Hydrological network modelling using GIS for supporting integrated water resources management

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Abstract This paper studies the possibility of integrated water resources management using GIS network analysis applications. It focuses mainly on yield-demand-management and allocation analysis by combining hydrological inflow (runoff generation) with the various competing user sectors in a river catchment, such as domestic, agricultural, industrial and environmental water demand. The integration of water yield and use information is done by linking supply and demand sites with the river network. By including all water resources relevant objects into an integrated network (source components modelled by a distributed hydrological catchment model, demand sites with or without water consumption, recycling objects like waste water treatment plants...), one can analyse water resources and their availability and allocation within a catchment in a spatially and temporally distributed manner. By applying GIS analysis functionality, such as network tracing and accumulating as well as location-allocation analysis, problems like equitable water allocation to user sites, water use management during drought situations and planning of new water abstraction permits can be analysed. Using standard PC-based GIS software, the proposed methodology is also applicable for local water resources planning with having only limited computing resources available.

1. INTRODUCTION

1.1 Integrated water resources management

In the past decade, water resources management has faced a multiple paradigm shift: from supply to demand management, from an engineering to an environmental perspective, from a top-down to a participatory management. There is a broad consensus of the need to achieve a better balance between economic efficiency and environmental quality in the sense of sustainable development of natural resources [Jamieson and Fedra 1996]. Such an integrated water resources management can be supported by analysing water quantity and quality and their temporal and spatial distribution within a river catchment based on its physical and socio-economic conditions, integrated with water demand and utilisation analysis. In this context, decision support systems can assist in turning a multidisciplinary management using separate tools into an integrated, interdisciplary framework system.

1.2 Spatial Decision Support Systems (SDSS) for integrated water resources planning

Important characterisitcs of a Decision Support System (DSS) for sustainable water resources management include flexibility for tackling various 'what-if?' scenarios, the facilitation of problem identification and solving by analytical tools enabling the end-user to manage, analyse and present information, and interaction and ease of use to involve the stakeholders into the management process themselves [Simonovic and Bender 1996]. Integrated water resources management comprises numerous complex and unstructured management problems including a geographical component. Resolving ill-structured problems, however, can be achieved by disaggregating them into a series of structured components, each of which tackled with its unique set of tools [Reitsma 1996], and integrated into a comprehensive framework system. That means, neither Geographical Information Systems (GIS), identified by many scientists and managers as a powerful decision support tool, nor physical process models alone do not constitute a decision support system [Lam 1997]. Using GIS and traditional DSS in an integrated way leads to the extended concept of SDSS, incorporating the capabilities of both GIS, which accounts for the spatial dimension of water resources management and is strong in visualisation, and DSS, which brings user assistance, models, a database, scenario-building and a generic framework into the system. The IWRMS project [Staudenrausch et al. 1999], of which the GIS component described in this paper forms a part of, is following these principles.

1.3 GIS network analyses

Generally, GIS network analysis is a suitable tool to model phenomena of the real world that are transported through a network. This could be power, traffic or, in this case, water and solute or solid substances transported by water. The system we use for managing water resources, the river basin, can be modelled as an assembly of spatial objects forming a network of links and nodes as well as attributes that control the type and behaviour of those objects [McKinney et al. 1997]. The network is the natural river system including artificial links like canals or pipelines. The nodes of this network are made up of water resources relevant objects: inflow nodes, demand nodes, diversion/confluence nodes, storage nodes, etc. For any of these objects, the hydro-topological integrity is preserved. Through GIS tools like network tracing and accumulating, it is possible to calculate balances of water runoff, storage, consumption and recycling. Spatial allocation modelling and siting of new water demands (industry, irrigation, domestic, environmental demand, etc.) is feasible using this approach. Sharing shortages or economical optimisation are other possible applications.

2. THE STUDY AREA

The Mupfure river basin, one of the major pilot study areas of Zimbabwe for an integrated catchment management approach according to its new water act has been chosen to study the possiblities of the proposed GIS based approach for planning purposes in the field of water resources management. This catchment is characterised by a high variablity of rainfall and runoff on the one side, and by a high pressure on the water resources due to population growth, resettlement activities and land use changes on the other hand.

