Use of remote sensing data in distributed hydrological models: applications in the Senegal River basin

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Abstract

Research activities aiming at integrating Earth Observation data in large scale distributed hydrological modelling will be presented. The focus will be on the Senegal River basin in West Africa where satellite data from various sensors and from different parts of the electromagnetic spectrum will be used in combination with a distributed model specifically adapted to utilize Earth Observation data. The work represents the initial results obtained by the ongoing INTEO project. The outcome and experiences gained so far are primarily related to low resolution optical data from the NOAA-AVHRR sensor, and results related to land cover classification, vegetation and soil moisture will be presented.

Keywords

Earth observation, remote sensing, hydrology, distributed hydrological modelling, West Africa, Senegal River basin, land cover, soil moisture, NOAA-AVHRR, SPOT, MIKE-SHE

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By the end of 1996 the Danish Research Council had launched a four-year research programme in Earth Observation (EO) with the long-term purpose of complementing and developing ongoing earth observation activities in Denmark. INTEO (INTegration of Earth Observation data in agrohydrological models) was one of the four projects that obtained funding through this initiative. This multi disciplinary project has the ultimate objective to integrate EO data and hydrological models with the perspective of improving water resource management. Research within INTEO focuses on the use of satellite remote sensing data combined with large scale hydrological modelling, in particular the Senegal River basin in West Africa, (Figure 1).

This paper presents the research done within INTEO, with focus on the general approach pursued for combining

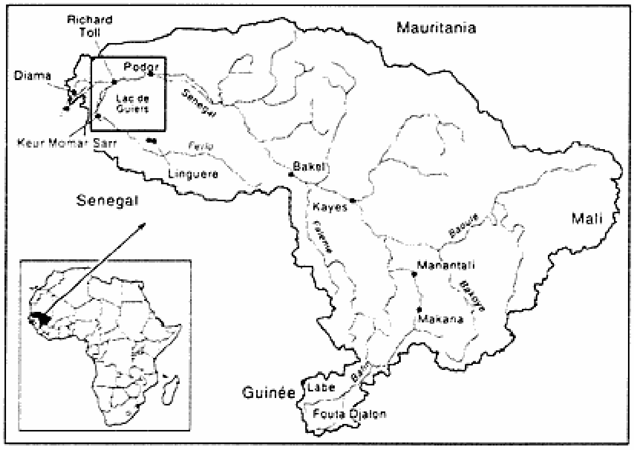

Figure 1: The Senegal River Basin, with the subset for more detailed modelling.

Earth Observation data and hydrological models. The first results and experiences that have been obtained so far will be presented. The paper will be concluded with pointers to future work within INTEO. A description of the context in which the hydrological model is applied, can be found in Rasmussen et al. (1999), which contains an elaboration of water management issues in the Senegal River basin, with special emphasis on agricultural practices in the river valley.

Background and state of the art

Earth Observation (EO) data is a potentially very useful source of information on the state and development of a long range of vegetation and hydrological parameters. EO data is particularly useful when conducting studies on a large scale, and when conventional data is scarce. An appealing characteristic with EO-data in combination with hydrological modelling, is the ability of EO-data to observe areas rather than point data. In some cases, EO-data enables entirely new measurements of hydrological variables. In addition to this, EO-data can provide time-series of data relatively easily, enabling periodical updating of variables. With the rapid development of new sensors (like the ones on board ENVISAT and Meteosat Second Generation), with improved spectral, temporal and spatial resolutions, the potential for deriving information on variables of hydrological interest is improved. The following paper is by no means meant to be an exhaustive review of hydrological applications of EO data, however, broad lines will be addressed, with special emphasis on hydrological modelling.

During the past two decades several reviews of the suitability of EO data, particularly for hydrological modelling purposes, have appeared (Engman and Gurney, 1991) (Schultz, 1993) (Engman, 1995), and many scientists have discussed the perspectives of integrating EO data and hydrological models ((Peck et al., 1981) (Kuttinen, 1985)). So far model applications have, with few exceptions, been confined to the mapping of land use/surface cover and snow cover.

The idea of combining hydrological models with EO-data is thus not new. Areal photography has been used for decades, and some of the earliest work on the application of satellite remote sensing data in combination with hydrological models dates back to the mid seventies, for instance, Jackson et al. (1977). The first attempts to use EO-data to provide information on the land cover, and the potential in map-like information were recognized early (Schultz, 1993). However, as late as 1995, remote sensing in combination with hydrology was still spoken of as promising (Engman, 1995), in spite of the progress in development of new methods that derive hydrological variables from EO-data, and the development and availability of new sensors.

Traditional hydrological models are not designed, nor well suited, for making use of EO data. In a comprehensive description of 25 of the most common hydrological models (Singh, 1995), only two models were reported to have had operational experience with direct use of remote sensing data, namely the SRM model (Rango, 1995), which used data from many different satellites for assessing snow cover, and the SLURP model (Kite, 1995) which used Landsat and NOAA data for assessing land cover and DMSP for snow water equivalent.

Hydrological models are often classified according to their spatial representation of data input and processes as either lumped or distributed (Wood and O'Connel, 1985); (Nemec, 1994). Most of the classical hydrological models are not well suited for EO data because they belong to the lumped group of models that consider input data and state variables as average values over an entire catchment or sub-catchment which typically has an area of hundreds of km^2. However, some examples of modified lumped models successfully using EO data, can be found (Kite and Kouwen, 1992),(Hardy et al, 1989). Distributed hydrological models (DHM), with a regular squared model grid, are most well suited for using EO data. DHMs which have detailed physically-based descriptions of surface processes and state variables, appear to have the largest potential for making full use of EO data. However, most classical hydrological models, even the distributed physically-based ones, require some modification to fully utilize EO data, as the input data and state variables, which can be assessed from the EO data, are not all explicitly included in the models.

