HAPEX-Sahel Hydrology GIS: towards regional water balance modelling in a semiarid area

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Abstract During the HAPEX-Sahel experiment (1991-1993), water redistribution processes were studied at the meso-scale (10 000 km^2) near Niamey, Niger. A project now under way at ORSTOM aims at modelling the regional water balance through a spatial approach combining GIS data organization and distributed hydrological modelling. The main objective is to extend the surface water balance, by now available only on a few, small (around 1 km^2) unconnected endoreic catchments, to a more significant part of the HAPEX-Sahel square degree, a 1500 km^2 region called SSZ which includes most of the environmental and hydrology measurement sites. GIS architecture and model design consistently consider data and processes at the local, catchment scale, and at the regional scale. The GIS includes spatial and temporal hydrological data (rainfall, surface runoff, groundwater), thematic maps (topography, soil, geomorphology, vegetation) and multi-temporal remote sensing data (SPOT, aerial pictures). The modelling approach attempts to produce the composite effect at the regional scale of highly variable and discontinuous component processes operating at the catchment scale, in order to simulate interannual aquifer recharge and response to climatic scenarios.

INTRODUCTION

Modelling of the meso-scale water balance is one of the major final objectives of the HAPEX-Sahel experiment, conducted from 1991 to 1994 over the Niamey square degree (Niger) (2-3°E, 13-14°N). Observations made at various space and time scales have evidenced strong peculiarities of this semiarid Sahelian environment, including extreme time and space variability of hydrological phenomena and absence of regional surface flow. Degradation of the hydrographic network makes this region a juxtaposition of hundreds of small endoreic systems, which do not normally connect under current climatic conditions. This unique structure means that a great number of temporary pools and the phreatic aquifer replace river flow as the main hydrological integrators, making common approaches to regional water balance largely inappropriate. Studies have been conducted on rainfall distribution (Lebel *et al.*, 1992), surface water redistribution at the plot and hillslope scales (Peugeot *et al.*, 1996), surface storage in temporary pools (Desconnets, 1994; Desconnets *et al.*, 1996), and aquifer recharge at the local and regional scales (Leduc *et al.*, 1996).

Working towards the ultimate goal quoted above, the project now under way at ORSTOM is building upon these process studies in two complementary ways:

- construction of a HAPEX-Sahel Hydrology GIS of the area, hereafter denoted HSH-GIS, that integrates pertinent information and knowledge on the main surface and subsurface processes. Gathering and providing access to cartographic or satellite data, and to more elaborate scientific products such as spatial rainfall and piezometric maps, as well as allowing integration of results produced by various sources at various scales, are major objectives of this work;
- developing or adapting methods and tools for physically-based, distributed hydrological modelling that can account for the nature of dominant processes, be compatible with the data available at the various scales and withstand the necessary scale changes, in order to produce interannual water balance simulations, test hypotheses, and assess hydrological responses to climatic scenarios.

Because of its importance as a resource, regional aquifer recharge is the main targeted output. One basic research theme to be answered is : how is water recharged to the aquifer in the 1500 km^2 part of the square degree, called the SSZ (Super Site Zone), where most of the environmental and hydrological measurement sites of the HAPEX-Sahel experiment were located.

DESCRIPTION OF DOMINANT HYDROLOGICAL PROCESSES

The Sahel region is characterized by a quasi-permanent climatic deficit (rainfall generally exceeds evapotranspiration only in August) with high precipitation variability at all space and time scales, and by relatively flat terrain covered with eolian sand deposits that can block talwegs. The combination of these climatic and surface conditions have led to a marked degradation of the regional drainage network, resulting in unconnected small endoreic catchments with intermittent surface flow during the rainy season (May to October). Surface runoff collects into temporary pools formed on plateaux, in sand-blocked river channels, and in depressions next to former river channels.