2.1 Physiographic properties

The development, management and planning of water resources is generally greatly influenced by the physiographic nature of the region. The Mupfure river basin (A=12,000 km^2) is situated in the central part of Zimbabwe and drains westwards into the Zambezi river. It is mainly characterised by a gently sloping terrain ranging between 750 and 1500 m aSl. The upper and mid parts are underlain by granitic rocks and are crossed by the Zimbabwean Great Dyke, which, however, does not form a pronounced relief. The lower Mupfure basin is characterised by more rugged terrain caused by a prominent rigde stretching NNE-SSW. The soils in the catchment are mainly fersialitic sand, loam and undifferentiated lithosols. The vegetation consists of Mopane and Miombo woodland-grassland associations; riparian vegetation is found along the river courses. The climate of the region is, due to its altitude and proximity to the Indian ocean, comparatively moderate. The catchment enjoys a hot and wet summer with high rainfall, mainly coming in December and January as heavy showers. The winters are very dry, cold at night and sunny and warm during the day. Generally, however, the region is characterised by a high annual variability of rainfall (MAP 750 mm), leading to severe droughts as well as floods [Mazvimavi 1998].

2.2 Socio-economic conditions

To understand the local management of and access to natural resources such as water and land, it is necessary to assess the land tenure system in the Mupfure basin. It resembles Zimbabwe's uneven distribution of resources and the population in general [Tevera 1994]. All of Zimbabwe's major land use classes occur in this region: communal lands (mainly subsistence farming, densely populated, underdeveloped, 30 %), large scale commercial farming areas (major water users, sparsely populated, economically important, 50% of the area) and small scale commercial farming and resettlement areas (20 % of the area, positioned between the communal and commercial land uses, strong potential for development, but little access to resources). Besides agricultural land uses, the other user sectors are in terms of water demand of minor importance, such as a few urban centres. Mining activities (mainly gold), however, play a considerable role as water users in the region.

2.3 Use and allocation of water resources

The new Zimbabwean Water Act from 1998 states a shift in water resources allocation priorities following the principles of Integrated Water Resources Management as described in Chapter 1.1, mainly to improve equity in access to water resources for all people, and to strengthen the evironmental demands. One of the major weaknesses of the former Water Act from 1976 was the water allocation on priority basis ("first come, first serve"), which in times of water scarcity led to unequitable sharing of the short water resources. There are more than 600 water rights in the Mupfure catchment [Madamombe and Merka 1997], both storage and abstraction rights. Those water rights are mainly found in the upper and mid catchment; the major proportion of them is held by large scale commercial farmers and used for irrigation purposes. In some areas, more than 90 % of the available water resources (mean annual flow) are committed to these water rights, not incorporating primary water demand, such as domestic use and livestock watering [Mazvimavi 1998]. Due to the policy change from a priority-based to a shared-based system, those water rights are now undergoing a regular review process, where demand (according to the priorities stated in the new water act) and availability of resources are being assessed, especially for dry period scenarios. To assist in the process of reviewing existing water use and simulate re-allocation of water resources according to planning scenarios, a GIS-based water resources decision support component is being developed.

3. METHODOLOGY

A catchment system can be described by acting objects of three different categories: (1) source components such as areas where surface and groundwater resources are produced as runoff or storage, (2) demand components such as irrigation fields, industrial plants and settlements, and (3) intermediate components such as treatment plants, irrigation return flow and other water-recycling facilities. A river basin system is made up of these objects and the relations between them, the water and substance fluxes. To integrate those components and inter-relationships for balancing and thus managing them, a network model consisting of nodes (representing the objects) and vectored links (representing the fluxes, such as rivers and canals) can be constructed and implemented in a GIS.

3.1 Integrating hydrological inflow

Since runoff generation, groundwater recharge and other hydrological dynamics are processes acting on areas, it is necessary to also use polygons within a catchment network model. In this approach, the hydrology of the areas is modelled externally in a physically-based, distributed hydrological model. The spatial distribution is based on Hydrological Response Units (HRUs). The generated runoff and groundwater recharge modelled on those units can be used as input attributes into the GIS, together with their reference units. Those HRUs are delineated by a knowledge-based GIS procedure including selection, reclassification and multilayer overlay, that, however, can be automated by statistical means. As result one obtains a pattern of distributed, fragmented modelling entities, all characterised by a unique combination of hydrological properties and parameters. HRUs are defined as „heterogeneously distributed modelling entities with common land use and pedo-topo-geological associations controlling their unique hydrological dynamics" [Flügel 1996]. This definition implies for each HRU, that the variation of the hydrological dynamics within it is

