Transactions in GIS, 1996, vol. 1, no. 2, p. 82

A GIS for hydrological modelling in the semi-arid, HAPEX-Sahel experiment area of Niger, Africa

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During the HAPEX-Sahel experiment (1991–94), 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 that 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, ground water), thematic maps (topography, soil, geomorphology, vegetation) and multi-temporal remote sensing data (SPOT, aerial pictures). The GIS supports the simulation of the composite effect at the regional scale of highly variable and discontinuous component hydrologic processes operating at the catchment scale, in order to simulate inter-annual aquifer recharge and response to climatic scenarios at the regional scale.

Introduction

Considering the many spatial parameters affecting hydrologic processes, it is not surprising that GIS is becoming an integral part of hydrologic studies. Soils, vegetative cover, topography, climate, spatially and temporally variable rainfall fields, and anthropogenic factors affect such hydrologic processes as evapotranspiration, rainfall runoff, infiltration, and ground water recharge. The advance of hydrologic modelling that relies on GIS, in turn, demands more detailed spatial data and management capabilities from the supporting GIS. Besides supporting hydrologic simulations, the purpose of the GIS described here is primarily the storage and analysis of hydrologic-related data collected during the Hydrologic and Atmospheric Experiment (HAPEX) Sahel experiment conducted from 1991 to 1994 over the Niamey square degree (Niger) (2–3°E, 13–14°N) in Africa. The public domain, UNIX-based GIS GRASS (Geographic Resources Analysis Support System) was used to manage the spatial data. In addition to cartographic functions, an internally integrated hydrologic model is used to simulate hydrologic processes using spatial data contained in the system. Physical and hydrologic characteristics of the region and the data collected determine the characteristics of the system. Figure 1a shows the location of Niger and the HAPEX square degree, which is located in the south-western region of the country. In Figure 1b, the enlargement of the HAPEX square degree reveals the capital, Niamey on the Niger River, which flows from north-west to south-east across the square degree. The various study areas of the HAPEX experiment are the South Super Site (SSS), the West Central Super Site (WCSS), the East Central Super Site (ECSS), and the larger grouping of the latter simply called the Super Site Zone (SSZ). The unique physical characteristics of the SSZ affect the design of the database and information management system.

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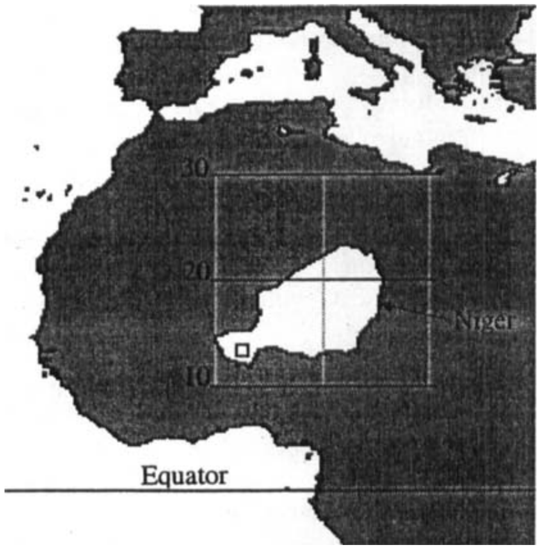


Figure 1a. Location of the HAPEX-Sahel square degree in Niger on the African continent.

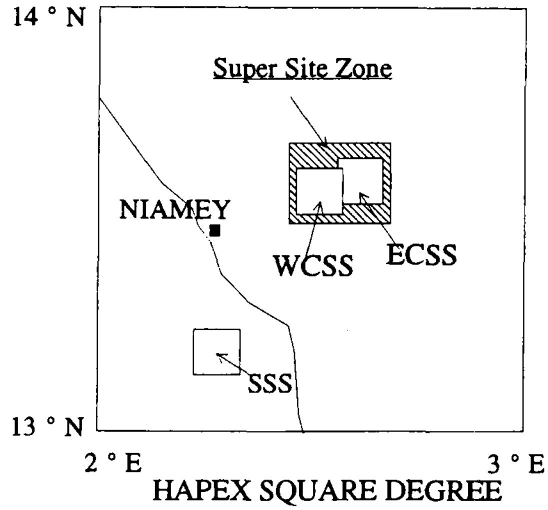


Figure 1b. Super-Site Zone (SSZ) location with the HAPEX-Sahel square degree.