Generally intense and short-duration rainfall produces high runoff on poorly covered and crusted soils (including cultivated fields), and relatively impervious plateaux escarpments. The transport of the runoff is largely by Hortonian overland flow to concentrated flow gullies which generally degrade at mid-slope into spreading zones. Runoff that does not infiltrate in the drainage network eventually reaches the pools where it either percolates to groundwater or evaporates. Estimations by Desconnets (1994) show temporary pools to have a dominant contribution to the recharge of the regional unconfined aquifer. Water that infiltrates into the channels and catchment surfaces is believed to be largely lost to subsequent evapotranspiration. Only a small fraction of total rainfall actually makes it to the aquifer via the pools, depending on the intensity and distribution of hydrological events in space and time.

METHODOLOGY

The environment peculiar to the Sahel region, where a great number of temporary pools and aquifer recharge are the only integrators of highly intermittent and varying hydrological processes, makes regional water balance modelling a particularly difficult enterprise in this area. These balances, and the aquifer recharge in particular, are the composite result of interactions among many spatially and temporally distributed processes that control loss mechanisms, and therefore depend strongly on the effects, scale, and spatial arrangement of the component processes. Further, the spatial and temporal scale of rainfall variability complicates the characterization of the water balance when scaling from the catchment to regional scales. The project described below aims at taking into account the composite effect at the regional scale of the component processes operating at the catchment scale. It entails a combined GIS-construction and hydrological modelling approach, with consistent space and time scales. Specific study areas include the SSZ corresponding to the regional scale, and catchments within, referred to as local scale. The Wankama and Sama Dey catchments are considered initially to gain an understanding of the component processes that control the water balance. Simulation at the catchment and the regional scale must account for the topographic, pedologic, anthropogenic, climatic, and geomorphic features that control the runoff production, transport, and aquifer recharge. Eventually, coupling the GIS and water surface model with a groundwater model is considered.

Scaling up from the catchment to the regional scale requires data sets that may have less local detail than the spatial data for the Wankama and Sama Dey catchments. Whereas detailed surveys of surface topography exist for these catchments, only general topographic maps exist for the SSZ. Distributed modelling at the regional scale requires a digital elevation model (DEM) synthesis based on available information. This includes sparse elevation data over the SSZ, and more precise topography over neighbouring areas that can be considered to have similar morphology as the study area. A DEM generation method is being developed that can merge these two information sources, through a special interpolation technique based on a Laplacian operator, boundary value, flux conservation analogy.

Distributed hydrological models require elaborate spatial parameters generated from raw data maps using GIS processing functions. The GRASS-based HSH-GIS, and the application of the internally integrated surface runoff model, *r.water.fea,* are described below. For recent applications, see Farajalla & Vieux (1995) and references cited therein.

The HSH-GIS database includes data that support hydrological simulations. Few hydrological models utilize directly the full spatial information content. The model, *r.water.fea*, generates maps of distributed runoff and infiltration, as well as, the traditional hydrograph, from maps of parameters. These maps include Green and Ampt infiltration parameters, slope, hydraulic roughness, and rainfall rates. Infiltration maps incorporate the effects of various land uses, soil crusting, and channel losses. Output from *r.water.fea* includes maps of distributed flow depth and cumulative infiltration that results from the composite of rainfall, topography, soil, and land use patterns, as well as hydrographs at stream junctions.

DESCRIPTION OF THE HSH-GIS

Most of the site observations and some satellite information, gathered during the HAPEX-Sahel experiment, are now available through the HAPEX-Sahel information system (HSIS; http://www.orstom.fr/hapex). Beyond the HSIS, the HSH-GIS is a database specifically meant for continental hydrology research purposes, and therefore serves a smaller number of scientists concerned with surface and subsurface water. In several ways, the HSH-GIS is complementary to HSIS. In particular, it includes both a more complete catalog of cartographic data, and elaborated hydrological data maps, relative to precipitation and water table fluctuations.

Organization of the HSH-GIS

The geographical base is constructed as two nested levels of information, which actually match two distinct observation scales within the HAPEX-Sahel experiment:

- a regional entity, denoted as SSZ, consisting of the 1500 km^2 geographical rectangle (2°25'-2°50'E, 13°25'-13°40'N) that contains the main HAPEX-Sahel experiment areas (East and West Central Super Sites; Goutorbe *et al.*, 1994), within the Niamey square degree;
- several local entities consisting of various endoreic catchments and pools, that have been studied during the HAPEX-Sahel experiment as part of the long-term monitoring program (Desconnets, 1994), and are included in the regional entity.