In addition to the further development of classical hydrological models, two recent trends have emerged, with regard to integration of hydrological models and EO data. First, a number of new models specifically designed for making use of spatially distributed EO data are being developed in GIS environments. An example is presented by Said (1996), who uses land cover maps derived from EO-data. Some of these models belong to the group of so-called ecosystem models or ecological models and use EO-data in various ways, e.g. to define basin geometry and channel routing, in addition to vegetation variables (Band et al., 1993). Second, with the availability of radar imagery, a new trend in the application of EO data and hydrological models has emerged. Radar data has been used for the assessment of soil moisture (Mauser et al., 1997) (Giacomelli et al., 1995) and for the monitoring of flooded areas (Bates et al., 1997).

A study of the integration of low resolution satellite data and an ecosystem model in the Sahel, has recently been published (Lo Seen et al., 1995), (Mougin et al., 1995). The model can be driven by vegetation indices, but the authors report a large sensitivity to atmospheric effects. Earlier work in the Senegal river basin, involved satellite derived rainfall estimates, based on the cold cloud duration index in a flow prediction context (Hardy et al., 1989). The study reports that the applied hydrological model performed as well as rain gauge data using satellite derived rainfall data, but also that the derivation of rainfall from satellite data is not straightforward. Climate research involved in coupled land surface/atmosphere modelling are developing grid-based hydrological models (denoted land surface parameterization schemes), a few of which are able to accommodate EO data. These models are to some extent based on the extensive work done on extracting hydrological relevant parameters from EO data, which is not covered by this review. At the present time there is increasing awareness, that should the potential in EO data be fully exploited, a combination of sensors is necessary, for instance in the study reported by Yin and Williams (1997) or by Troufleau et al., (1997).

The INTEO project

It is the intention of the INTEO project to develop and validate methodologies for estimating key input parameters and state variables in a hydrological model, for a large river basin using EO data. In particular, the project focus on the identification of model variables that can successfully be provided by EO-data, including development of methods and the identification of what kind of EO-data is relevant for input and/or model validation. The main strength of the work undertaken in the project is that, with the combined use of a distributed hydrological model and EO-data, model calibration and validation are not necessarily restricted to river flow data, but the spatial information from the EO data source can also be used.

The distributed hydrological model requires daily or longer intervals input, for a number of variables. INTEO carries out research aiming at using EO data for providing information on land cover, leaf area index (daily) or vegetation greenness (daily), soil moisture (daily) and rainfall (daily). Different sources of EO data are applied for different applications as can be seen in Table 1, where a list of the available EO data is shown. The combined use of data from different parts of the electromagnetic spectrum and of different spatial resolutions are considered to

Sensor	*Spatial Coverage*	*Spatial Resolution*	*Temporal Coverage*	*Applications*	*No of images*
AVHRR	*Basin*	*1 km x 1 km*	*1986-1998*	*Soil moisture* *LAI* *Land Cover*	*> 500*
SPOT	*Subset*	*20 m x 20 m*		*Land Cover* *Vegetation*	*3*
Landsat	*Subset*	*30 m x 30 m*		*Land Cover* *Soil moisture* *Vegetation*	*3*
Radarsat	*Subset*	*app. 26 m*	*1998*	*Soil moisture* *Land Cover* *Vegetation*	*3*
ERS	*Subset*	*app. 27 m*	*1991-1998*	*Soil moisture* *Land Cover* *Vegetation*	*40*
METEOSAT	*Basin*	*4 km x 4 km*	*?*	*Precipitation*	*?*
SMM/I	*Basin*	*?*	*?*	*Precipitation*	*?*

Table 1: *EO data available to the INTEO project, and the applications of the data.*

be central in the optimal exploitation of EO data. The research efforts are undertaken at two scales, a basin wide large scale, where NOAA-AVHRR data in combination with SMM/I and METEOSAT are the main data sources, and at a smaller scale where a 140x140 km^2 subset of the basin comprising irrigated areas in the northern part of the basin has been modelled (Figure 1). On the smaller scale, high resolution optical data (SPOT and Landsat) will be used in combination with SAR data (Radarsat and ERS2), and the results from the large scale modelling will also be included. The work has so far concentrated on the use of AVHRR data on the large scale model, and the work on the subset has only just been initiated.

The hydrological model

The hydrology of the Senegal River basin has been modelled with the MIKE SHE code (Refsgaard and Storm, 1995). MIKE SHE is a further development of the European Hydrological System – Systeme Hydrologique Europeen, SHE (Abbott et al, 1986). It is a deterministic, fully-distributed and physically-based modelling system for describing the major flow processes of the entire land phase of the hydrological cycle. It is applicable for a wide range of water resource problems related to surface and ground water management, contamination and soil erosion.

The applied version of MIKE SHE in this study is based on the standard version of MIKE SHE, with a replacement of the standard complex groundwater module by a simple groundwater module (Christierson, 1997). This approach, which for the groundwater component aims only at simulation of the interflow and baseflow, is similar to the one successfully tested by Knudsen et al. (1986). The new MIKE SHE version, as illustrated in Figure 2, is oriented towards surface water studies, such as the coupling of a hydrological model to remote sensing data for the Senegal River basin, so that detailed description of groundwater conditions may not be required.