The Sahelian landscape is flat to gently undulating. Within the study area, relief between plateaux and valley bottoms is generally between 200 and 250 m above mean sea level. Annual grass, scattered bush savanna, and extensive rain-fed cultivation, such as millet, typify the vegetative cover. The geomorphological features include plateaux, sand plains, and fossil river valleys and drainage networks. In fact, the drainage network is largely non-functioning because of Pleistocene deposits of eolian sands. Surface runoff in the form of overland flow may exist only over a scale of a few hundred metres in small endoreic catchments on the order of a few square kilometres or less. The rainfall in this region is isolated to a rainy season, from May to October, ephemeral pools form in sand-clogged river channels collecting runoff, which usually percolates to the ground water or evaporates. The persistence of these pools to hold water ranges from going dry between rain events, in the case of pools with small drainage areas, to those pools which supply limited water during the dry season. It is the water in these pools that has the most potential to percolate to the regional water table, which is generally 15 to 40 m below ground level and is unconfined except below laterite plateaux. The spatially and temporally variable hydrologic processes distributed across many endoreic catchments, in the composite, form the regional water balance. The SSZ study area, which is annually in a rainfall deficit, falls between isohyetal lines of inter-annual rainfall of 500 and 600 mm/year. Rainfall increases approximately 1 mm/km in a north–south direction with increasing rainfall towards the equator. The only other major water resource in the region is the Niger River, deriving its runoff from mountains in Guinea. It is not influenced by runoff processes within the study area since the sand-clogged drainage network does not convey water. Although beyond the scope of this paper, the main hydrologic studies that have been conducted in this region are 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).

Two roles are required of the GIS: one is storage and data management; the other is the support of hydrologic simulations. Construction of a HAPEX-Sahel Hydrology GIS for the study area, hereafter denoted HSH-GIS, integrates diverse sources of cartographic or satellite data, and derived scientific products such as spatial rainfall and piezometric maps, and assembles these data in a single database. Physically based, distributed hydrological modelling requires maps of data that represent model parameters. Thus, digital representations of rainfall, terrain, soils, and vegetative cover are used to simulate the hydrologic processes that influence how much rainfall is partitioned into runoff by the soil, how much runoff travels through the drainage network, and how much ultimately reaches the ephemeral pools where it either evaporates or percolates to the regional water table. The major input to the system is rainfall which is linked to the fluctuation of the ground-water and pool level through complex runoff and runoff-loss mechanisms. The catchment-scale simulation attempts to connect these two phenomena to form a regional water balance which is the composite of many such catchment-scale processes.

Simulations require data collected at both regional and catchment scales. The GIS integrates results produced by various sources at various scales. Scale in the hydrologic sense, catchment versus regional, determines the GIS development and design. Data have been assembled for three selected catchments which are on the order of several km^2, and on the regional scale, on the order of 1500 km^2. The inherent difficulties of multiple-scale and resolution data are examined in the following sections describing the design of the HSH-GIS and the hydrologic simulations supported by the system.

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 spatial database specifically designed for continental hydrology research purposes. In several ways, the HSH-GIS is complementary to HSIS. In particular, it includes both a more complete catalogue of cartographic data, and elaborated hydrologic data maps, relative to rainfall and water-table fluctuations.

Software environment

The HSH-GIS project has been developed using ver. 4.1 of GRASS, which offers many raster functions that are particularly useful for hydrological applications. The internally integrated hydrologic model, ***r.water.fea*** (Vieux et al 1996) is a GRASS module that simulates spatially distributed runoff using maps of parameters (http://chief.ecn.uoknor.edu/r.water.fea.html). The major data types and organization are described below.

Organization of the HSH-GIS

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

1 A regional entity, denoted as SSZ, consisting of the 1500 km^2 geographical rectangle (2 25' E to 2 50' E, 13 25' N to 13 40' N) that contains the main HAPEX-Sahel experiment areas (East and West Central SuperSites; Goutorbe et al 1994), within the Niamey square degree.
2 Several local entities consisting of various endoreic catchments and pools (e.g., Wankama and Sama Dey), that have been studied during the HAPEX-Sahel experiment as part of the long-term monitoring programme (Desconnets 1994), and are included in the regional entity.

Consistent resolution and scale are maintained for each entity. However, a disparity in scale and resolution exists between the local catchment-scale and regional-scale entities.

The HSH-GIS data

From a dimensional point of view, three categories of information make up the spatial and spatio-temporal data for the regional and local-scale entities:

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 rain-gauge observations in the monitored endoreic catchments),
2 Spatial information, consisting of vector and raster maps of the physical environment for each entity of the database,
3 Spatio-temporal information, both for the input (rainfall) and output (water table) hydrological variables.

Though not exhaustive, example maps contained in the regional and local entities are

SSZ region	Sama Dey catchment	Wankama catchment
Raster	**Raster**	**Raster**
Surface features:	*Surface features:*	*Surface features:*
Soil-crust classification	Soil-crust classification	Soil-crust classification
Agricultural utilization	Landscape units	Landscape units
Vegetation classification	*Topography:*	*Topography:*
Landscape units	Raster surfaced from point elevations	Raster surfaced from point elevations
Soils		
Hydrography		
Aerial photography		
Piezometric levels		
Pluviometric maps:		
event and ten days		
Site	**Site**	**Site**
Rain gauge locations	*Topography:*	*Topography:*
Piezometric well locations	Surveyed elevations	Surveyed elevations
Topography:		Rain gauge locations (2 to 3)
Point elevations		Piezometric well locations
Vector	**Vector**	**Vector**
Topography:	None	Watershed boundary
Vector contours		

Table 1. Examples of spatial data contained in the HSH-GIS for the regional and local entities.

shown in Table 1. The vector contours and point elevations at the regional scale are at 1:200 000 with contour lines at 200 and 240 m. Thus, only the tops of the plateaux and the valley bottoms are represented at this scale (recall that the SSZ lies between 200 and 250 m, msl). At the local-entity scale, the topography has been field-surveyed for a few catchments (Wankama and Sama Dey) and is more representative of the land surface than the regional-scale map.