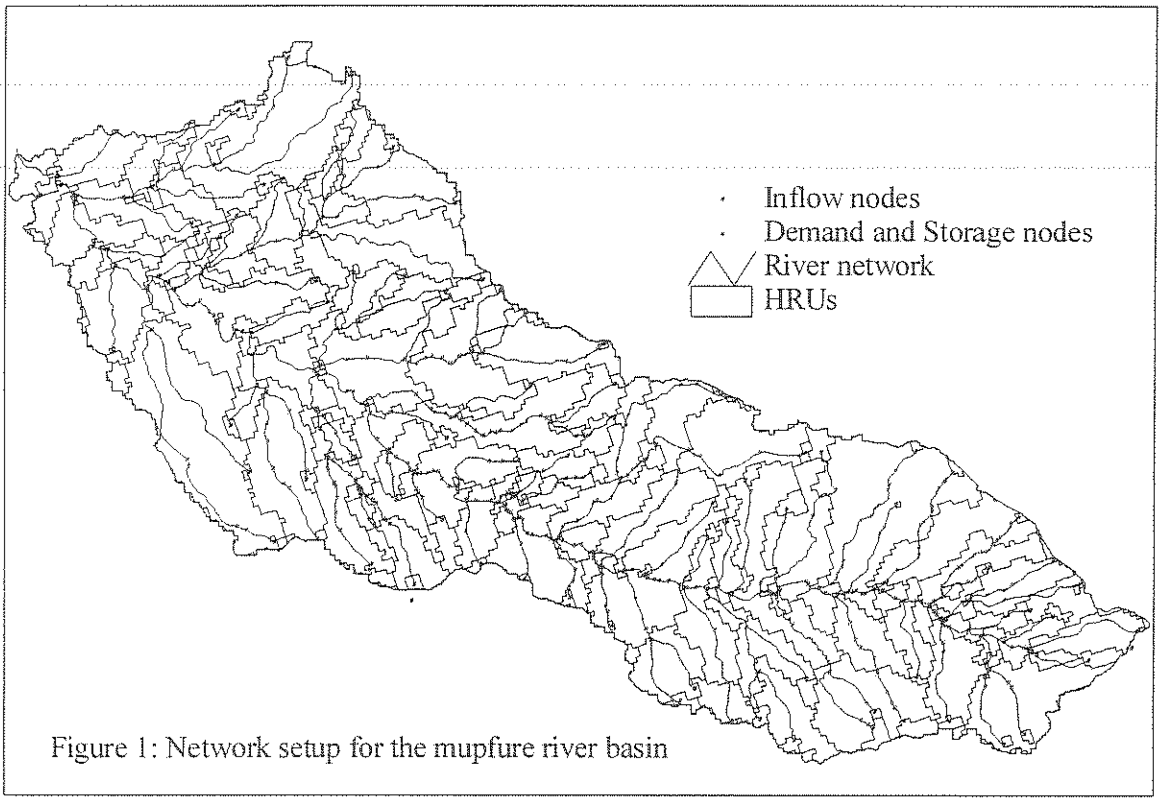

Figure 1: Network setup for the mupfure river basin

negligible if compared with the difference to a neighbouring HRU“.

The quantity and quality of runoff generated on those HRUs, modelled externally in a distributed physically-based catchment model, can be linked to the GIS by the framework system used. This rainfall-runoff model simulates the hydrological processes such as interception, evapotranspiration, infiltration, soil water dynamics, groundwater recharge and runoff generation splitted in the components surface flow, interflow and groundwater flow. These processes are modelled on a daily timestep on each HRU, depending on their physiographical properties.

These source areas representing the natural system's dynamics (runoff and groundwater recharge) have to be linked in a next step, since they might be distributed more or less arbitrary throughout the system, depending on the method used to delineate them; the relationships amongst these polygons might be unclear. By a special process of topology creation (developed as a GIS procedure), those polygons are converted into point objects and can be linked with each other and to the channel system in a topologically correct way (see figure 1), using digital elevation data only [Staudenrausch 1997]. The naturally generated runoff can now be routed through the areas (HRU's) and subsequently through the channel network downstream towards the outlet.

