



Spatial Hydrological GIS Analysis and Estimations of Runoff in Khor Gowb Drainage Basin in the Red Sea State –Sudan

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Abstract: The magnitude and availability of surface waters in Khor Gowb of the Red Sea State was examined using spatial hydrological analysis in Geographical Information Systems (GIS). As a system with advanced geo-modelling capabilities, GIS is used to integrate spatial analysis with hydrological modelling. Several levels of spatial hydrological modelling such as parameterization, spatial integration, regionalization and assessment of hydrologic problems were made. Four physical / deterministic and stochastic models were developed and applied at both catchment's and regional scales to estimate the water volume of many drainage basins in the area. The results evaluated using the general error term to compute the differences between the estimated areal runoff and the observed runoff in the Khor Gowb drainage basin in Erkowit area of the Red Sea State. Accordingly, one stochastic model has been tested and regionalized. The significance of the catchment and regional runoff estimates was evaluated in relation to errors inherent in the spatial database, GIS analysis, and hydrological modelling (e.g., the Rational Formula). Finally, it is concluded that Khor Gowb basin and the Red Sea State at large, contributes an annual surface runoff that exceeds the human and animal needs with a considerable surplus that can be used for agriculture (i.e., the region is water sufficient). Conversely, this sufficiency is limited by the problem of spatial distribution and related storage difficulties. With regard to human, animal and agricultural water supply, only few catchments can support the proposition of water sufficiency in the State.

Keywords: *Red Sea State; spatial or geographical hydrological analysis; GIS; deterministic and stochastic hydrological models; water resources; water sufficiency and deficiency.*

1. INTRODUCTION

In arid regions i.e. the Sudanese Red Sea State, hydrological systems, including surface runoff, are sensitive to aridity and dryness/drought occurrence and persistence. Naturally, in the study area, water resources are highly dependent on rainfall regime and surface configuration and structure. This situation reduces retention capacities and water storage, and releases most of the runoff water to the Red Sea or the Nile systems/basins. Hence, water systems require more studies and construction of a regional model to consider the hydrological components and characteristics of water systems and use requirements of e.g., humans and animal at both spatial and temporal domains. Furthermore, there is a need for an integrated, systematic and regional analysis of the hydrological systems in the state. The ordinary empirical hydrological models, however, can partially aid in estimating surface water magnitude. Respectively, much is to be done with regard to parameterization, data collection

and generation, characterization of components and linkages of the system, calibration, scaling (catchment-regional), synthesis and integration.

In this context, three questions were raised. The first one is; how to render the geographical or spatial analysis more useful in surface water investigations? The second is; how to use and link the results of surface hydrologic analysis and modelling to other hydrologic systems? And the third one is; given the complexity of hydrological systems, can a geographical information system (GIS) be effectively used and applied in arid lands hydrological research as an indispensable method and means for surface water quantification?

Geographical (*spatial*) hydrology or the geographical approach to hydrological problems based on contemporary development in Geographical Information Systems (GIS) can be applied in the study of surface hydrology in arid lands.. Such developments were inspired by:

1. Recent trends in geographical and hydrological research and the role of geography (geographical hydrology) in hydrological research¹.
2. Many geographical studies in the Sahel *e.g.*, desertification and climate, have revealed the need to emphasize aspects of geographical analysis such as geotechnologies, geographic indicators and regional studies²⁻³⁻⁴.
3. The implementation of some water management projects in Eastern Sudan (Tokar Delta Agricultural Scheme, Arbaat groundwater yards and Khashm Al-Girba Dam) has developed some socio-ecological management difficulties⁵⁻⁶⁻⁷⁻⁸⁻⁹.

Geographical Information Systems/Science (GIS) integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically or spatially referenced information. The technology works on different levels and sizes of databases and uses various types of programs and software. The spatially based technology can help to answer questions about location, occurrence, adjacency, cause-effect, mapping, integration of information and visualization scenarios, in addition to handling complex issues and develop effective solutions for decision support¹⁰⁻¹¹.