At the local-entity scales (under 1:50 000), there exist very few topographic and cartographic documents in the Sahelian zone, a major limiting factor for GIS analysis and hydrologic modelling. The most important source of information at the regional scale of the SSZ has been the SPOT and aerial photography (Table 1). From the SPOT imagery, the soil-crust classification, vegetative cover (millet, grass, bare soil, and brush are major types), maps were derived. From the aerial photography, the hydrography was photo-interpreted showing the location of gullies and sand-clogged river valleys. The local-entity scale data shown in Table 1 is much more limited. Figure 2 shows the primary spatial data consisting of a Digital Elevation Model (DEM) and several pre-existing information maps. The major part of the HSH-GIS consists of elaborated data sets produced for the purpose of hydrological modelling through specific spatial processing procedures (Figure 2). Digital elevation data are processed to form slope maps, drainage direction, accumulation, stream networks, and catchment boundaries. SPOT imagery reclassified into soil-crust classification and vegetative cover are processed into hydrologic parameters. Soil crusts are reclassified into hydraulic conductivity, using the method of Casenave and Valentin (1989). Vegetative cover is reclassified into a map of hydraulic roughness. Several of the processing procedures shown in Figure 2 are discussed in more detail below.

Topographic and cartographic data

Topography is a key data set that often exists at the regional scale at a very coarse resolution, or only at the catchment scale at very fine resolution. This is a problem of scale and extent. Large-scale maps are not easily obtained over large areas. At the regional scale, description of the physical environment is based on two main documents:

1 A 1:200 000 topographic map, which provides a generalized description of relief (40 m-spaced contours, high and low points) and of the major hydrological objects (residual hydrographic network, permanent and temporary ponds, depressions).

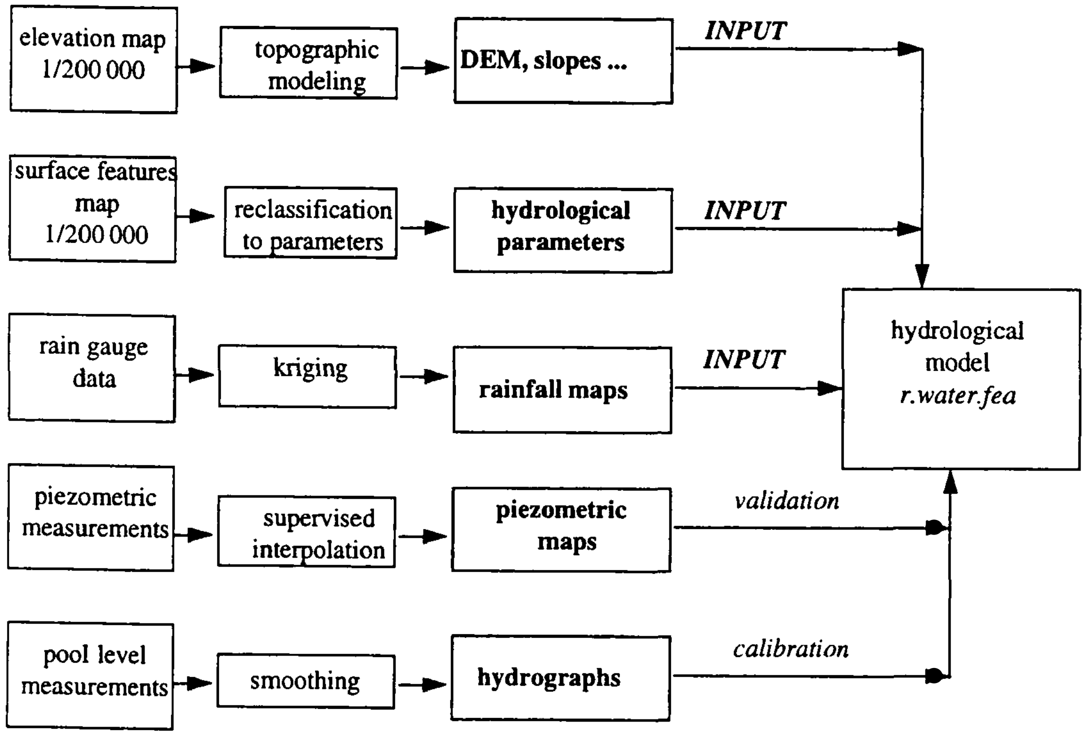


Figure 2. Data production for hydrological modelling.

2 Surface-feature maps at 1:200 000 (D'herbès et al 1992), derived from 1988 and 1992 SPOT images. They include soil-crust classification based on the scheme of Casenave and Valentin (1989), and describe the spatial variability of surface hydrodynamic characteristics, from which infiltration and hydraulic roughness parameters were derived.

At the local-entity scale, topography and landscape units have been mapped more finely based on field surveys at 1:5000 and 1:10 000, respectively, over the Sama Dey and Wankama catchments. These maps are more detailed than exist at the regional scale.

