Hydrological Services: The Need to Integrate Space-Based Information

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Enormous socio-economic and environmental pressures in both developed and developing countries are making proper integrated management and efficient exploitation of water resources, often in a trans-boundary approach, an absolute necessity. This requires better information and management systems. Space-based systems that integrate weather, remote-sensing and communication satellites could provide a major contribution. A recent ESA-sponsored study has shown that the use of satellite remote sensing leads to an economically attractive solution compared with conventional monitoring and ground-based survey methods.

Introduction

Two different hydrological business cases have been investigated in the framework of an ESA study. 'Service Case 1' addressed run-off forecasting for the hydro power generation chain on the Austrian Danube. 'Service Case 2' looked at a trans-boundary river-basin management system embracing agriculture, forestry, environment, flood and risk management within a shared watercourse, for the Limpopo River in Mozambique.

Case 1: Operational run-off forecasting for the Danube River Basin

Along its 2857 km length, the Danube drains water from much of central Europe, with the total catchment area amounting to 817 000 km^2. In Austria itself, an area of 80 700 km^2 (97% of the country) drains into the Danube, which is about 10% of the river's total catchment area. The topography is broadly divided into the alpine area in the west, and the pre-alpine region in the east. The Austrian part of the Danube is 350 km long, and the fall in altitude of 157 m together with the substantial flow rate (1980 m^3/s average discharge at the Slovakian border) provides important potential for energy production.

There are in fact ten major power stations on the Austrian stretch of the river, all of which are multi-purpose schemes, including power generation, flood protection, navigation, and environmental protection issues.

The main interest of the inhabitants of the river-bank zones is early warning of flooding and the reduction of damage to property and infrastructure. Knowledge of the potential impact of flood events is a prerequisite for the planning and installation of appropriate protection measures.

The main interest for river navigation is to ensure regular shipping conditions. Timely notification of shipping companies of expected changes in water level and flow forecasting – both of low water and of potential flooding – is essential for secure navigation and economically efficient river-based operations.

The main interest for energy-production forecasting is to optimise the operation of the hydro and thermal power plants. This can be ensured by gathering real-time data and making short-term forecasts, ranging from a few hours to one day ahead.

Mid-term forecasts (over a few days) are essential for the economic optimisation of electricity generation and supply from the service-provider's point of view. So far, these forecasts have been based on ground-based hydrological, and even more importantly ground-based meteorological parameters. Longer term forecasts (one week or more) would be essential to optimise decision making in the de-regulated European electricity marketing sector. The meteorological parameters, particulary precipitation and snowmelt, are therefore of critical importance.

Forecasting on a regional scale (about 100 000 km^2) calls for the modelling of run-off and flood routing, based on:
- rainfall forecasts
- soil-moisture models
- snow-melt models.

The efficiency of the proposed combined control of the hydropower plants along the Austrian Danube based on existing numerical approaches has been questioned because of the restrictions imposed by the weir operation rules (which are specific for each power plant and establish the background for a fine-tuned system for coordinated discharge control) and limited application possibilities (once or twice per year). The economic advantages achievable by the optimised operation of the hydropower chain with better run-off forecasting are therefore restricted. However, improved flood forecasting based on the integration of satellite-gathered data would still be highly advantageous for the timely implementation of flood-protection measures along the Austrian stretch of the Danube.

Integrated river-basin management for the Limpopo

The Limpopo is the second largest river in Mozambique, stretching for more than 1450 km and draining an area of approximately 412 000 km^2. Its catchment area extends over four southern African countries (Fig. 1): South Africa, Botswana, Zimbabwe and Mozambique. The river actually rises South Africa, near Pretoria, at an altitude of 1500 m, and eventually drains into the Indian Ocean at Xai-Xai.

The basin has an annual mean rainfall of 560 mm, varying from 400 to 1500 mm year on year. The mountains situated between the Limpopo and Elefantes rivers receive between 800 and 1500 mm of annual rainfall. The annual precipitation in the remaining catchment area varies from 400 to 800 mm.