The model solves the equations of interception, evapo-

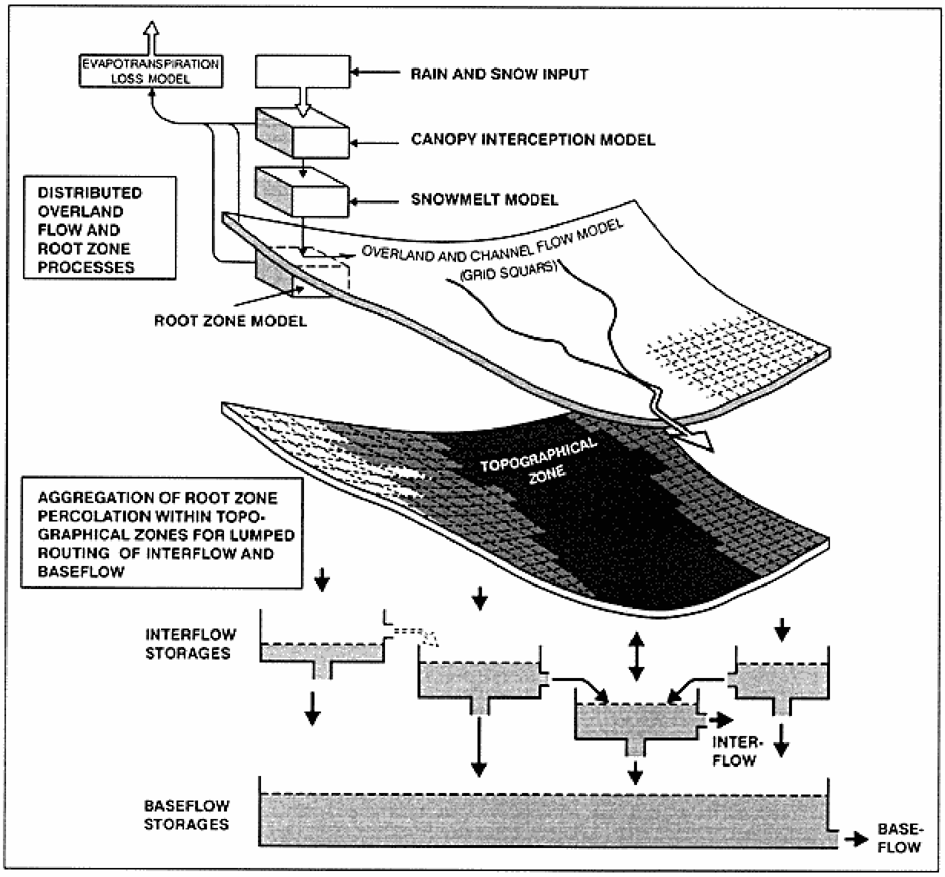

Figure 2: Schematic presentation of the modified version of MIKE SHE.

transpiration, overland flow, channel flow, unsaturated flow and routing of saturated subsurface flow and in this way describes the major flow processes of the entire land phase of the hydrological cycle. The model is fully distributed and physically based except for the new groundwater module which is only semidistributed and conceptual.

In the horizontal plane the catchment is divided into a network of grid squares. The river system is assumed to run along the boundaries of these. Within each square the soil profile is represented by a number of computational nodes in the vertical direction

In the simple groundwater module the catchment is divided into a number of subcatchments. Within each of these the groundwater zone is represented by a series of interdependent interflow and baseflow storages. These storages behave as linear reservoirs, implying that the outflow through each outlet is linearly proportional to the water content in the storage, with the proportionality factor being a time constant by which each reservoir outlet is fully characterised.

The percolating water from the root zone may either contribute to baseflow recharge or move laterally as interflow towards the stream. Hence the interflow storages have two outlets, one "horizontal" outlet that contributes to the baseflow storage in the next downhill topographical zone, and the other "vertical" outlet which contributes to the interflow storages. The structure of this module will enforce a redistribution of water in favour of the topographical zone adjacent to the stream, where the water content is generally higher than in the rest of the catchment. In low lying wetlands and floodplain areas, the water table may in periods be located above or very close to the terrain surface and hence contribute more to the generation of overland flow and evaporation. In order to simulate this mechanism, water held in the lowest topographical zone may, as indicated in Figure 2, be allowed to contribute to the root zone when the soil moisture is below field capacity.

Previous experience has shown that the linear reservoir approach for the groundwater zone, as applied here, is sufficient for an accurate description of the discharge hydrographs (Refsgaard and Knudsen, 1996). The advantage of this approach is that is requires much less geological data, is less demanding with respect to computational requirements and is easier to calibrate.

The Senegal River basin

A map of the Senegal River basin is shown in Figure 1. The river receives most of its water from the "the water tower" of West Africa, the Fouta Djalon mountains in Guinea, where annual precipitation exceeds 2000 mm. Precipitation has a very large north-south gradient, from a mean annual precipitation that exceeds 2000 mm in Fouta Djalon, to the northern parts of the basin that receive less than 200 mm/year. Thus the major part of the basin belongs to the semiarid part of West Africa. The temporal distribution of rainfall in the source area is unimodal with a maximum between June and September, and thus the river flow has a very large variation over the year. The total drainage area is approximately 350,000 km^2 and the main tributaries are Bafing, Bakoye, and Faleme (Fig. 1).

The MIKE SHE modelling of the Senegal River basin

The first hydrological model created in the INTEO project is a conventional model based on standard, non EO generated data, of all the distributed information. Table 2 lists the used input data, including a source reference.

As can be seen from table 2, the distributed data sets are taken either from the internet, from FAO's digital soil map or created on behalf of other data in a GIS. Since the basin covers four countries it is very difficult to obtain consistent data that can be merged into one map covering the whole basin. This accounts for the use of the large number of data types as mentioned in table 2. Since the model resolution used is very coarse with a spatial discretization of 4 x 4 km^2, the input data is also only needed at a low resolution. This has favoured the use of global data sets which are easily available and much more spatially consistent when compared to nationally collected data sets.

The vegetation types are based on a NOAA land cover classification for Africa, where the originally 196 classes have been reduced to 6 classes. FAO's soil map (FAO, 1996) has the main hydrologic information in three texture classes and therefore, represents the spatial distribution of soil information. Soil depth has shown to be a very sensitive parameter when modelling. The information provided by the used FAO data set (FAO, 1996) is very coarse and only of little use. It has, therefore, been necessary to calibrate this parameter.