Future extension of the HSH-GIS to the entire HAPEX-Sahel square degree is considered. Image-maps derived from SPOT would cover more physically heterogeneous areas in support of meso-scale hydrological modelling.

The HSH-GIS data

Hydrological data were collected over a period from 1992 to 1994. From a dimensional point-of-view, three categories of information make up the database (Fig. 1):

- site information, providing a description (location and nature) of measurement points both at the local and regional levels, and the non-spatial hydrological data "collected within the local entities (e.g. pool level variations and raingauge observations in the monitored endoreic catchments);
- spatial information, consisting of physical environment maps for each entity of the base;
- spatio-temporal information, both for the input hydrological variable as series of 1-km resolution rainfall maps, and for the output variable as water table maps with a 5-km resolution. Various time scales are used for these two variables, namely the event and the ten-day scales for rainfall maps, the 3-month and the 1-year time steps for piezometric maps. Rainfall spatialization was performed on site data from the EPSAT-Niger dense network (one gauge per 100 km^2, Lebel *et al.*, 1995), with interpolations being based on event-wise variograms. Groundwater measurements are represented by piezometric maps obtained by supervised linear kriging on a network of 300 wells covering the entire square degree.

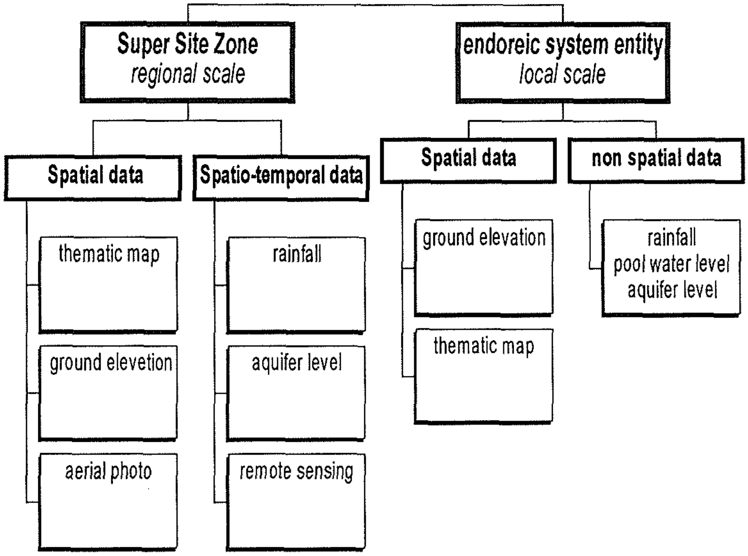

Fig. 1 GIS HSH organization and dimensional data characteristics.

MODELLING OF THE WANKAMA CATCHMENT

Data used in calibration and validation

Calibration and validation of the infiltration and hydraulic roughness parameters relies on the measured pool data for selected storm events. Hydrographs are not directly measured at any point on the stream network in the catchment, but rather, they are extracted from pool level variations. For the Wankama pool, estimated hydrographs showed large instabilities due to stage level measurement precision and round-off errors. A smoothing technique has been devised based on propagation of raw data uncertainties. These have been taken as $\pm$ 1 cm and $\pm$ 0.5 min for stages and times, respectively. Rainfall events have been extracted at 1 minute intervals for events that produced significant pool level rises. Eventually three rainy seasons will be used in the calibration and validation, 1992, 1993, and 1994.

Infiltration is largely controlled by the soil crusting. Within these channels, large amounts of runoff are lost due to high exfiltration rates on the order of 45 cm h^{-1} (Esteves, 1995; Peugeot, 1995). Figure 2 is a map of soil crust classification in the HSH-GIS for the SSZ area, based on the classification scheme of Casenave & Valentin (1989). Estimated infiltration rates for each crust classification, together with channel exfiltration rates were used to calibrate the runoff volume. The hydraulic roughness map controls the timing and peak discharge of the hydrograph. Three objective criteria, volume, timing and peak are optimized through adjustment by multiplicative factors of the input parameter maps. Figure 3 shows the hydraulic conductivity map derived from the map in Fig. 2. The DEM is derived from surveyed point data using the GRASS command, *s.surf.tps* which uses a spline interpolation to generate a raster DEM. Maps shown in Figs 3 and 4, and derivatives thereof (e.g. slope, sub-basins, stream network, drainage accumulation and drainage direction), are the principal inputs to *r.water.fea*.