Agriculture can be considered the main economic activity of the Limpopo catchment area, in Gaza Province, with a cultivated area of 345 000 ha, corresponding to 4.6% of the total area of 7.5 million ha. The main crops are:

Maize	59%
Rice	8.2%
Peanuts	4.3%
Manioc	12.3%
Beans	9.0%
Sweet potatoes	2.7%.

Compared to the water-supply needs for irrigation, those for the urban population can be neglected today, the two main urban centres being Xai-Xai and Chokwe.

The most serious problems in the Limpopo River Basin, which are typical also for similar river basins in both Africa and Asia, can be summarised as:
- irregular seasonal variations in water supply over the year

Figure 1. The Limpopo River Basin in Southern Africa

- disastrous droughts and floods
- increasing demands on water for irrigation purposes
- growing importance of crop yield
- progressive erosion caused by floods, deforestation and inappropriate agricultural practices
- uncontrollable inflow from upstream basins
- periodic floods causing public calamities
- insufficient waste water treatment
- threats to groundwater quality by pollution and salt intrusion.

Comprehensive analysis of the above problems in integrated water-resource management terms requires a very extensive set of capabilities. Many different hydrological and ecological models are needed to describe the water-quantity and water-quality processes (Fig. 2). The integration of the most appropriate sources of available information, using the latest Geographical Information Systems (GIS) and other special environmental and hydrological models, is critical to achieving a successful strategy .

To assist the Limpopo River Basin Management Unit (UGBL) with an improved information system to support its decision making, the following processes have to be addressed:

(i) Planning processes

- Flood protection/flood-plain management
- Watershed run-off forecasting
- Water distribution and reservoir management
- Land-use and forestry management
- Detection of erosion-prone areas
- Estimation of agricultural water demand and crop yield.

(ii) Operational processes

- Precipitation forecasting
- Flood forecasting and warning
- Detection of flood-prone areas
- Determination of soil moisture
- Determination of evapo-transpiration
- Monitoring of water quality and quantity
- Irrigation management and water accounting
- Data communication (telematics).

Most of the population of Gaza province lives close to the river banks, in cities like Massingir, Pafuri, Chókwé, Guij , Chibuto and Xai-Xai. They are therefore very vulnerable to flooding of the Limpopo. An adequate observation network and a comprehensive hydrological information system are therefore fundamental requirements for human safety and prosperity. The construction of such a system would allow:

- optimal operation and management of the hydro-meteorological network
- optimal operation and management of the water resources
- access to the different types of information needed for decision-making in flood situations and dry periods
- optimisation of the water-distribution procedures
- event-dependent, continuous communication system
- better management and evaluation of the flow received from neighbouring basins and improved flood alarms
- implementation of an appropriate 'Decision Support System'.