The most import time series for this model is the rainfall

Data Type	Data Source
Distributed Maps	
Vegetation	*NOAA based Land Cover Clas. (edcwww.cr.usgs.gov/landdaac/glcc/)*
Topography	*USGS 1 km² DEM (edcwww.cr.usgs.gov/landdaac/gtopo30/hydro)*
Rivernet	*Digital Chart of the World (www.maproom.psu.edu/dcw)*
Soil types	*Digital FAO Soil Map of the World in 1:5,000,000 (FAO, 1996)*
Soil depths	*Digital FAO Soil Map of the World in 1:5,000,000 (FAO, 1996)*
Precipitation zones	*Stations (points) distributed by Theissens Polygon Method*
Potential evapotranspiration zones	*Stations (points) distributed by Theissens Polygon Method*
Catchment boundary	*Extracted from DEM using GIS algorithms (ESRI, 1996)*
Subcatchment boundaries	*Extracted from DEM using GIS algorithms (ESRI, 1996)*
Topographical zones	*Created as buffer zones around rivernet using GIS tools*
Time Series	
Precipitation	*National Meteorological Institutions, 112 stations*
Potential Evapotranspiration	*National Meteorological Institutions, ~15 stations*
Discharge	*Transnational organisation for the River basin (OMVS), 11 stat.*
Leaf Area Index	*Standard values chosen for all six vegetation types used*
Root depths	*Standard values chosen for all six vegetation types used*

Table 2: *The distributed maps and time series needed for the applied MIKE SHE model with reference to the source.*

and discharge data which are respectively the main driving input parameter and the main output controlling parameter. Daily rainfall data from 112 stations and discharge data from 11 gauging stations covering a ten-year period has been available for calibration and validation purposes. The first calibration has been carried out for a five-year period using only the downstream Bakel discharge station (Figure 3).

The results achieved from the first calibration seem to be acceptable allthough one should keep in mind that a good fit on this catchment scale does not ensure a good fit internally, e.g. on the grid scale. A step towards such an internal validation, will be carried out by th comparison of simulated discharge against other upstream discharge stations for the same period. Finally, a split sample validation test will be carried out by compairing data from the other five year period that had not been used for calibration.

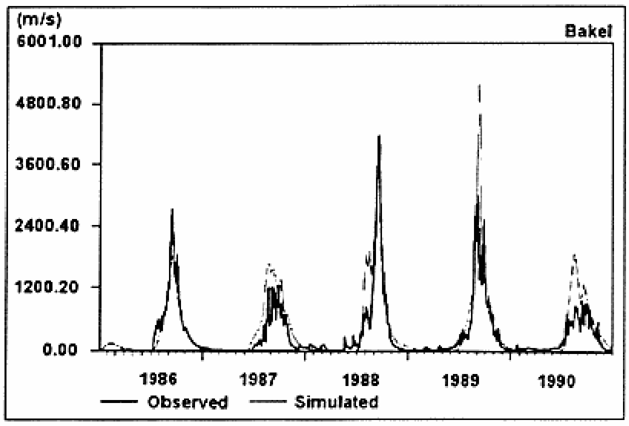

Figure 3: *The first calibration results from the Bakel station. The location of the station is shown in Figure 1.*

The use of EO data as an input to the hydrological model

Low resolution land cover classification.

Temporal NOAA AVHRR data can be used for large scale classification of natural vegetation types, which form input to the hydrological model. The vegetation dynamics are reflected in the vegetation index curves (NDVI) which can be derived from the visible and near infrared channels of the AVHRR sensor, for each pixel in the image. The NDVI curves can be described using four parameters: A) the average level of NDVI, B) the difference between maximum and minimum NDVI, C) the duration of the period of elevated NDVI, and D) the time of the onset of the growing season. These four parameters may be extracted from a sine curve, fitted to the data volume, as shown in Figure 4. The chosen parameterization results in a desirable reduction in data. Image representations of the parameters A, B, C and D are shown in Figure 5. The parameter A (average NDVI level) shows the expected strong north - south gradient, with highest values towards the south. The amplitude, B, is very low for the northern regions of Mauritania, and has a maximum value in the central part of the basin. The area of maximum amplitude

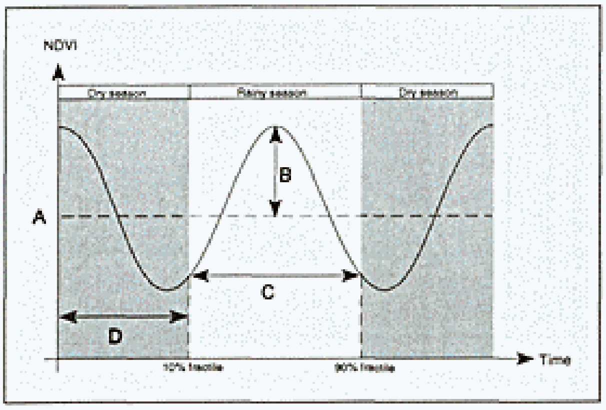

Figure 4: Graphical representation of the four parameters on the sine curve. The curve is fitted to NDVI timeseries from AVHRR data.

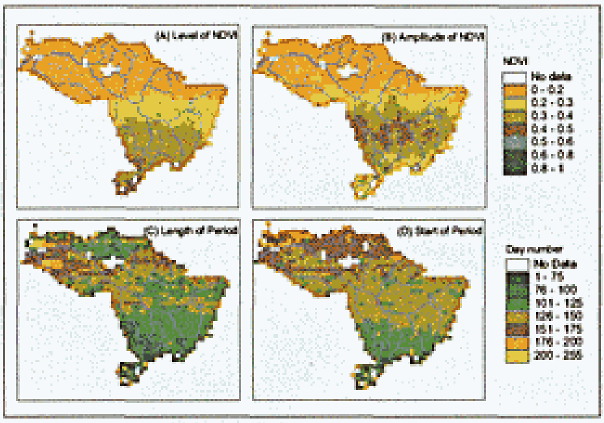

Figure 5: Image representations of the four classification parameters. The parameters define the fitted sine curve.