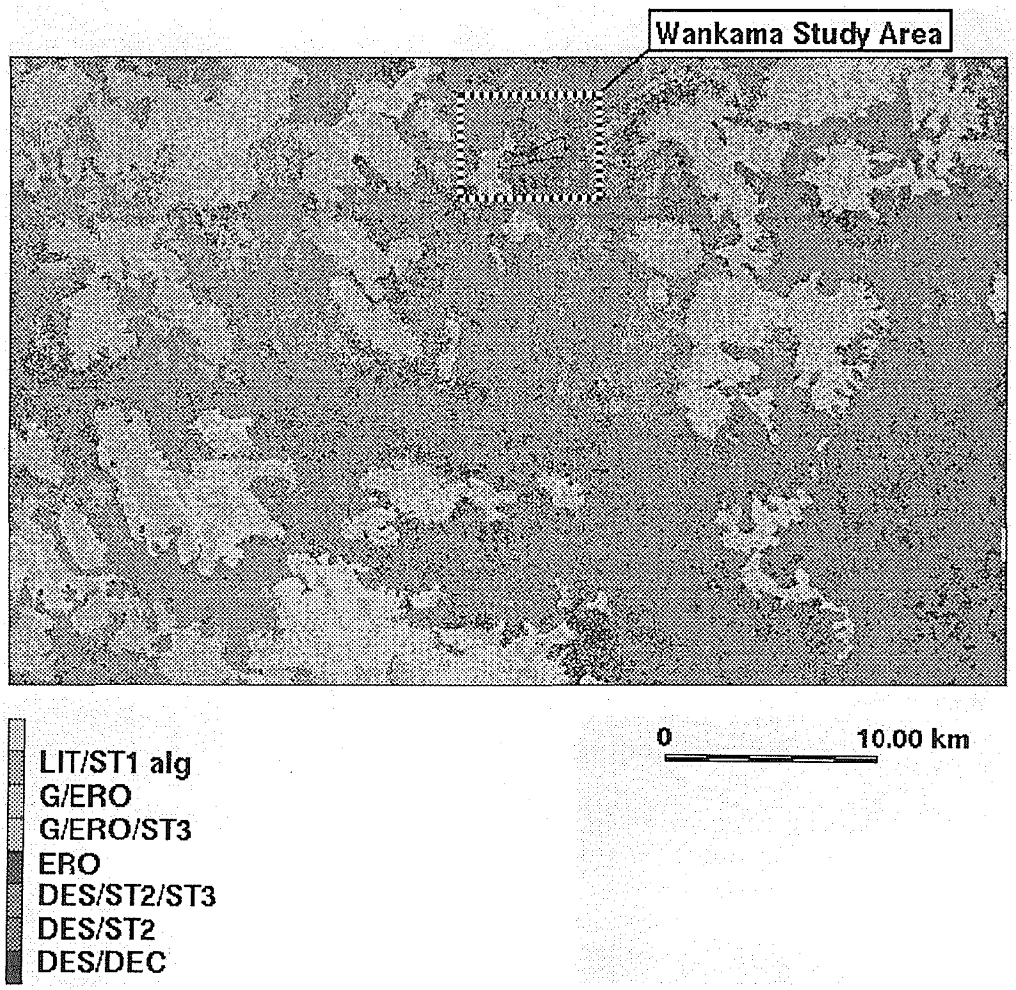

Fig. 2 Surface crust classification (based on SPOT image of 11 September 1992).