Finally, the HSH-GIS includes high-resolution aerial imagery (3 × 3 m, panchromatic) stored as imagery (only limited rectification has been performed to date). The data shown in the bottom three processing flow lines in Figure 2 are point data. At each location in the map, for example, a rain gauge, there exists a series of text files for each storm event giving rainfall amount recorded at break points. Point data include the locations of the rainfall, hydrometric (ephemeral pool level), and piezometric measurement sites (ground-water fluctuations). Besides point data and corresponding time series of rainfall, there exist raster maps of rainfall produced by accumulating data and kriging the data over the SSZ regional scale.

Hydrological data

Rainfall and water-table fluctuations are major hydrologic variables and essential inputs and outputs in the hydrologic simulation. Spatially distributed estimates of these variables are required in order to account for their strong spatio-temporal variability in the modelling of hydrological processes at the regional scale. All hydrology data in the HSH-GIS are available over the four-year, 1991–94 period. Various time scales were used for these two variables: namely, the event and ten-day time steps for rainfall maps, and the three-month and the one-year time steps for piezometric maps (due to the longer temporal response of the water table).

Spatial interpolation of rainfall was performed on site data from the EPSAT-Niger dense network (one gauge per 100 km^2, Lebel et al 1995), with interpolations kriged using variograms for each event. A 1 km resolution was chosen for rainfall maps, which is the finest acceptable resolution given the network density and the known rainfall variability. Uncertainty on rainfall fields is provided by maps of estimation error, drawn from kriging interpolation. The advantage of kriging for spatial interpolation is that besides the rainfall field itself, the uncertainty of the variate is included in the spatial data set. To obtain the ten-day rainfall maps from the event rainfall maps, the kriged maps were accumulated in each ten-day period. The rainfall spatial and temporal distribution is highly variable. The general atmospheric circulation pattern is from east to west during the rainy season. Formation of the Intertropical Convergence Zone draws moisture from the Gulf of Guinea into the Sahelian region beginning in June. Squall lines form producing bands of intense precipitation oriented from north to south travelling across the Sahel from east to west. Locally intense storm patterns produce strong gradients in precipitation. This spatial variability makes regional estimates of the hydrologic water balance possible only by kriging the point measurements to produce a statistical model of the precipitation over space.

Mapping of water-table fluctuations is derived from piezometric monitoring of up to 300 wells (from 1000 to 2000 yearly measurements) covering the entire square degree. The spatial variability of ground-water recharge, which occurs mostly as local infiltration under endoreic pools, makes it necessary to map piezometric variations in two different ways: regional-scale water-table elevation is obtained by supervised linear kriging with a 5 km resolution (the average density of the gauge network), and local-scale water-table elevation represented by point data reflecting fluctuations in monitoring wells at the selected pools. Finally, stage fluctuations have been monitored in ten pools from 1991 to 1995. The rise and fall of the stage in response to rainfall runoff, evaporation, and percolation is a primary hydrologic integrator used in the simulation of the catchment scale water balance. The stage data are represented as point data taken at five-minute time intervals.

HSH-GIS Supported hydrological modelling

Dominant hydrologic processes

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 (rainfall rate exceeds infiltration rate) to concentrated flow gullies which generally degrade at mid-slope into spreading zones. Runoff that does not infiltrate in the drainage network or spreading zones eventually reaches the pools where it either percolates to ground water or evaporates. Desconnets (1994) estimated that temporary pools are the 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.

The peculiar environment of the Sahel region, where a great number of temporary pools and aquifer recharge are the only integrators of highly intermittent and spatially varying hydrological processes, makes development of a supporting GIS, and regional water balance modelling, a particularly difficult enterprise. These balances, and the aquifer recharge in particular, are the composite result of interactions among many spatially and temporally distributed processes that control runoff-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 Wankama and Sama Dey catchments are small endoreic catchments for which detailed data have been collected in order 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. The internally integrated GIS hydrologic model, *r.water.fea*, and the data sets necessary to run the model are described below.

The *r.water.fea* hydrological model

The HSH-GIS database includes data that support hydrologic simulations. Few hydrologic models utilize directly the full spatial information content. The model *r.water.fea* solves the kinematic wave equation using finite element in space and finite difference in time. Each grid cell is connected together by a finite element which is then used in the routing of water from grid cell to grid cell. The production of runoff by rainfall rates exceeding infiltration rates is coupled with the routing of runoff down slope. The resulting output includes maps of distributed runoff depth and infiltration at intervals during the storm period, as well as hydrographs at stream junctions. 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. The maps of distributed flow depth and cumulative infiltration result from the interaction of rainfall rates with soil and channel infiltration rates, drainage networks defined by topography, and hydraulic roughness affected by land use/cover patterns. The system of equations derived from the connectivity of each grid cell in the DEM results in a system of ordinary differential equations in time which are then solved at a time step on the order of minutes with updated values of rainfall as determined by the rain gauge break points. This numerical technique is used to route flow (rainfall runoff) from each cell to the next. Thus, in hydrologic terms, the transfer of runoff and the generation of runoff interact in the model such that the two functions affect each other. That is, runoff generated in one cell may infiltrate and be lost in the next. The numerical solution of this process is described in Vieux (1988) and Vieux et al (1990); the integration of the numerical model within a GIS is described in Vieux (1991) and Vieux and Gaur (1994); and the influence of map resolution and error propagation are described in Vieux (1993), Vieux and Farajalla (1994), Farajalla and Vieux (1995), and Vieux et al (1996). Internally integrated hydrologic modelling greatly facilitates the simulation of complex spatially and temporally variable processes using maps of parameters. An important component of such simulations is having adequately detailed information such as a DEM that is sufficient in describing the land surface for the particular scale and hydrologic process.