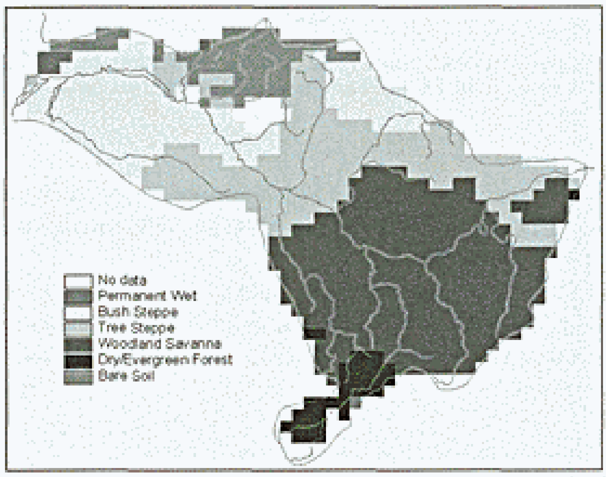

Figure 6: Unsupervised classification of seven classes based on the four parameters in figure 5.

corresponds to savanna woodlands, where extreme variations in the greenness of vegetation between the dry and wet periods, are evident. The length of the green period, parameter C, shows a less pronounced north - south gradient. The apparent lengthy green period in the far north (bright colour) is an artifact, due to the fact that variations in atmospheric water vapour masks the temporal evolution in NDVI, which has a very low amplitude in the northern parts of the basin. The time for onset of vegetation growth, D, has no spatial trend, indicating a more random nature of rainfall in the beginning of the rainy season.

Results from an unsupervised classification based on 78 NOAA AVHRR images from 1990 are shown in Figure 6. This classified image is the land cover map used as input for the hydrological model.

Leaf Area Index

In order to generate a time series of Leaf Area Index (LAI), a conversion of NDVI is used. The overall idea is to transform the NDVI values for each pixel, using a linear transformation of the fraction of photosynthetically active radiation absorbed by a canopy (fAPAR) as described by Troufleau et al. (1997) and then perform a conversion of fAPAR to LAI using the relation established by Myneni and Williams (1994):

$$LAI = LAI_{(\max)} * \frac{\ln(1 - fAPAR)}{\ln(1 - fAPAR_{(\max)})}$$

where:

LAI is estimated leaf area index

$LAI_{(max)}$ is maximum leaf area index

fAPAR is the fraction of photosynthetically active radiation as estimated from NDVI

$fAPAR_{(max)}$ is the fAPAR corresponding to maximum leaf area index

This allows for the standard LAI tables, used in the hydrological model, to be replaced by real timeseries.

Soil moisture

Information on the soil moisture status is not used directly as input in the hydrological model, rather the information is used as a means to update the model or for validation of the model. River discharge is typically the only variable that can be used for model validation or calibration. When spatially distributed information about the soil moisture status can be derived from remotely sensed data, a much more powerful tool is then available for model validation and calibration. Although the remote sensing data does not provide ground truth, this comparison may be considered as a kind of validation test of the model's ability to simulate spatial patterns of soil moisture. Such a test is a soft one, because the remote sensing data contains a considerable amount of uncertainty, however, on such a large scale remote sensing data appear to be the only possibility for conducting internal validation tests for the distributed model.

NOAA-AVHRR data are well suited to derive spatial and temporal information about the soil water status covering a large river basin, using a combination of the visible, near infrared and thermal channels to derive surface temperature (Ts) and the Normalized Difference Vegetation Index (NDVI). The basic approach is to interpret the location of image pixels in the so-called Ts/NDVI-space, in terms of their soil moisture status, as indicated in Figure 7.

From observations of Ts and NDVI, the Temperature Vegetation Dryness Index (TVDI) (Sandholt et al., 1999) can be calculated for each image:

$$TVDI = \frac{Ts - Ts_{\min}}{a + bNDVI - Ts_{\min}}$$

where:
Ts is observed surface temperature
NDVI is observed vegetation index
$Ts_{\min}$ is minimum observed temperature in the image a and b are constants in the equation defining the upper edge of the triangle.

TVDI is related to the soil moisture status, so that high values indicate dry conditions and low values indicate moist conditions. This is based on the fact that surface temperature is mainly controlled by the energy balance and thermal inertia, factors that integrate moisture conditions at the surface. A dry surface will have higher temperature than a moist surface everything else being equal. This method is a simplification of the approach described by Moran et al. (1994). The main advantage is that the method is valid for vegetated, as well as bare surfaces and only relies on remotely sensed information, and is conceptually and computationally simple. Consequently the operational use of the index is straightforward.

In Figure 8, the TVDI for 17th November, 1990 is shown. The wilting of the vegetation has started, as the last rain event occurred on the 12th November in the southern part of the basin. The relation to MIKE SHE-simulations is shown in Figure 9.

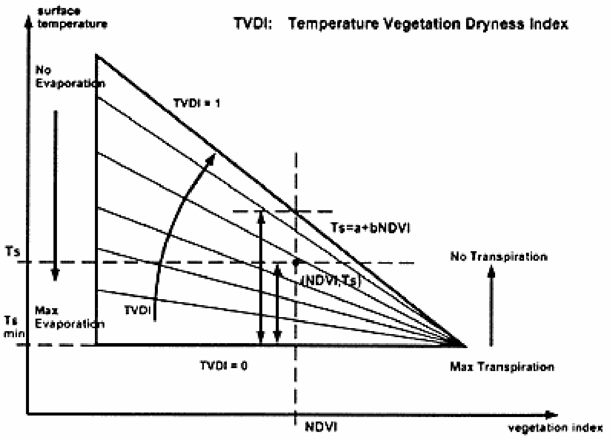

Figure 7: Definition of the Temperature Vegetation Dryness Index (TVDI). TVDI for a given pixel (NDVI,Ts) is estimated as the relation between the distance of the pixel from the wet edge (TVDI=0) and the span of Ts in the Ts/NDVI-space for the given NDVI (the difference between Ts and the dry edge (TVDI=1) and Ts at the wet edge).