Results

The distributed hydrological model, *r.water.fea*, was used to simulate a selected runoff event, 22 August 1993, in the 2.48 km^2 Wankama catchment at 30-m resolution. Calibration sensitivity studies indicate that channel losses are significant. Without the channel exfiltration rates of 45 cm h^{-1}, the map of hydraulic conductivity must be multiplied by increased by 50% for the simulated volume to compare with the measured volume. With this channel exfiltration included, the hydraulic conductivity map falls within the ranges estimated for the soil crust. Thus, omission of the channel losses causes parameter distortion in the hydraulic conductivity map.

CONCLUSION

The first phase of the HSH-GIS and modelling project has produced a hydrology-

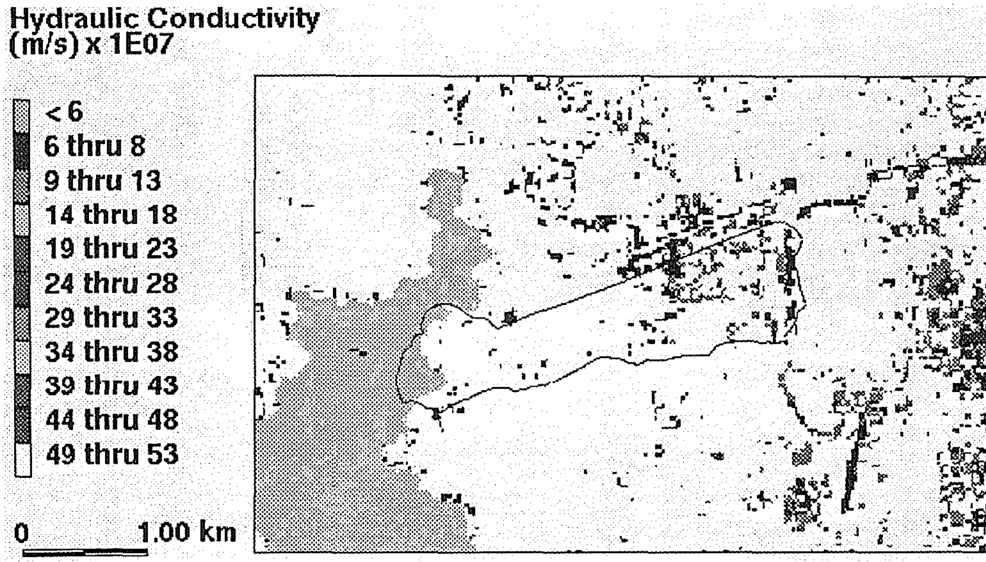

Fig. 3 Hydraulic conductivity map of Wankama catchment.

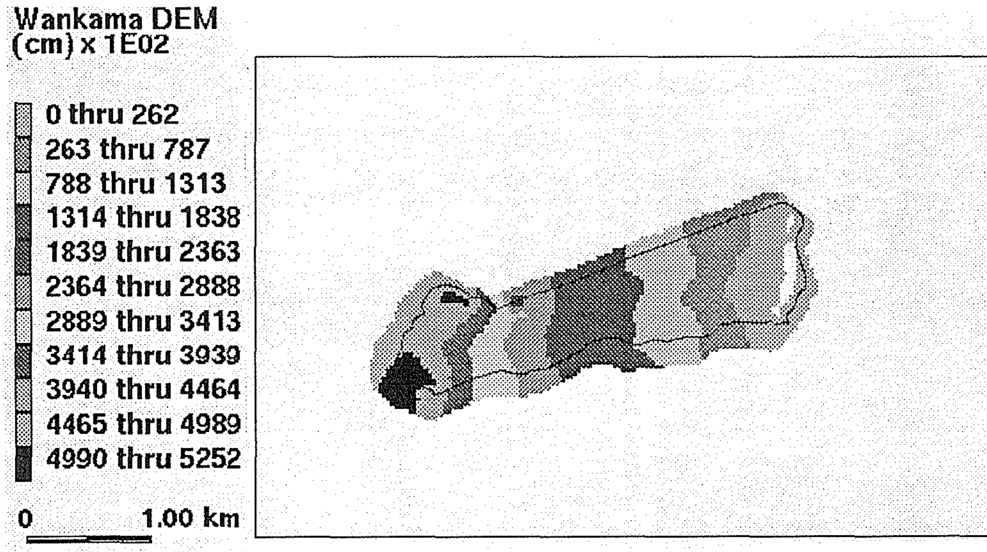

Fig. 4 Digital elevation model of Wankama catchment.

oriented geographic database, through spatialization of the main hydrological variables and parameters that are necessary for regional water balance modelling. Inclusion of two information levels, namely local (elemental endoreic systems) and regional (the 1500 km^2 SSZ) entities, has made it possible, as a first step, to test and validate a physically-based, distributed hydrological model, *r.water.fea*, on the Wankama catchment where spatial information is the densest.