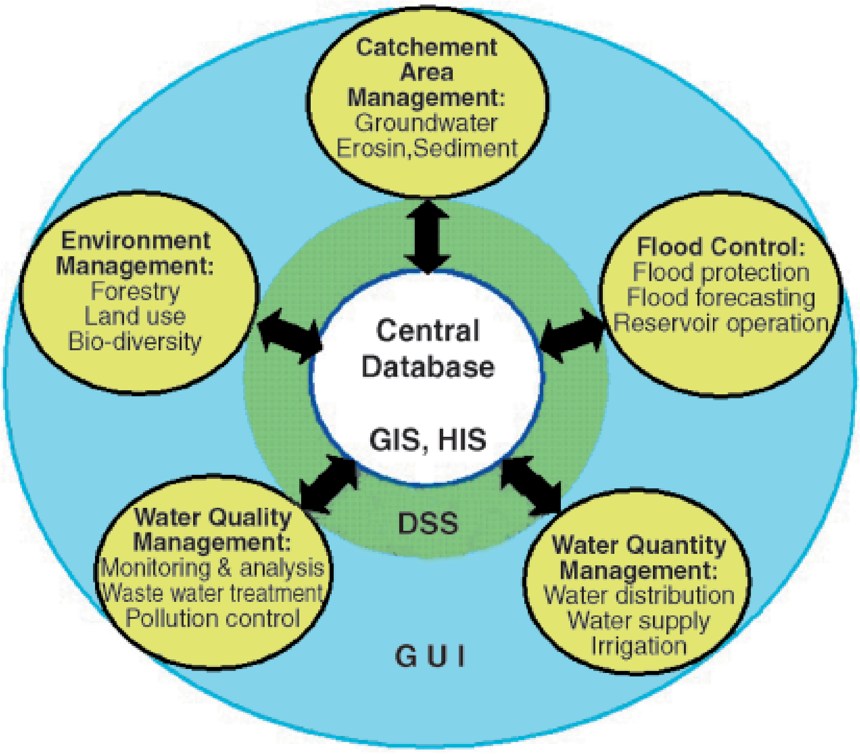

Figure 2. Schematic of the proposed data integration approach for the Limpopo River Basin, with a central database and user-friendly Graphical User interface (GUI). The Decision Support System (DSS) represents the backbone of the system for the various applications

The role of satellite-based technologies

Remote-sensing technologies

Space-based Earth-observation techniques can be applied to:

- optimise the management of the water resources through utilisation of combined rainfall run-off routing and reservoir operation models based on monitoring data and meteorological satellite images
- improve the information system, allowing immediate decision-making before flood situations occur and in case of drought through additional global meteorological information
- improve and optimise the assessment of flow transfer and flood warning from neighbouring countries through additional 'trans-boundary' meteorological information
- improve flood-risk assessment and delineation of flood hazard areas using satellite imagery
- improve agricultural development by the optimisation of land irrigation through registration of cultivated areas and observation of the changes in the vegetation cover

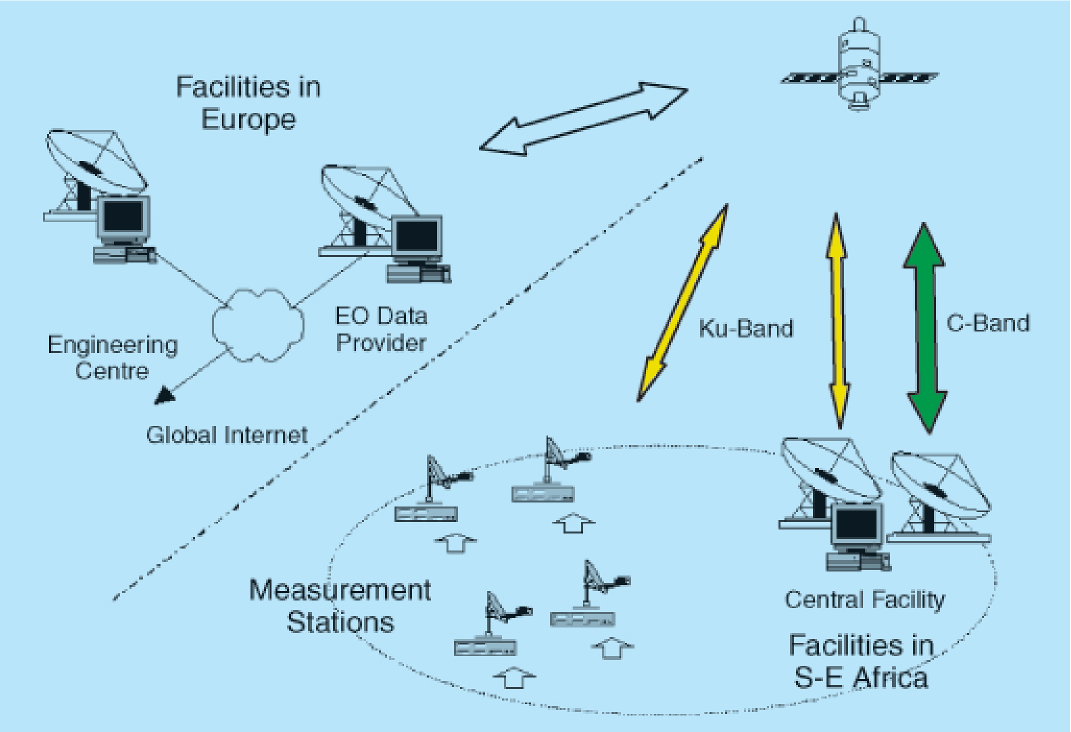

Figure 3. A satellite-based telemetry and data-transmission network for the Limpopo River Basin