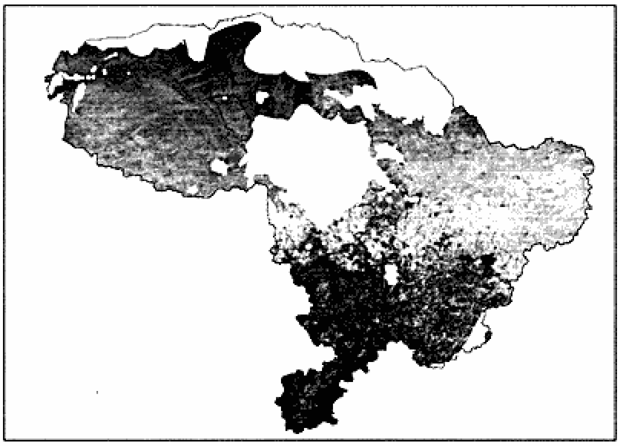

Figure 8: AVHRR based TVDI in the Senegal River basin, 17th November, 1990. The black areas have been masked out due to cloud cover.

There seems to be an agreement in the overall trend in data. The potential of using the index lies in the ability to obtain a better description of the spatial variation in soil moisture.

High resolution mapping of irrigated areas

In the selected subset of the Senegal River valley (Figure 1), irrigated agriculture is the main activity, with the main

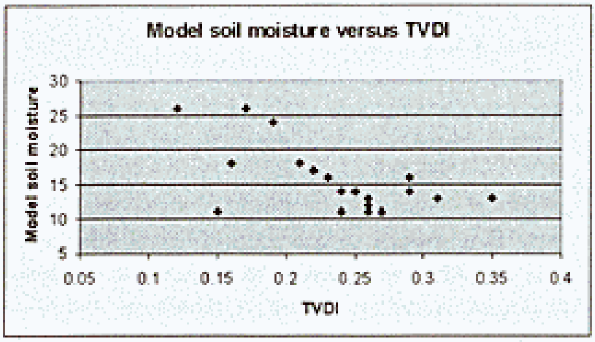

Figure 9: Comparison of TVDI and the results from the hydrological model. Locations of the sampled values have been indicated in Figure 8.

being crops rice and sugar cane. Sugar cane cultivation is practised in the agro-industrial fields of "Compagnie Sucrière Sénégalaise" (CSS), and it differs to a great extent from the agricultural practices in rice production, the latter having been described in Rasmussen et al., (1999). Distributed hydrological modelling is especially important in areas where spatial information, related to vegetation and moisture status of the surface, is crucial to proper water management. This is the case in irrigated areas. In addition, the subset is well investigated due to the intensive irrigation activities in the area, and extensive data sets exist on soil types, land use, water allocation as well as time series of meteorological data. Data from CSS will be used as ground truth and the calibration of the remotely sensed data, in particular SAR data.

The first results concerning the use of SPOT data will here be illustrated using a SPOT XI image, acquired 8th October, 1998. The image consists in four bands (green, red, near IR and mid IR). The image has been classified using a supervised maximum likelihood classification algorithm, with an overall classification accuracy of 97.5% (Fig. 10). This accuracy is relatively high, compared to other classification results based on a single image acquisition. A closer look at the separability between land cover classes, shows that the mid IR band is especially well suited to separate vegetation classes in the delta.

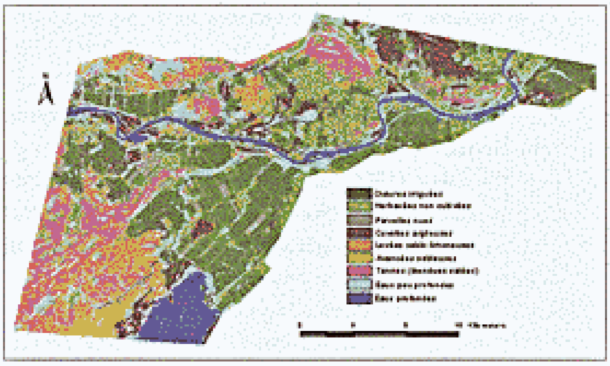

Figure 10: Senegal River delta: cartography of irrigated zones classified from SPOT SI of 8th October, 1998. Overall classification accuracy is 97.5%

Future INTEO research priorities

The future activities with INTEO, will be directed towards the integration of the results obtained from NOAA-AVHRR data and the hydrological model. At this time, the model code has been modified in order to accommodate EO data, and the calibration and validation of the large scale application, based on conventional data, is in its final phase. The work related to the refinement of TVDI will continue, and the approach for the estimation of LAI and the broad scale land cover classification, will be automatized.

Analysis of the possibilities of estimating precipitation using a combination of two data sources, namely METEOSAT and the passive microwave data (SMM/I) will be investigated. A recent study has demonstrated, that it is possible to obtain estimates of rainfall using passive microwave data (Kidd, 1998). It is anticipated that the shortcomings in the method (eg. only two image acquisitions per day is possible) can be overcome by using METEOSAT data to determine the positions of clouds between SMM/I-coverages.

At the same time the smaller scale study in the northern part of the basin will continue and the sub-model will use the large scale model to define the boundary conditions. An important component in the smaller scale model, is the application of SAR data, and specifically the synergy effects of optical and SAR data. Results from various applications of SAR data are beginning to emerge (for instance Cognard et al., (1995), Griffiths and Wooding, (1996), Jackson et al. (1997), Paloscia (1998)). Synergy effects have been addressed by for instance Moran et al. (1997). It is the intention, that the two types of SAR data that the project has at its disposal, (cf. Table 1) will be used to assess information about spatial variation in soil moisture, in combination with high resolution as well as low resolution optical data. However the activities will also encompass land cover classification and the assessment of vegetation status.

The hydrological model run based on conventional data will serve as a reference run. For comparison, another run will be used with EO data on LAI and precipitation. Furthermore the EO data on TVDI and radar soil moisture will be used for model validation and the possibilities of using this for updating of soil moisture in the model will then be analysed.