2. Material and Methods

The Sudanese Red Sea State includes the hilly and coastal parts of Eastern Sudan. In the south-eastern part of this region, an area of about 7000 km² between latitudes 18° 30' 00"-19° 05' 00" N and longitudes 36° 30' 00"-37° 30' 00" E is focused including the Khor Gwob drainage basin (350 km²) for study. The analysis area is covered by 1:250 000 [(N. E. 37-A) and (N. E. 37-E)] and 1:100 1000 [(165-N. E. 37-A-5), (166-N. E. 37-A-6), (193-N. E. 37-E-2), and (194-N. E. 37-E-3)] map sheets¹²⁻¹³⁻¹⁴⁻¹⁵⁻¹⁶. Unlike other water systems *e.g.*, Khor Arab and Khor Arbaat, the Gwob catchment falls entirely within the study area (**Fig. 1**). Relatively long and continuous discharge records since 1958 cover the catchment. The gauging station at Khor Gwob is located at a point in the Gwob gorge with a cross-section c. 50m wide, c. 40 m deep and relatively level bed, covered by coarse sandy alluvium. The gauging station (*Gwob A*) is located approximately 200 m *a.s.l* in the Gwob gorge (Lat 19 00 00 and Long 37 20 00). For better gauging, the station was transferred at the same elevation as station A to a location about two kilometers upstream and renamed *Gwob B*. According to SRWC gauging files, the *Gwob A* site has a recording period from 1957-1975 while *Gwob B* has operated since 1975 (**Fig. 2**, **Fig 3**). With respect to both stations, only 18 years between 1957 and 1980 have no data gaps. The measurement was performed during the flood seasons in summer and winter (June-January). The flood level is read each quarter an hour and the mean velocity is computed¹⁷. Some physical (*e.g.*, changing channel cross-section area) and empirical measurement problems (such as flow fluctuation), and human errors in the runoff gauging were mentioned¹⁸.

2.1 Objectives

The status of the region's surface waters has been examined by much research contributed by hydrologists, hydrogeologists, climatologists as well as other geographers and civil engineers¹⁹⁻¹⁷⁻²⁰⁻²¹⁻¹⁸⁻²²⁻²³.

The research objective is to examine the views coined by these studies about the status of surface waters in the arid/semi-arid Sudanese Red Sea region. In this respect, there are two major views:

1. The region has no deficiency in water resources. Rather, the problem is formed by the uneven spatial and temporal distribution of surface water, and other technical problems. These difficulties are solvable only through intensive local management to improve information and actions in recharge/discharge relationships, storage and distribution²³.
2. Irrespective to the various evaluations, the Red Sea area is a water deficient. Therefore, a regional hydrologic program is needed. That is to say, importing more supplies from different potential drainage systems within and outside the region (*e.g.*, Tokar Delta, River Atbara and River Gash). This is regarded possible through *e.g.*, surface engineering and flow modification (divergence and linkage). Although it sounds achievable, these propositions sound costly¹⁹⁻¹⁸.

To achieve the objective, surface water estimation and analysis in GIS was made to:

1. Estimate monthly rainfall and evaporation as key atmospheric elements of the surface water system;
2. Develop spatial and hydrological models to estimate monthly runoff and infiltration;
3. Quantify the catchment and regional runoff as well as to synthesize the region's surface water resource.

2.2 Previous Surface water studies

Previous surface water investigations in the area are few. Much of the work is in the form of surveys or inventories. Some reports on surface-and groundwater have been produced through joint projects with some international groups studying water resource and the growing demand for fresh water from the ports. Within the Red Sea Area Program (RESAP), Musa²³ briefly addressed the regional issue of surface water in his investigation of the potential water resources in the region. The frequency distribution method is used to estimate rainfall depth. He then estimated district runoffs at different probabilities by using estimated runoff coefficients (0.02-0.13), infiltration coefficients and discharge records. The study showed the need to evaluate the influence of landforms, slope, soils, evaporation and vegetation that have been lumped or link-lumped in the estimation of runoff coefficients particularly in the ungauged areas. The results revealed adequacy of runoff waters (at different probabilities) enough for a higher

demand. According to the study, the uneven distribution of surface water over time and space is a problem that can be solved by developing the storage and distribution systems.

In another study, Hobler *et al.*¹⁸ compiled a report (for the Bundesanstalt für Geowissenschaften und Rohstoffe) summarizing the results of a Sudanese-German Exploration Project on ground and surface water resources in the coastal area of the Sudan. The project area covered about 90,000 km² between the Red Sea basin and the Nile basin water divide. The area has been investigated from hydrological, hydrogeological and engineering points of view. The study investigated several catchments including the Khor Gwob. The report constitutes two parts. The first includes the reconnaissance of water resources, while the second part covers water problems in relation to the ports and addresses possible solutions. The report concluded that water demand exceeds the present water supply in the Red Sea.