- detect changes in the water bodies, e.g. chlorophyll and turbidity
- facilitate forestry management and erosion control using satellite imagery.

Satellite remote-sensing and ground-truth data have to be: (i) acquired, (ii) made available, i.e. transferred to the point of data utilisation, and (iii) merged and converted into information through ingestion into a state-of-the-art information system (Fig. 3) equipped with an appropriate graphical user interface (GUI). The ‘Hydrological Information System’ (HIS) must therefore be capable of receiving and processing data from several different sources in order to produce the desired output. The reception path could be via land lines, but satellite links might be the more convenient or the only solution in this region.

Space-based data transmission and computer-network connectivity

A satellite-based data and computer communication system for the Limpopo River Basin management system would include:

- two-way low-bit-rate data transmission between ground measurement devices
- high-bit-rate Earth-observation data transmission
- transcontinental computer-network connectivity.

The ground measurement stations should be equipped with satellite terminals which can communicate (in Ku-band) via a geostationary satellite with a hub at the central facility in Xai-Xai. For the reception of Earth-observation data, a satellite link is foreseen from Xai-Xai to the provider location in Europe or Africa. The

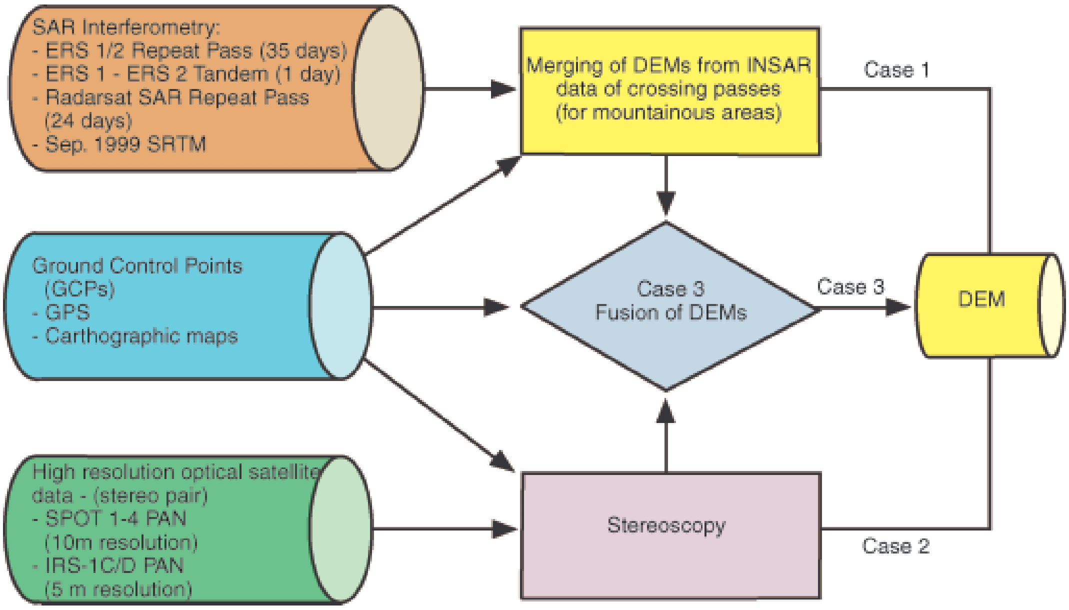

Figure 4. Flow chart for data integration and DEM generation

system implementation, maintenance and network management can be supported by an ‘engineering and training centre’, located in Europe, until full hand-over of system operations to the central facility in Xai-Xai has taken place. Global Internet access can also be established via the same lines.