The resolution of the DEM has important consequences on derived slope maps, resulting drainage network, and hydrologic simulations. While detailed topographic maps or digital elevation models exist for the Sama Dey and Wankama catchments, the same resolution data do not exist for the SSZ or the entire square degree. In order to extend the hydrologic simulations to other catchments, synthetic generation of a DEM with suitable topographic detail is required.

Synthetic topography for spatial hydrologic modelling

In the HAPEX-Sahel area, only very coarse topographic information is available at the regional, SSZ scale, compared to that which is needed for physically based, distributed hydrological modelling purposes. DEMs covering regional to continental scales such as those constructed by the USGS at 1 km resolution, or by Hutchinson et al (1996) at 5 km resolution for the African continent, are too coarse for catchment-scale runoff processes in this region. One such 5 km grid cell encompasses the entire scale of runoff generation (on the order of a few hundred metres) in the SSZ, rendering the DEM useless for anything but the most general representation of continental topographic or climatic studies. On the other hand, fine-scale DEMs produced from interpolation of field surveyed measurements are impractical except at the local-entity catchment scale. An intermediate solution is required where distributed physically based hydrologic models are to be applied over regional areas where only general DEMs and coarse topographic maps exist.

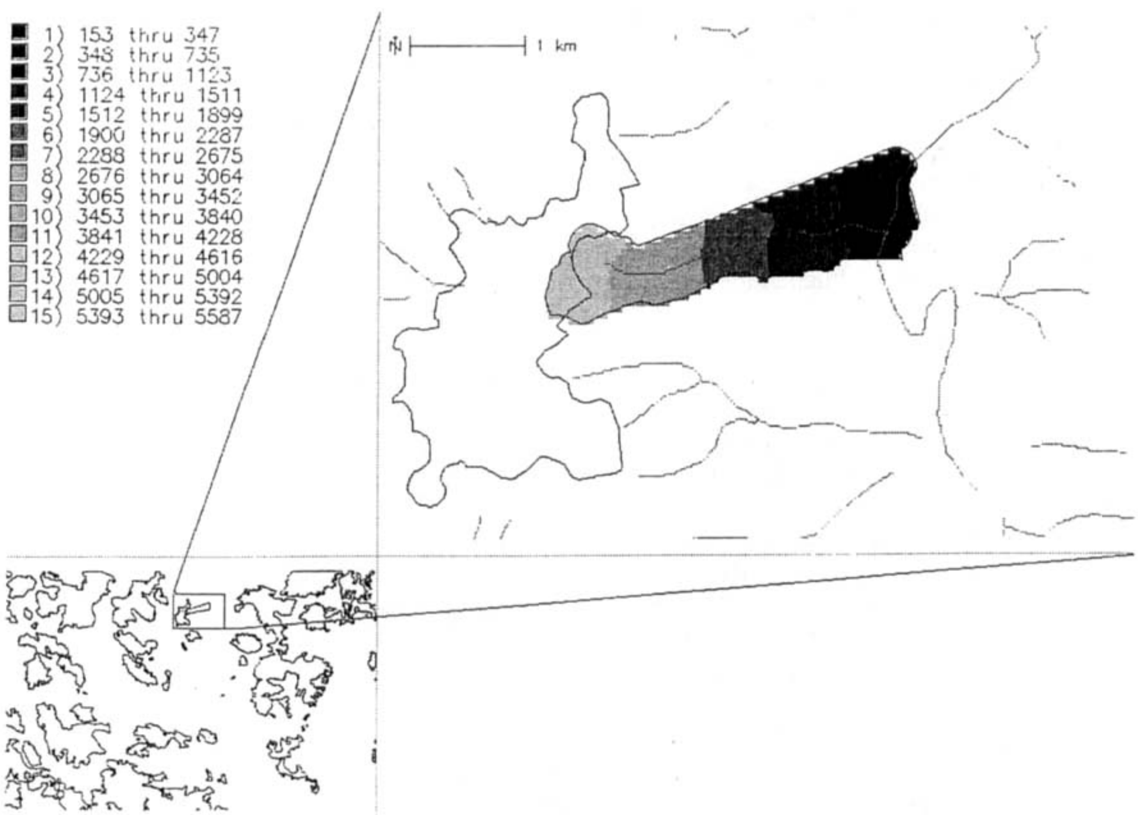
Drawing from the fact that the terrain surface is very often controlled primarily by the main morphological features of the landscape for which maps are generally available, a method is being developed to model relief, based on the most readily obtained information: sparse elevation data (contours and scattered points) and location of the main morphological elements. In the HAPEX-Sahel area, these morphological features include koris (channels in valley bottoms), ravines, spreading zones, and plateaux edges. These morphological features are interpreted from the panchromatic aerial photography as well as from base maps produced for the region. This DEM synthesizing method considers the topographic surface as a 2D potential field which is submitted to fictitious, conservative fluxes controlled by the potential field and by the morphological features, and is constrained by imposed potential values at known elevation points. This method amounts to solving a boundary-value problem for distributed flux resistances over the various landscape components; plateaux, ravines, and koris.