Other studies and mapping of the surface include geomorphology, geology, soils, and plant cover. Brief geomorphologic accounts are found in some geological studies and reports. The geological studies include general and specific descriptions, contributed by many²⁴⁻⁶⁻²⁵⁻²⁶⁻²⁷⁻²⁸. Detailed field descriptions about soil in relation to hydrology were not identified by this research. The vegetation cover is documented by also by many²⁹⁻³⁰⁻³¹⁻⁶⁻³³⁻³⁴ besides the RESAP botanical study group³⁵⁻³⁶⁻³⁷⁻³⁸. The paucity of earlier research makes it difficult for this research. There is a need to establish and re-evaluate the many components of surface water hydrology in the area. This, for example, is considered in the parameterization of runoff and infiltration. Nonetheless, the figures provided by Musa²³ and Hobler *et al.*¹⁸ can be regarded useful in relation to modelling, calibration and the general synthesis of surface waters.

2.3 Material

Ideally, surface hydrological research demands various types of data sets. Broadly speaking, the required data sets include geographical, geomorphologic and hydrological information. However, the data set has been derived from both field and non-field sources. The set includes surface data and thematic maps, Landsat TM images, soil data, time series (discharge and meteorological data) and other estimated figures from previous research. The fieldwork was designed to observe and measure surface conditions and structures. Field observations were linked to field base-maps. The units identified include; the coastal plain, Erkowit/Bramyou plateau (Karsaqa plains), the eastern forelands, the sand zone, the western forelands, the high regions, the highlands' basins, the alluvial plains, and slope regions. The sampling size was determined by the size of the class, degree of variation, stratification criteria and accessibility. Under no circumstances was the number of samples per stratum less than 35. Within a unit, the samples were selected to represent the real variations within the observed class *e.g.*, alluvial. Over 310 GCPs (Ground Control Points) for every 5000 meter interval along

predetermined field traverses were recorded using a Global Positioning System GPS. Approximately 300 TAs (Training Areas) were registered in the field. The GCPs and TAs were used in the geometric correction and the supervised classification of the Landsat TM images. The observed and measured parameters included surface structure; soil texture and vegetation cover density.

Morphometric features such as wadi cross-sections were measured³⁹. Depth to sub-surface water at some well sites was measured. The field mapping was based on geomorphologic and thematic maps, which are considered as systematic recordings of all pertinent hydro-geomorphic characteristics of the area's land units. Photographic data of surface cover elements (*i.e.* geomorphology, soil and plant cover) was obtained. Other data included the following:

- a. Topographic maps (1:100,000 and 1:250,000) and a 1: 200,000 geological map.
- b. Landsat TM April 1990 images (digital and hard copy).
- c. Monthly rainfall (26 stations), evaporation and temperature (9 stations) records for the period 1950-1979 (data after 1979 are either not available or incomplete).
- d. Hydrological records for Khor Gwob catchment 1958-1981 (data after 1981 are either not available or incomplete)
- e. Evapotranspiration estimates.

The acquired data stored in GIS database files (*e.g.*, digitized map layers and coverages, image files and tabular files). With the exception of rainfall data, evaporation, discharge and infiltration data are incomplete, not standard or not available. The data analysis methods included image classification, surface mapping, geo-statistics, DEM, map algebra.

2.4 Methodology and Analysis

GIS spatial hydrological analysis and modelling methods and techniques were used. The analysis considered the smallest surface units or grid cells as fundamental parts of the system. Within these units many attributes and physical hydrological relationships (spatially and temporally) have been defined. The implementation of the models was carried out in these units and their aggregated classes and quantitative hydrological values *e.g.*, water magnitude. Using the appropriate parameters, the spatial models aim at quantitatively explaining the runoff and infiltration relationships within the fundamental spatial unit or grid cell. The explanation was inferred from five independent physical attributes and twenty classes. The explanations are based on the attribute hydrological characteristics (physical) and frequency distribution of class grid cells and class runoff contribution rank (stochastic).

Runoff and infiltration generalized concepts, measurements and methods were used to weight the areal magnitude for each spatial cell from the parameterized catchment inputs.