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References

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connel, P.E. & Rasmussen, J. (1986): An introduction to the European Hydrological System - Systeme Hydrologique Européen "SHE", 2: Structure of a physically-based distributed modelling system. Journal of Hydrology, 87: 61-77.

Band, L. E., Patterson, P., Nemani, R., & Running, S. W. (1993): Forest ecosystem processes at the watershed scale: incorporation hilslope hydrology. Agricultural and Forest Meteorology, 63:93-126.

Bates, P.D., Horritt, M.S., Smith, C.N., & Mason, D. (1997): Integrating remote sensing observations of flood hydrology and hydraulic modelling. Hydrological Processes, 11(14): 1777- 1796.

Christierson, B.V. (1997): WATBAL-MIKE SHE Integration. Linear Reservoir Module. DHI Report 4710. Danish Hydraulic Institute

Cognard, A.-L., Loumagne, C., Normand, M., Olivier, P., Ottle, C., Vidal-Madjar, D., Louahala, S., & Vidal, A. (1995): Evaluation of the ERS-1/synthetic aperture radar capacity to estimate surface soil moisture: Two-year results over the Naizin watershed. Water Resources Research, 31(4):975-982.

Engman, E. (1995): Recent advances in remote sensing in hydrology, u.s. national report to iugg, 1991-1994. Rev. Geophys., American Geophysical Union, 33 Suppl.

Engman, E. & Gurney, R. (1991): Remote Sensing in Hydrology. Chapman & Hall, London.

ESRI (1996): Arc View spatial analyst. Advanced spatial analysis using raster and vector data. ESRI, Redlands, CA 92373, USA

FAO (1996): Digital Soil map of the world and derived soil properties. FAO, 00100 Rome, Italy.

Giacomelli, A., Bacchiega, U., Troch, P. A., & Mancini, M. (1995): Evaluation of surface soil moisture distribution by means of SAR remote sensing techniques and conceptual hydrological modelling. Journal of Hydrology, 166 (3-4): 445-460.

Griffiths, G. H. & Wooding, M. G. (1996): Temporal monitoring of soil moisture using ERS-1 SAR data. Hydrological Processes, 10:1127-1138.

Hardy, S., Dugdale, G., Milford, J. R., & Sutcliffe, J. V. (1989): The use of satellite derived rainfall estimates as inputs to flow prediction in the River Senegal. Pp 23-29 in: New Directions for Surface Water Modeling, Proceedings of the Baltimore Symp., IAHS Publications, 181

Jackson, T. J., McNairn, H., Weltz, M. A., Brisco, B., & Brown, R. (1997): First order surface roughness correction of active microwave observations for estimating soil moisture. IEEE Transactions on Geoscience and Remote Sensing, 35(4): 1065-1069.

Jackson, T. J., Ragan, R. M., & Fitch, W. N. (1977): Test of Landsat based urban hydrologic modeling. ASCE Journal of Water Resources Planning and Management Div. V 103: 1065-1069.

Kidd, C. (1998). On rainfall retrieval using polarization-corrected temperatures. International Journal of Remote Sensing, 19(5): 981-996.

Kite, G. (1995): The SLURP model. In Singh, V., editor, Computer Models, pages 521-562. Water Resources Publications.

Kite, G. & Kouwen, N. (1992): Watershed modeling using land classifications. Water Resources Research, 28(12):3193-3200.

Knudsen, J., Thomsen, A. & Refsgaard, J.C. (1986): WATBAL: A semi-distributed, Physically based hydrological modelling system, Nordic Hydrology, 17, 347-362

Kuttinen, R., editor (1985): Report on application of remote sensing to hydrology in the Nordic countries., in Nordic Hydrological Program, 9. NHP, Helsinki, Finland. The Coordinating Committee for Hydrology in Norden KOHYNO.

Lo Seen, D., Mougin, E., Rambal, S., Gaston, A., & Hiernaux, P. (1995): A regional sahelian grassland model to be coupled with multispectra satellite data. II: Toward the control of its simulations by remotely sensed indices. Remote Sensing of Environment, 52:194-206.

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References

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connel, P.E. & Rasmussen, J. (1986): An introduction to the European Hydrological System - Systeme Hydrologique Européen "SHE", 2: Structure of a physically-based distributed modelling system. Journal of Hydrology, 87: 61-77.

Band, L. E., Patterson, P., Nemani, R., & Running, S. W. (1993): Forest ecosystem processes at the watershed scale: incorporation hilslope hydrology. Agricultural and Forest Meteorology, 63:93-126.

Bates, P.D., Horritt, M.S., Smith, C.N., & Mason, D. (1997): Integrating remote sensing observations of flood hydrology and hydraulic modelling. Hydrological Processes, 11(14): 1777- 1796.

Christierson, B.V. (1997): WATBAL-MIKE SHE Integration. Linear Reservoir Module. DHI Report 4710. Danish Hydraulic Institute

Cognard, A.-L., Loumagne, C., Normand, M., Olivier, P., Ottle, C., Vidal-Madjar, D., Louahala, S., & Vidal, A. (1995): Evaluation of the ERS-1/synthetic aperture radar capacity to estimate surface soil moisture: Two-year results over the Naizin watershed. Water Resources Research, 31(4):975-982.

Engman, E. (1995): Recent advances in remote sensing in hydrology, u.s. national report to iugg, 1991-1994. Rev. Geophys., American Geophysical Union, 33 Suppl.

Engman, E. & Gurney, R. (1991): Remote Sensing in Hydrology. Chapman & Hall, London.

ESRI (1996): Arc View spatial analyst. Advanced spatial analysis using raster and vector data. ESRI, Redlands, CA 92373, USA

FAO (1996): Digital Soil map of the world and derived soil properties. FAO, 00100 Rome, Italy.

Giacomelli, A., Bacchiega, U., Troch, P. A., & Mancini, M. (1995): Evaluation of surface soil moisture distribution by means of SAR remote sensing techniques and conceptual hydrological modelling. Journal of Hydrology, 166 (3-4): 445-460.