Figure 3 shows the DEM generated using the flux analogy and the morphological features; the plateaux, kori, and ravines. Simulations are used to compare the DEM generated by the flux analogy and the DEM generated from surveyed data. Validation of the method is provided by comparing the simulated hydrologic responses of catchments (the GIS local entities), obtained with the synthesized surface model *vis-à-vis* the DEMs derived from field survey. In the latter case, the DEM is produced from the surveyed point data using the *s.surf.tps* GRASS command, which performs spline interpolation through measured elevation points. The proposed terrain modelling method can also be used for general interpolation of a set of site elevation data. Maps derived from DEMs (for example, slopes, sub-basins, stream network, drainage accumulation, and drainage direction), serve as principal inputs to hydrological models such as *r.water.fea*.

Spatially distributed infiltration and runoff parameters

Infiltration in *r.water.fea* is modelled by the Green and Ampt infiltration equation. Maps of saturated hydraulic conductivity, wetting front suction head, porosity, and initial soil saturation are required. In the HAPEX-Sahel area, infiltration is largely controlled by soil crusting, that is, a thin layer of soil

Figure 3. Digital elevation model of Wankama catchment.



Classification[1]	Description[2]	Hydraulic conductivity[3] (mm/hr)
LIT/STx	Litter/non-cultivated crust structure consisting of x micro-horizons.	15
G/ERO	Large boulders/crusted eroded surface	2
DES/DEC	Desiccated crust formed on sandy soils/ crust formed on clayey soils.	20

Notes:

1 These classifications are used by Casenave and Valentin (1989) to classify soils in the Sahel according to hydrologic characteristics. These classifications are abbreviations of the French terms used to describe the soil-crust type. DES represents *une surface de type dessication*, which is non-cultivated with less than 20% vesiculas (macro drainage structure), and less than 40% cover by large pebbles or rocks. The crust is weakly developed and associated with a sandy soil. The estimated range of the infiltration capacity for DES is 10–20 mm/hr.

2 The infiltration capacity was estimated by Casenave and Valentin (1989) for each soil-crust type. Their infiltration model utilized a parameter that corresponds to the saturated hydrologic conductivity.

3 The saturated hydraulic conductivity is achieved rapidly because the crust controls the rate at which water infiltrates and saturates quickly.

Table 2. Crust classification, description, and infiltration capacity.

sealed by soil particles dislodged by raindrop impact. The crust formation occurs both on cultivated, fallow fields, and on natural soil surfaces. Infiltration parameters are mapped based on a reclassification of the HSH-GIS surface feature maps for the SSZ area. Casenave and Valentin (1989) classified nine major types of soil crusts in the Sahel. Estimates of infiltration characteristics account for crust type, presence of termites or worm vesiculas, mulch or gravel armouring, erosion, and cultural practices. Several typically associated soil-crust classifications found in the Sahel together with the corresponding estimates of infiltration rates are reported in Table 2.

These values were used in a look-up table to reclassify each type of crust interpreted from SPOT imagery into a hydraulic conductivity map.

Figure 4 shows the map derived from supervised classification of SPOT imagery. Reclassification of the soil-crust classification using Table 2 as a look-up table results in a hydraulic conductivity map affecting the overland flow runoff. The behaviour of the HAPEX-Sahel catchments is also affected by the high infiltration rates in the collecting ravine network, where large amounts of runoff can be lost. These rates are estimated on the order of 45 cm/hr, after Esteves (1995) and Peugeot (1995).

Hydrograph shape – that is, timing and magnitude of peak discharge – is largely controlled by the distribution of the hydraulic roughness parameter governing overland and channel-flow rates. A similar approach described for the hydraulic conductivity was used for the overland hydraulic roughness parameter. Hence, an *a priori* roughness map is produced by reclassification of the surface feature maps (again, SPOT classification was used to classify land surface/cover) and assessment of relative roughness magnitudes by qualified ORSTOM investigators using a Delphi technique. That is, those hydrologists who have been on-site were asked to rank each surface classification on a relative scale. Then each surface was given an estimated hydraulic roughness coefficient maintaining relative roughness. Although infiltration parameters predominantly act on hydrograph volume and roughness on shape, they are not independent. Calibration must therefore be performed iteratively between these parameters, to optimize the objective criteria (volume, timing, and peak). Figure 5 shows the hydraulic conductivity map derived for the Wankama catchment from the crust classification map shown in Figure 4. Both the infiltration and hydraulic roughness parameter maps are adjusted by multiplying the parameter map by an adjustment factor. If a ten per cent increase in hydraulic conductivity is desired, then the map is multiplied by 1.1. This is done in order to bring the volume of the runoff event to within pre-defined calibration criteria. Simulated and observed hydrographs are matched by adjusting the maps of hydraulic conductivity and hydraulic roughness. The adjustment preserves the spatial