3.2 Creating a network

In such a network (figure 1), nodes represent all source, demand and intermediate components, no matter whether the length dimension of a component is significant or not. There are two kinds of links: on the one hand natural links, e.g. a link between two consecutive river nodes (the actual water course); the others are conceptual links, representing either the water supply-demand relations (e.g. a link between a reservoir node and a demand site node) or a node representing a runoff producing area. Therefore, links in the network are abstract objects, which only represent one node linked to another node and determine the direction of flow. However, attributes describing the flow impedance (e.g. Manning's roughness coefficient for river reaches), are necessary prerequisites for flow routing. Runoff gages can be used as nodes to validate or calibrate the network model results; reservoir nodes intercept channel flow for a while, increase it through releases or are used for water abstraction, which is also possible directly from the channels. The proposed method accounts for this by integrating these objects into the overall network model as objects that reduce or increase generated runoff during certain times, depending on season, by the proportion of its upslope drainage area of overlaying HRUs. Routines are

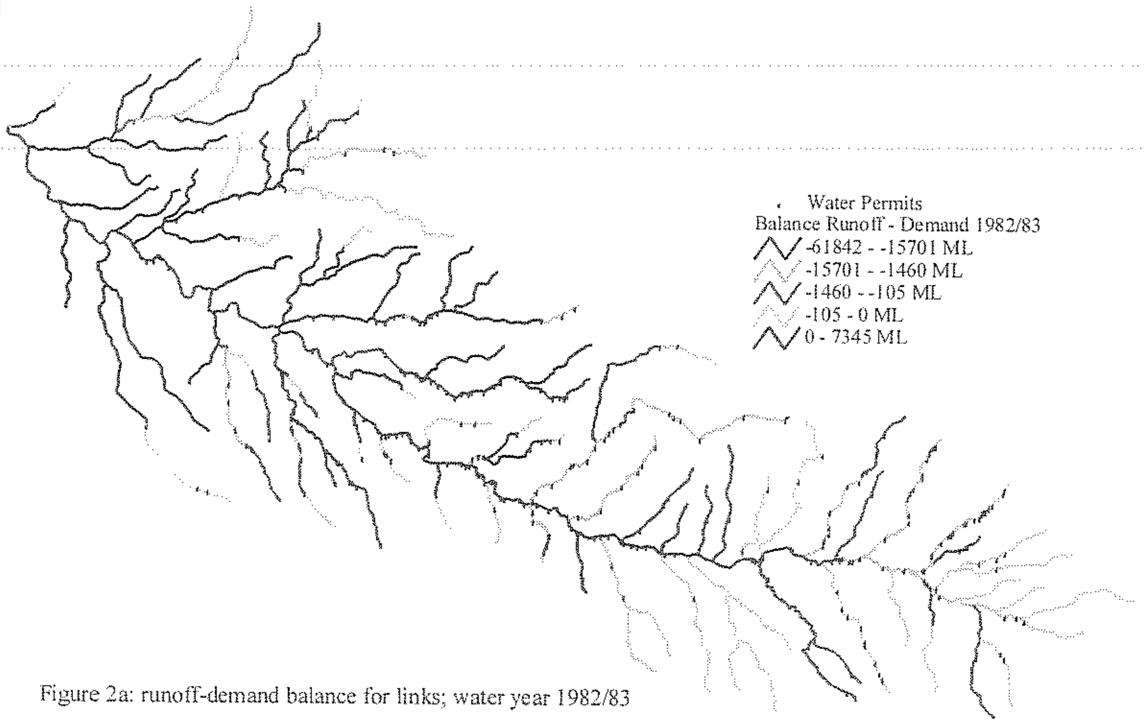

Figure 2a: runoff-demand balance for links; water year 1982/83

available to make use of ordinarily available geodata like rivers and water rights by checking and deriving connectivity of the network, snapping points to the network and convert them to nodes by splitting the links at the appropriate locations.