The Integration of Earth-observation information

Our studies have identified six key targets for monitoring and measurement via satellite:

- precipitation run-off
- detection of flooded areas and flood plains
- agricultural water management
- surface-water quality
- erosion
- forest monitoring.

To achieve this, the following source elements need to be integrated:

Digital Elevation Model (DEM)

The mathematical-hydrological descriptions of the interrelations leading from precipitation to run-off within river basins, or selected river sub-basins, form the basis for river run-off prognosis, the operation of flood warning systems, flood-control planning and the operation of reservoirs for drinking water, hydropower generation and irrigation and drainage. The DEM raster size and accuracy needed for water-management activities in the Limpopo Basin still have to be specified exactly, but will be more in the metre rather than in the 10 m domain. For distributed run-off modelling and forecasting, a coarser resolution would probably be sufficient. For deriving physiographical information and for terrain-corrected geo-coding, it can be assumed that a 50 m spacing would be sufficient, but lower resolutions might be used for sites for which special activities (e.g. flood protection and other construction work) are planned. Figure 4 shows an example of a data-integration approach for DEM from different optional data sources.

Precipitation intensity and distribution

Knowledge of the spatial and temporal variability of rainfall is of primary importance for water management and run-off forecasting. Conventional rain gauges only provide point measurements. The combination of ground-based measurements and complementary Earth-observation data will significantly improve the input for run-off calculations, especially for convective events in small sub-basins. For the Limpopo River Basin, a combined system with geostationary satellite (Meteosat) data is proposed, as these data are already available operationally.

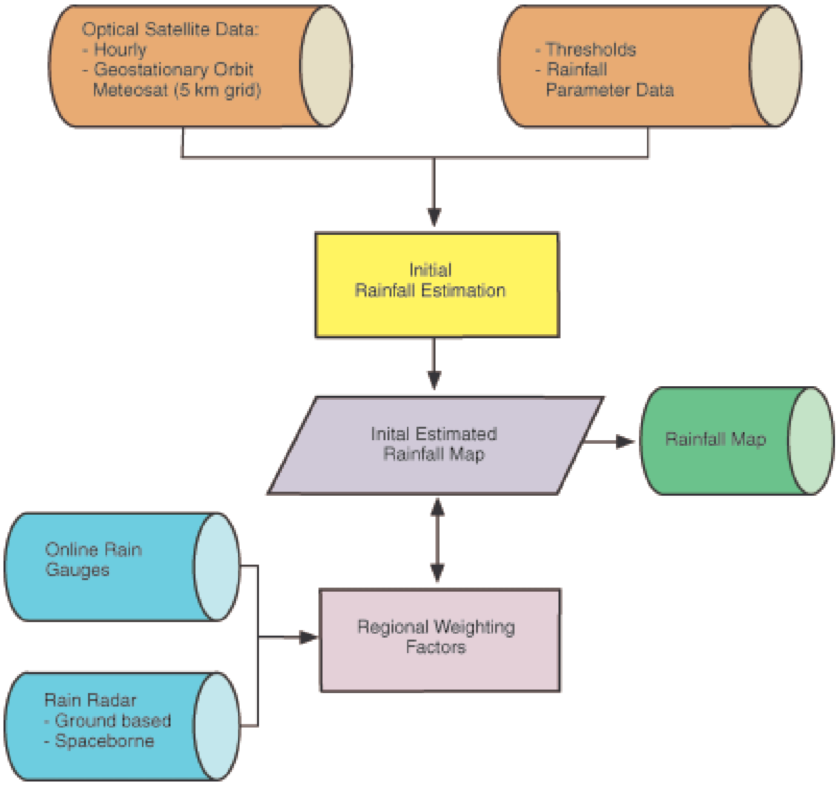

Figure 5. Data integration concept for rainfall monitoring in the Limpopo Basin (rain radar optional)

The data-integration concept is shown in Figure 5. Future extension of the system to include ground-based or satellite radar data is optional. The initial data source would be Meteosat, with its 30 min imaging sequence, and its visible (VIS: 2.5 km resolution at nadir), infrared (IR) and water-vapour (WV) absorption band (5 km resolution at nadir) channels. The Meteosat Second Generation (MSG), with a 15 min imaging sequence, will eventually provide improved resolution and additional spectral bands.

