surveyed data older than the reservoir structures (thus representing the reservoir floors), one is capable to estimate the current storage volume of the reservoirs. Using this information, a sound water allocation modelling based on the river network can be established (STAUDENRAUSCH & FLÜGEL 2000), if it is combined with abstraction and storage permit data and the outcome of a distributed hydrological model, as described in chapter 4.

The GIS-based water allocation model structures a river catchment as a system of interactive and interlinked objects which are grouped in three different categories: (i) source components such as areas generating surface runoff and groundwater recharge, (ii) demand components such as irrigation fields, mining sites and settlements; and (iii) intermediate components such as storage objects or treatment plants. They are linked via the river system transferring the water between them. Within the GIS-network they are represented by nodes; vectored links represent the fluxes of water and solutes between them in the river channel network system. The application of GIS network analysis functionality allows to balance supply and demand, to optimise shortage sharing in drought situations and to assess new abstraction permit applications by testing them with the existing setup.

4. HYDROLOGICAL MODELLING

The information obtained by Remote Sensing methods, as described in the previous section, is used for two major purposes, both serving as input for the hydrological catchment model. On the one hand, the data generated by remote sensing is used to parameterise the process

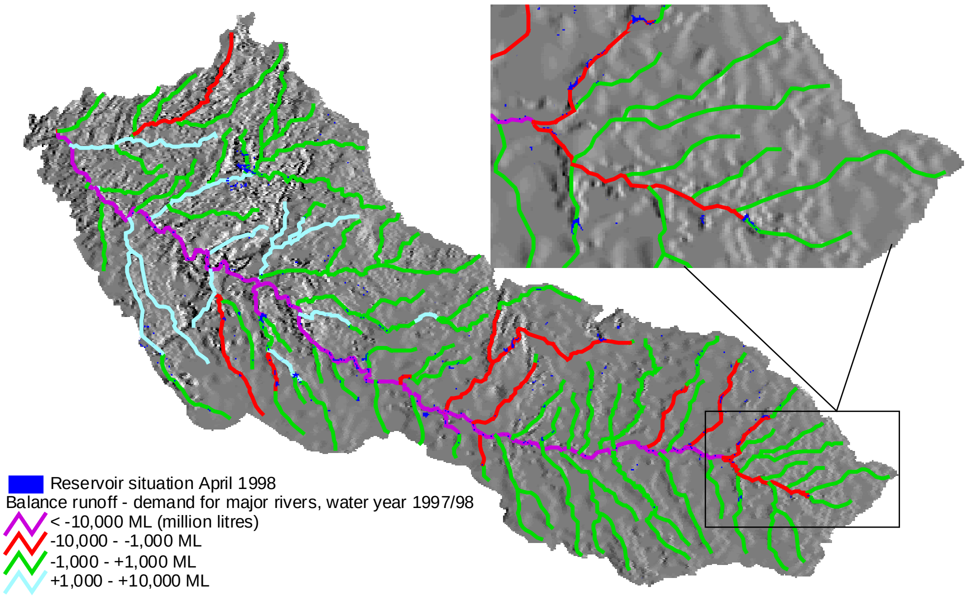


Fig. 6: Mapping of reservoir area and volume using a DEM in combination with optical and microwave data. This information is subsequently used for network based water allocation modelling.

algorithms. An example is the calculation of rainfall interception in the canopy layer; this algorithm needs information about the leaf area index as a measure for the canopy storage capacity. Besides model parameterisation, Remote Sensing data can be very valuable for validating a model's performance when comparing the real world scenario results to remotely sensed data (HOCHSCHILD et al. 2000).

On the other hand, static information like land use and elevation can be used to delineate spatial model entities generated by GIS overlay analysis (FLÜGEL 1996). On basis of each of those entities, the hydrological processes are modelled in a distributed manner.

To account for the heterogeneity of the physical and planning conditions of a catchment, first the physical properties (topography, soils, vegetation, climate) are considered. By reclassifying and overlaying the relevant layers, one obtains Hydrological or Erosion Response Units (HRUs, ERUs), accounting for the physiographic heterogeneity, and serving as base unit for modelling the natural hydrological cycle (FLÜGEL 1996, MÄRKER et al. 1999). However, if one wants to create spatial entities as basis for modelling water resources management aspects, anthropogenic features like land use diversity, reservoirs, gauging and sampling sites and planning locations have to be included into the response units delineation procedure. This leads to the extended concept of Water Resources Response Units (WRRUs).

Applied to a catchment, a unique model unit configuration results for each of the area. Fig. 7 illustrates the conceptualisation of the Mkomazi catchment into distributed, interconnected WRRUs using the outlined methodology. For each subunit, the major delineation criteria is given.

After a successful validation using again remotely sensed data, the model now can be used to perform prognostic "What if?" scenario analyses. The provision of a distributed model setup accounts for the need of changing specific land segments according to future scenario simulations. Such scenarios include impact analysis of land use and climatic change on water quantity and quality.