Griffiths, G. H. & Wooding, M. G. (1996): Temporal monitoring of soil moisture using ERS-1 SAR data. Hydrological Processes, 10:1127-1138.

Hardy, S., Dugdale, G., Milford, J. R., & Sutcliffe, J. V. (1989): The use of satellite derived rainfall estimates as inputs to flow prediction in the River Senegal. Pp 23-29 in: New Directions for Surface Water Modeling, Proceedings of the Baltimore Symp., IAHS Publications, 181

Jackson, T. J., McNairn, H., Weltz, M. A., Brisco, B., & Brown, R. (1997): First order surface roughness correction of active microwave observations for estimating soil moisture. IEEE Transactions on Geoscience and Remote Sensing, 35(4): 1065-1069.

Jackson, T. J., Ragan, R. M., & Fitch, W. N. (1977): Test of Landsat based urban hydrologic modeling. ASCE Journal of Water Resources Planning and Management Div. V 103: 1065-1069.

Kidd, C. (1998). On rainfall retrieval using polarization-corrected temperatures. International Journal of Remote Sensing, 19(5): 981-996.

Kite, G. (1995): The SLURP model. In Singh, V., editor, Computer Models, pages 521-562. Water Resources Publications.

Kite, G. & Kouwen, N. (1992): Watershed modeling using land classifications. Water Resources Research, 28(12):3193-3200.

Knudsen, J., Thomsen, A. & Refsgaard, J.C. (1986): WATBAL: A semi-distributed, Physically based hydrological modelling system, Nordic Hydrology, 17, 347-362

Kuttinen, R., editor (1985): Report on application of remote sensing to hydrology in the Nordic countries., in Nordic Hydrological Program, 9. NHP, Helsinki, Finland. The Coordinating Committee for Hydrology in Norden KOHYNO.

Lo Seen, D., Mougin, E., Rambal, S., Gaston, A., & Hiernaux, P. (1995): A regional sahelian grassland model to be coupled with multispectra satellite data. II: Toward the control of its simulations by remotely sensed indices. Remote Sensing of Environment, 52:194-206.

Mauser, W., Bach, H., Demircan, A., Eibl, B., Riegler, G., & Schneider, K. (1997): The contribution of microwave data to distributed hydrologic modelling. In The 3rd ERS symp. (ESA), Florence, March 1997 - http://florence97.ers-symposium.org/

Moran, M. S., Clarke, T. R., Inoue, Y., & Vidal, A. (1994): Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. Remote Sensing of Environment, 49:246-263.

Moran, M. S., Vidal, A., Troufleau, D., Qi, J., Clarke, T. R., jr., P. P., Mitchell, T. A., Inoue, Y., & Neale, C. M. U. (1997): Combining multifrequency microwave and optical data for crop management. Remote Sensing of Environment, 61:96-109.

Mougin, E., Lo Seen, D., Rambal, S., Gaston, A., & Hiernaux, P. (1995): A regional sahelian grassland model to be coupled with multispectral satellite data. I: Model description and validation. Remote Sensing of Environment, 52:181-193.

Myneni, R.B. & Williams, D.L. (1994): On the relationship between FAPAR and NDVI, Remote Sens. of Environ., 49: 200-211.

Nemec, J. (1994): Distributed hydrological models in the perspective of forecasting operational real time hydrological systems (forths). Pp. 69-84 in: Rosso, R., Peano, A., Becchi, I., & Bemporad, G., (ed): Advances in Distributed Hydrology, Water Resources Publication.

Paloscia, S. (1998):An empirical approach to estimating leaf area index from multifrequency SAR data. International Journal of Remote Sensing, 19(2):359-364.

Peck, E., Keefer, T., & Johnson, E. (1981): Strategies for using remotely sensed data in hydrological models. NASA-CR- 66729.

Rango, A. (1995): The snowmelt runoff model SRM. Pp 477-520 in: Singh, V., (ed): Computer Models of Watershed Hydrology, Water Resources Publications.

Rasmussen, K., Larsen, N., Planchon, F., Andersen, J., Sandholt, I., & Christiansen, S. (1999): Agricultural systems and transnational water management in the Senegal River basin. Danish Journal of Geography, 99: 59-68.

Refsgaard, J.C. & Knudsen, J. (1996): Operational validation and intercomparison of different types of hydrological models. Water Resources Research, 32(7): 2189-2202.

Refsgaard, J.C & B. Storm (1995): MIKE SHE. In: Singh, V.P. (Ed) Computer Models of Watershed Hydrology. Water Resources Publ., Highlands Ranch, Colorado, 1995: 809-846.

Said, M. (1996): Water resources modelling of the worfe river catchment and perak state using remote sensing and gis. IAHS Publ, (235):605-612.

Sandholt, I., Andersen, J., & Rasmussen, K. (1999): A simple interpretation of the surface temperature/vegetation index space for assessment of soil moisture status. Submitted for publication.

Schultz, G. (1993): Application of GIS and remote sensing in hydrology. IAHS Publ., (221):127-140.

Singh, V., editor (1995): Computer Models of Watershed Hydrology. Water Resources Publications.

Troufleau, D.:Institute of Geography, University of Copenhagen, http://www.natgeo.lu.se/HCM/hcmindex.htm

Troufleau, D., Vidal, A., Beaudoin, A., Moran, M. S., Weltz, M. A., Goodrich, D. C., Washburn, J., & Rahman, A. F. (1997). Optical-microwave synergy for estimation surface sensible heat flux over a semi-arid rangeland. Remote Sensing Reviews, 15:113-132.

Wood, E. & O'Connel, P. (1985): Real-time forecasting. Pp 505-558 in: Anderson, M. & Burt, T., (ed): Hydrological Forecasting, John Wiley & Sons.

Yin, Z. & Williams, T. H. L. (1997): Obtaining spatial and temporal vegetation data from Landsat MSS and AVHRR/NOAA satellite images for a hydrologic model. Photogrammetric Engineering and Remote Sensing, 63(1):69-77.