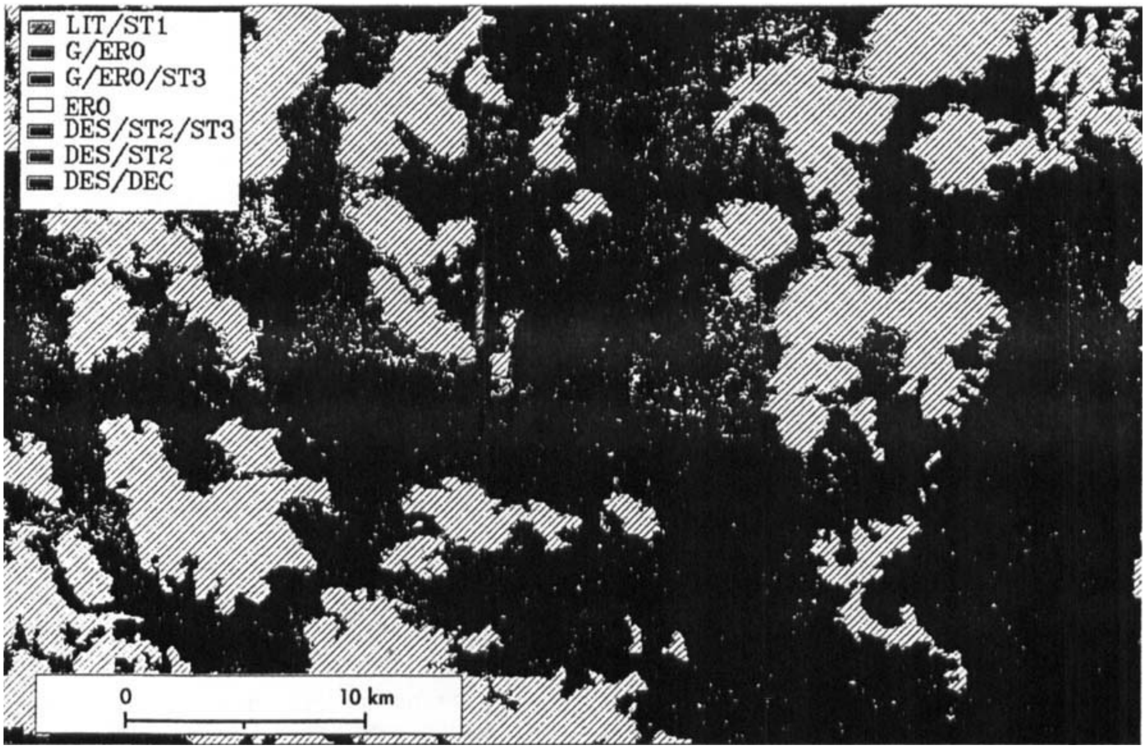


Figure 4. Surface crust classification in the SSZ (based on 11 September 1992 SPOT image).

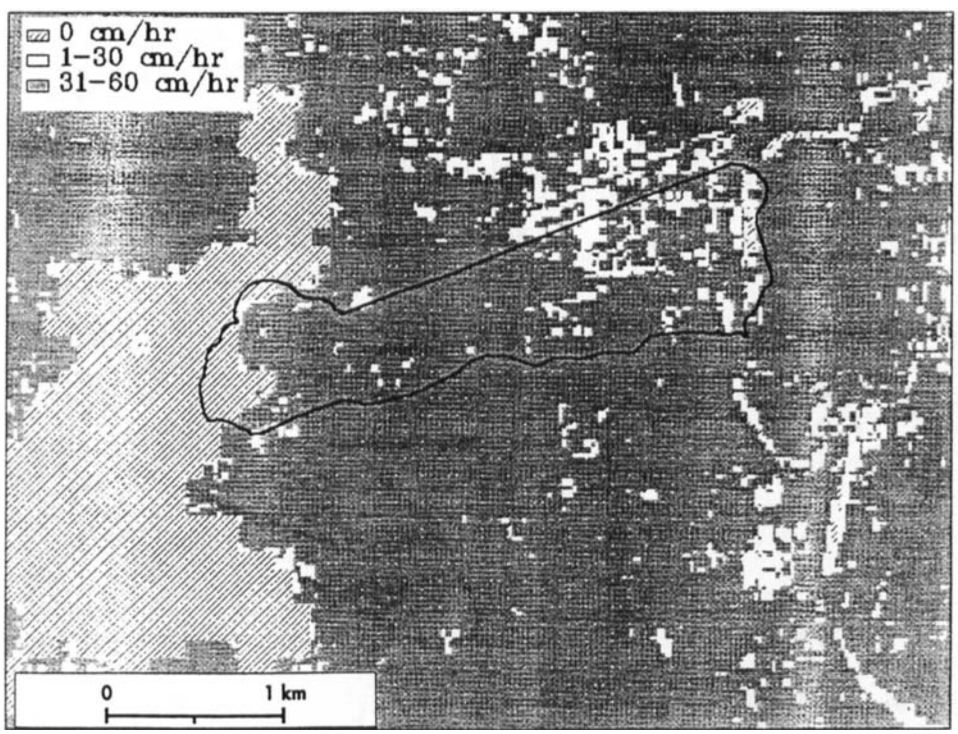


Figure 5. Hydraulic conductivity map of Wankama catchment.