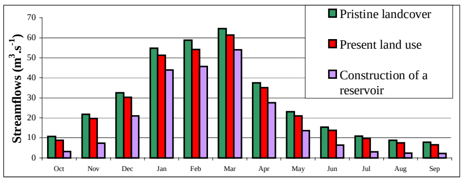


Fig. 8: Impact of land use scenarios on median streamflow of the Mkomazi River (TAYLOR et al. 1999).

For the Mkomazi catchment, it can be shown that a construction of a reservoir projected for the water supply of the Durban metropolitan area has a significant

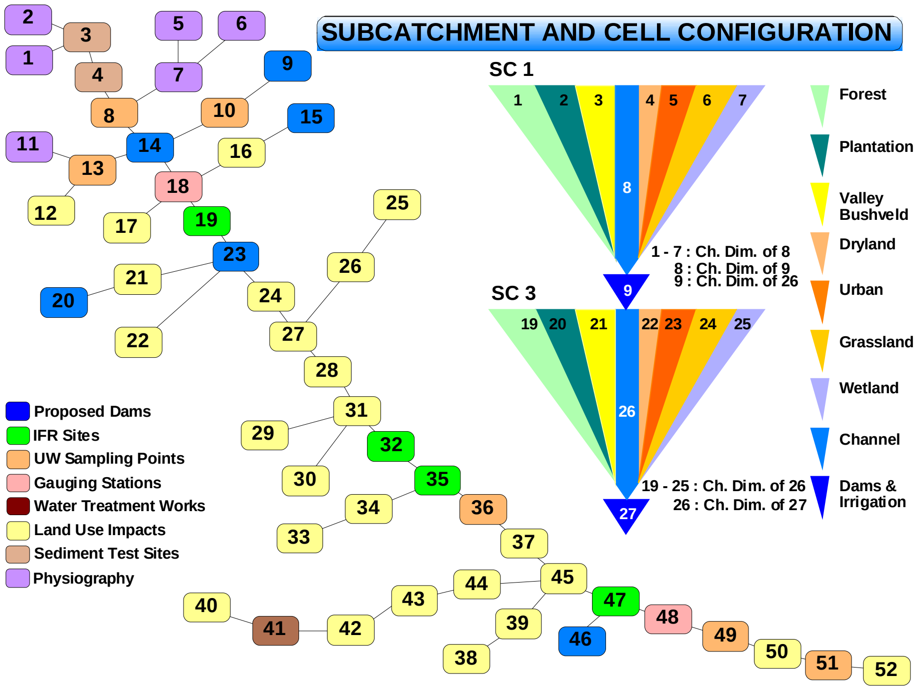


Fig. 7: WRRU conceptualisation for the Mkomazi catchment (TAYLOR et al. 1999).

impact on streamflow. Another result is the quantification of the impact of present land use on the natural streamflow, which is important in the light of the new water legislation of South Africa (TAYLOR et al. 1999).

5. COMPONENT INTEGRATION

As outlined before, water resources management is considered to be a highly complex and unclear problem including numerous implications in many parts of society and environment; therefore also often referred to as an “ill-structured” problem (REITSMA 1996). Resolving such problems however, can be achieved by disaggregating them into a series of structured components, including Remote Sensing, GIS, process models and a database and information system. Each of these can be tackled with its unique set of tools, that are integrated into a comprehensive framework system using object oriented concepts (DAVID 1999).

A suitable user interface is another important component to make such an Integrated System applicable to users in the water resources management community in Southern Africa.

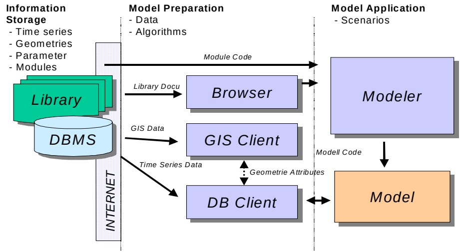


Fig. 9: Technical framework of the Integrated Water Resources Management System.

6. CONCLUSIONS AND OUTLOOK

The example presented in this paper demonstrate, that using Remote Sensing and GIS, in combination with a distributed hydrological model are appropriate tools in water resources planning. The system comprises these components and integrates them using object-oriented technology. A user-friendly graphical interface providing important GIS functionality and with data base access complements this setup.

A major step towards integrated water management is a detailed analysis of water demand (rural primary, urban, irrigation, industry, mining etc.) which is currently ongoing. The findings of these analyses will be integrated with the hydrological models as socio-economic rules and models.

Large DEM data sets covering major parts of the described test areas from the recently completed Shuttle Radar Topography Mission (SRTM) will be integrated into the system as well, thereby improving all relief related parameters on the catchment scale.

During practical tests and demonstrations at water management authorities in the study catchments in Southern Africa, a prototype system had proven to be a valuable toolset for online water resources planning. The system will be further improved based on the experiences obtained so far, which indicate, that the ease of use of this toolset also permits users with limited IT knowledge to design and simulate water allocation scenarios. This is of importance for the immediate application by competing stakeholders within a participatory water board.

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