Land-use classification

Using hierarchical and statistical classification schemes, combining GIS and satellite data, will provide the best results. With NOAA-AVHRR input, the classification can be based on the Normalised Difference Vegetation Index (NDVI), augmented if necessary by thermal-infrared data. This already enables the separation of several classes of vegetation, but future satellite sensors, such as those of the MERIS instrument on Envisat, will have better spectral capabilities and will provide more sophisticated products on a pre-operational basis.

Evapotranspiration

Evapotransporation (EVPT) is by far the dominant loss factor as far as the water balance in the Limpopo Basin is concerned. In addition, EVPT data are required for irrigation planning and estimation of reservoir losses. In conventional run-off models, EVPT is estimated from meteorological measurements, which is insufficient particularly for semi-arid regions.

River Basin Management	Satellite Applications and Methods	Status	Improvements
1. Planning:			
Flood Protection (high-precision Digital Elevation Model: DEM)	High-resolution optical satellite data Stereoscopy	Poor vertical accuracy	Laser altimeter; very high resolution panchromatic stereo data
Flood Plain Management (flood monitoring)	Optical images (VIS channels) Active MW (change detection)	Disturbances by clouds Active MW: poor time resolution	Wide-swath SAR with higher repeat cycle and beam-steering capabilities
Watershed Definition for Run-off Forecasting (DEM)	Stereo imagery matching with high-resolution optical data (VIS, NIR) SAR interferometry (ERS, SRTM)	Operational	SRTM data (depending on data delivery policy)
Irrigation and Drainage (registration; land-use classification)	Multispectral data (VIS,NIR,SWIR) Active MW (SAR)	Operational	High spatial and spectral resolution
2. Main Services:			
Precipitation Forecasting (indirect determination) (direct observation)	Cloud indexing (VIS, IR) Thresholding (VIS, TIR) Cloud life history (VIS, TIR) Passive MW (18-85 GHz) Rain radar: active MW (13 – 25 GHz)	Partly operational Link to operational run-off models still missing	Satellite rain radar with increased swath width used in synergy with other sensors due to restricted repeat cycle of radar
Snow Cover Snow Water Equivalent	VIS,NIR,SWIR; Active MW Passive MW for dry-snow mapping Active MW for wet-snow mapping	Operational for optical sensors and for SAR wet-snow mapping	Multichannel imaging MW Radiometer with improved spatial resolution
Determination of Soil Moisture (soil moisture content in the top layer)	Active and passive MW Wind scatterometer for very large scales	Experimental	Dual L- / X- band SAR and 3 to 5 day coverage.
Estimation of Evapotranspiration	Temperature maps (meteorological satellites) (indirect method, statistical approach)	Poor spatial and spectral resolution	SVAT-models and high-resolution VIS/IR sensors
Quality of Surface Water (empirical and analytical methods)	High spectral resolution (VIS,NIR) Thermal maps (TIR) Active MW (oil slicks)	Poor spectral resolution and need for thermal IR	Several narrow spectral bands (MERIS standard bands VIS)
3. Communication:			
Data Transfer from On-site Monitoring Stations	C-, Ku- or L-band on-demand access mode (64 kbit/s)	Operational	Operational costs have to be reduced

Table 1. Satellite applications within River Basin Management, and the proposed technical solutions for improvements

Satellite Earth-observation data enable spatially distributed estimation of EVPT.

Successful operational applications of satellite EVPT monitoring have been reported not only for semi-arid areas, but also for the mid-latitudes. In both cases the hourly VIS- and IR-Meteosat data are being used in synergy with ground-based measurements.