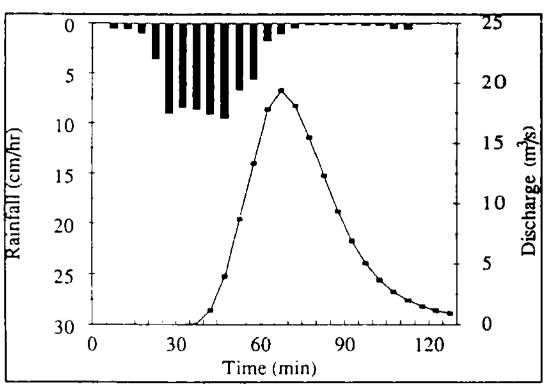
pattern while changing the magnitude of the map. Catchment-scale calibration and validation is used to improve the accuracy of these parameters over the region.

Simulation of the Wankama catchment

Calibration and validation of the infiltration and hydraulic roughness parameters rely 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 ± 1 cm and ± 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.

The distributed hydrologic model, *r.water.fea*, was used to simulate a selected runoff event, on 22 August 1993, in the 2.48 km^2 Wankama catchment at 30 m resolution. The hyetograph and simulated hydrograph for this event are shown in Figure 6. Besides hydrographs, runoff simulated by *r.water.fea* is computed in the form of a series of maps depicting runoff depth distributed throughout the basin. Both runoff depth and cumulative infiltration maps are produced showing the amount and location of infiltration as affected by runoff and run-on. Because the production and routing of runoff are linked in the solution process, these maps are the result of complex interactions between soils, topography, vegetation, and rainfall. Figure 7 shows the runoff depth map for the selected storm that occurred on 22 August 1993, after 15 minutes into the storm representing nearly complete coverage of the basin by runoff. Depths

Figure 6. Hyetograph and resulting simulated



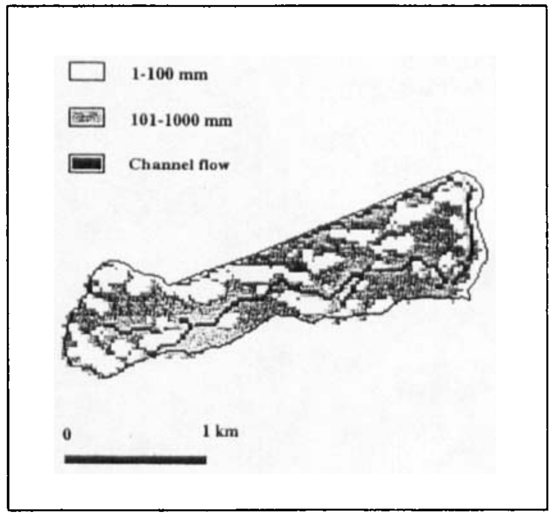
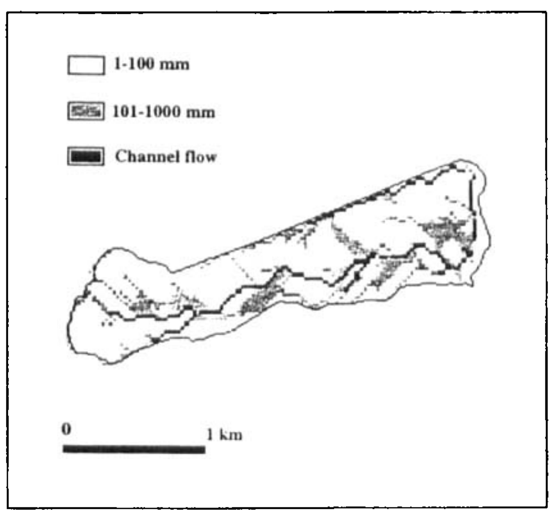


Figure 7. Runoff depth map for the 22 August 1993 storm 15 minutes from the beginning of the storm where nearly all of the basin is contributing runoff.

Figure 8. Runoff depth from 75 minutes after the beginning of the storm representing a recession phase where the basin is only partially covered with runoff in topographically low areas.



vary according to the rainfall rate in relation to the hydraulic conductivity of the soil and the topography which contributes run-on from upslope. Figure 8 shows the runoff depth after 75 minutes into the storm, representing a recession phase where the basin is only partially covered with runoff in the topographically low areas. Future efforts will be directed to applying *r.water.fea* to all of the catchments in the SSZ.

Conclusions

The first phase of the HSH-GIS and modelling project has produced a hydrology-oriented geographic database through spatial distribution 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.

Development of the HSH-GIS revealed special issues related to resolution and scale peculiar to distributed hydrologic simulations at the catchment and regional scales. These include the synthetic generation of a DEM suitable to rainfall-runoff simulation; disparity of scale and resolution between local and regional entities; and improving the accuracy of the HSH-GIS spatial database through calibration and validation of a hydrologic model.

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