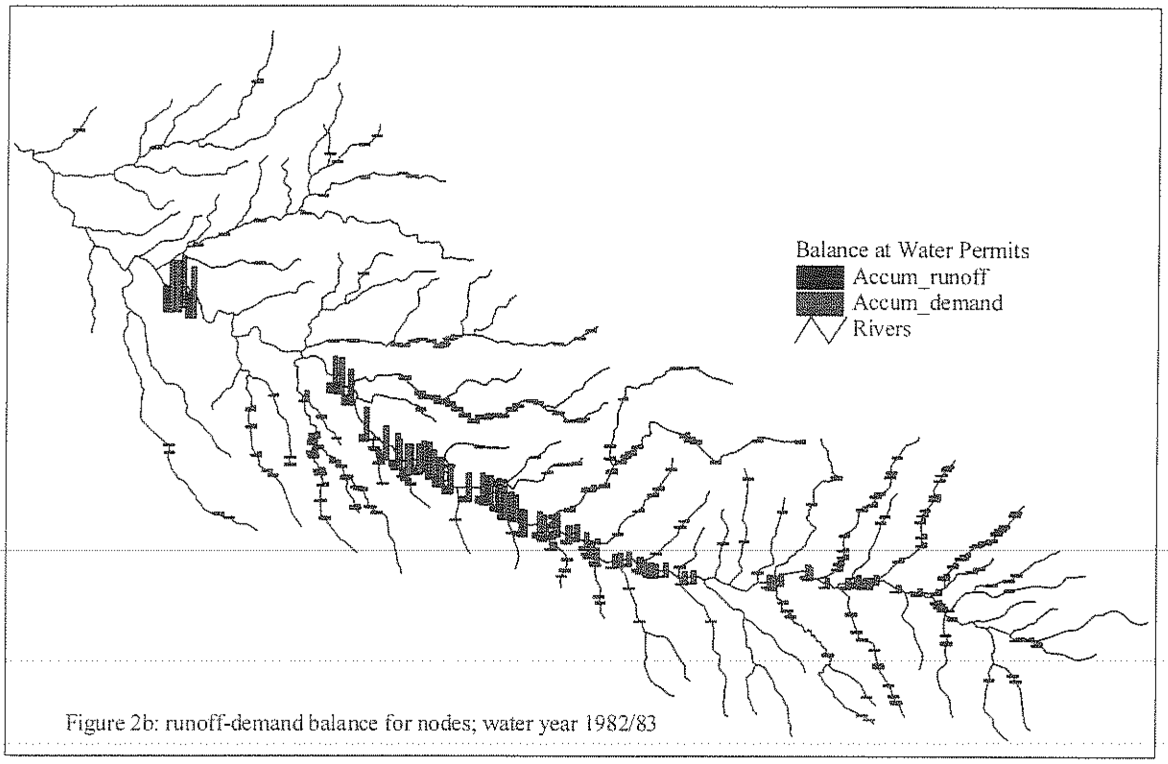

Figure 2b: runoff-demand balance for nodes; water year 1982/83

3.3 Tracing, accumulating and balancing water yield and demand

As the data model of the GIS used for this application (shapefile/ArcView©) has no explicite topology, an algorithm, that identifies the downstream neighbour of each link and stores it as an attribute, is used to establish link/node topology. When the topological connectivity of all water resources objects has been defined, up- and downstream tracing of the network can now be used to analyse water supply and demand at any object of the network for any given timestep.

By tracing and accumulating upstream, the water available at a certain site, both nodes and links, can be assessed, if the given demand will be met under the chosen runoff conditions. Tracing and accumulating downstream analyses, how much water has to be passed through, if all downstream demands should be satisfied. To model environmental demand, links of the network can be assigned with a minimum required flow that has to be met. By changing the node or link attributes, scenarios of water re-allocation, e.g. in drought situations, can be modelled. It is also possible to add new nodes or links to assess the feasibility of re-allocation of water to new users or constructing a water transfer and their impact on existing downstream users.

By using input runoff series of landuse or climatic change cases simulated by the external physically-based distributed catchment model, one can incorporate these scenarios into the water allocation analyses. Temporal aggregation of the input data can be applied to analyse seasonal or long-term effects (Figure 2).

The ease of use of this application allows users with relatively scarse knowledge to simulate scenarios by themselves. This could be of importance for the mediation of competing water users and demands within a participatory water board. The board representatives could perform online simulations to assess water allocation proposals immediately.

Figure 2a shows clearly, that water demand is met very differently throughout the catchment. Some sections, particularly on the main river are under enormous pressure, whereas other areas still have idle resources available. A thourough review of existing water permits in conjunction with other water demands (primary water use, environmental low requirements) is necessary and can be implemented by a toolset like the this.

4 CONCLUSIONS AND OUTLOOK

This study shows, that using a GIS in combination with a distributed hydrological model can be very useful for water resources planning purposes. By applying a desktop software, standard functionalities and a user-friendly graphical interface implementing all functions, this application becomes a tool for online water allocation scenario modelling to be used by a stakeholder committee in order to facilitate mediation between competing water users.

The application of a mathematical optimisation routine could be another option to find the best solution to allocate water in times of shortage following given rules and priorities, such as:

- minimize the differences of water shortage among the demand sites,
- maximize the downstream flow in the main river.

The full potential for water resources management, though, is revealed only as application within a framework system as explained in Chapter 1.2.

5 ACKNOWLEGDEMENTS

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