Initial calibration results for the rainy season of 1993 indicate that the model adequately represents the component hydrological processes. Sensitivity of runoff volume to variations in hydraulic conductivity indicate that parameter values are within the range of measured flow values. This indicates that the major hydrological processes are represented in the model without parameter distortion.

These encouraging results recommend the second phase of this project, the extension to the SSZ region. Coupling with stochastic rainfall and deterministic groundwater models will then be considered in order to estimate long-term trends of the meso-scale hydrological balance.

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Application of Geographic Information Systems in Hydrology and Water Resources Management

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Proceedings of the HydroGIS'96 conference held in Vienna, Austria, from 16 to 19 April 1996. This conference was jointly organized by:

Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau, Universität für Bodenkultur, Vienna

the International Commission on Groundwater (ICGW) of the International Association of Hydrological Sciences (IAHS)

the International Committee on Remote Sensing and Data Transmission (ICRSDT) of IAHS

the United Nations Educational, Scientific and Cultural Organization (UNESCO) – Division of Water Sciences

The conference was sponsored and supported by: the International Association of Hydrogeologists (IAH), the International Ground Water Modeling Center (IGWMC), the International Institute for Applied Systems Analysis (IIASA), Austria, the American Society of Testing and Materials (ASTM), the American Society for Photogrammetry and Remote Sensing (ASPRS), the Austrian Hydrological Society, the International Association for Hydraulic Research (IAHR).

IAHS Publication No. 235
in the IAHS Series of Proceedings and Reports

Published by the International Association of Hydrological Sciences 1996

IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire OX10 8BB, UK.

IAHS Publication No. 235.

ISBN 0-947571-84-1

British Library Cataloguing-in-PublicationData.
A catalogue record for this book is available from the British Library.

IAHS is indebted to the employers of the editors for their invaluable support and services provided that enabled the editors to work effectively and efficiently. Support from the National Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands, for the first editor – Karel Kovar, who produced the camera ready text for each paper, is particularly appreciated and acknowledged.

The convenors would like to express their thanks to all who assisted in organizing the conference. They especially would like to thank the members of the Scientific Advisory Committee who were:

Dr G. Barroccu (Italy)
Dr M. Brilly (Slovenia)
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It is highly appreciated that Dr K. Fedra took responsibility for organizing a computer workshop during the conference to provide an opportunity for participants to demonstrate their software applications.

The convenors of the conference would also like to express their thanks for financial support obtained from the following persons, companies and institutions:
UNESCO, Division of Water Sciences
Datamed GmbH, (Vienna, Austria), vendor of ARC/INFO
Austrian Airlines, official carrier for the conference
Mayor and Governor of Vienna
The Austrian Federal Ministry for Agriculture and Forestry

The convenors give special thanks to the members of the Organizing Committee, especially to Mr A. I. Johnson, Honorary President IAHS, to Dr J. Fürst and Dr H. Holzmann, both from the Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau at the Universität für Bodenkultur, Vienna, Austria.

The editors would like to express their sincere thanks to Dr Terence O'Donnell, Editor IAHS, for editing the English of a number of papers by non-English speaking authors. Finally, the editors wish to acknowledge the conference authors for their patience and cooperation during the editing process.

The papers were checked and reformatted by Sarah Cage (freelance editor, Birmingham, UK) and Penny Kisby (IAHS Press, Wallingford, UK) using files provided by the first Editor; Penny Kisby assembled the final camera-ready pages.

Printed in The Netherlands by Krips Repro, Meppel.