Flood-plain maps

Maps of flooded areas are required in near-real-time for the taking of emergency measures and for the short-term prediction of changes in the flood level and of flood propagation. Satellite-based Synthetic-Aperture Radar (SAR) is then the best source of data due to its cloud penetration and hence all-weather operation, with geodetic, and if possible accurate digital-elevation data as complementary information:

– *SAR data sources:* ERS SAR precision-image (PRI) and Radarsat SAR SGF data, with day and night acquisition independent of cloud cover. A change-detection method can then be applied (e.g. ratioing) using data for times with and without flooding.

- *Optical images:* e.g. SPOT HRV, Landsat TM/ETM+; the flooded parts cannot be mapped for cloud-covered areas. A method for the classification of open-water areas can be applied. This data is, however, only of secondary interest because of the weather dependence.

Agricultural water management
Registration and development of agricultural regions requires detailed geographical information on land use, cropping and irrigation infrastructure. With multi-spectral high-resolution sensors and with a two-step strategy for surface type-classification, high-resolution land-cover maps can be derived for agricultural areas for irrigation and crop-yield surveying. SPOT HRV, Landsat-5 TM and Landsat-7 ETM+ can be exploited.

Water quality
Detection of water parameters can be carried out on a weekly basis with imaging spectrometers for the reservoirs of Massingir, Macarretane and other natural lakes close to Chókwe, which are large surface-water bodies. Data sources can include the MODIS instrument on NASA's Terra platform and the MERIS instrument on ESA's Envisat (due to be launched in 2001).

Forest monitoring
Forested areas have positive effects in terms of floods and erosion, and therefore need to be treated differently from other surface types in distributed hydrological models. The two parameters of most relevance for hydrology are the forest area and its temporal changes, and the forest type. Both require high-resolution data, but due to the reduced need for repeat surveys, aerial photographs may be suitable for surveying small areas. For large drainage basins, however, satellite imagery is the only economic source of data.

A business plan

Establishing a realistic business plan involves investigation of the relevant market and potential clients, as well as the development of a market strategy and financial planning. For the Limpopo Water Service case, we have to distinguish between national water sector planning, which falls to the national government and/or its autonomous corporations, and the policies of the international financing institutes. The main objectives are to provide capacity building to the water sector and to promote regional co-operation by translating global water concerns into regional initiatives. The financing for a trans-boundary water resource project of this nature, in a developing country, can be sought from such international financing institutes as the European Union and the World Bank. River-basin management has on the one hand the nature of a public good, which can be used by anybody regardless of financial means, and on the other that of a technical-assistance project where the objective of the investment is primarily to create conditions for sector reform rather than to generate a high return on investment.

Careful analysis of the needs in this particular case have shown that the estimated costs of completing the project (initial investment, operations and maintenance) using conventional means are approximately 18% higher than when using satellite-based data, based on the defined investment, operation and maintenance cost conditions.

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Conclusion

The capacity to monitor the global state of hydrological elements faces several technical, economic and institutional limitations, which have tended to result in restrictive data policies worldwide as well as severe delays in data availability to research institutions. Remote areas also suffer from a scarcity of hydrological observations and great difficulties in acquiring data in near-real-time, especially in the developing countries.

Remote-sensing techniques, particularly from space, have the potential to provide permanent surveillance of hydrological parameters on both a continental and a global scale. Satellite-based sensors can therefore be expected to play a major and growing role in hydrology and water-resource management in the coming years.

For the Limpopo River Basin Management System, our studies have shown the clear advantages of space-based Earth-observation technology for hydrological services in terms of:

- improved product quality by integrating spatially distributed information from satellite in place of ground-based point measurements
- less dependence on trans-border hydrological information systems, and
- better access to remote regions.

The Least Cost Analysis (LCA) method has also conclusively demonstrated the greater cost-effectiveness of using satellite-based technology, which can also open up new market possibilities for the region, with the prospect of additional commercial benefits.