The generated weights are used as scalars in the construction (from slope, roughness, soil texture, soil moisture and plant cover images) of Geographic Runoff Capacity Index (GIIC) for Khor Gwob catchment. The index layers were coupled to monthly rainfall depth to quantify the monthly areal runoff and infiltration magnitude at a catchment level. Using the physical, stochastic (semi distributed) and lumped (derived from 8 and 12 month floods) models, the monthly areal runoff magnitudes in the Khor Gwob catchment are estimated. These models are coupled in a GIS to the hydrological Rational Formula.

Excluding the lumped models, the mean monthly runoff differences from the measured (obtained from the four physical and stochastic models) are ranked in a descending order as follows: The *Std* (0.003 m m^{-3}), the *Sta* (0.052 m m^{-3}), the *Pha* (0.232 m m^{-3}) and the *Phd* (0.242 m m^{-3}). Followed by the *Sta* (0.052 m m^{-3}), the *Phd* (0.242 m m^{-3}) and the *Pha* (0.232 m m^{-3}) models, the stochastically explained runoff coefficient (*Std*) model based on the dominant class contribution shows the minimum difference in the set (0.003 m m^{-3}), and can therefore be a possibility to apply. The *Std* model is used to estimate runoff in the ungauged lower parts of the Khor Gwob catchment as well as in the estimation and mapping the monthly runoff magnitude in the whole Khor Gwob catchment. Furthermore, the *Std* model has been implemented in the Sudanese Red Sea region at both catchment and regional scales. Though stochastic, the *Std* model strongly linked through class ranking system to the runoff relationships of the five physical attributes used in modelling the surface contribution to runoff in the region.

The model inputs-outputs are spatially and temporally changing and dynamic. The *Std* model is a spatially defined linear rainfall-runoff weighting model and linked to the Rational formula. Hence, the formula is better implemented in terms of spatial and physical characteristics of runoff coefficients. The validity of the catchment and regional estimation of runoff in region was evaluated in terms of errors inherent in spatial databases and GIS analysis (e.g., GIS error propagation). In addition, the systematic and random errors that are inherent in hydrological models (e.g., the Rational Formula) were also discussed, considering the spatial generalization (e.g., from catchment to a region) of these models. The generalization of model and the arrangement of spatial units show that every individual unit has likelihood to be hydrologically characterized. Two possibilities of characterization are distinguished. The first one explains that the simple (or less distributed) rainfall-runoff models tend to aggregate (largely) heterogeneous units into a larger homogenous unit by means of simple averaging, *i.e.* no satisfactory spatial-physical characterization takes place. In the second possibility, the spatial model developed by this research recognizes the hydrologic contribution of every individual pixel with more attribute classes develop when the surface area increases; and the generalization of the model in similar conditions *e.g.*, the Red Sea region is possible.

3. Results

3.1 Mapping and modelling of climatic, surface and hydrological characteristics

The analysis has provided basic thematic information about the surface characteristics in the study area. At this point, twenty-four monthly rainfall and evaporation layers and five surface layers (*e.g.*, slope, surface roughness, soil texture, and plant cover) have been prepared (**Fig 4**, **Fig 5** and **Fig 6**). Using empirical data and estimated figures, these primary and intermediate data layers are used by the GIS to estimate the areal monthly runoff and loss to infiltration in the region.

3.2 surface runoff estimations in the Red Sea State

A runoff coefficient *K* or *C*, represents the percentage runoff produced by an input rainfall in a particular area. Empirical runoff coefficients are determined to estimate runoff in catchments of varying surface properties. Richards ⁴⁰ estimated *C* values between 0.80-1.00 for rocky and impermeable cover types, 0.60-0.80 in slightly impermeable or bare cover types and 0.40-0.60 in slightly permeable, partly cultivated or vegetated cover. In cultivated absorptive soil, sandy absorptive soil, and heavily forested catchments, *C* values range between 0.30-0.40, 0.20-0.30, and 0.10-0.20 respectively. Considering space and time variations, these figures can be used for comparison of the hydrological behaviour of the various surface covers.

The methods and results of two previous studies in the area are reviewed. The first study by Hobler *et al.*¹⁸ carried out in $90\,000 \text{ km}^2$ study area in the Sudanese Red Sea region. They found poor correlation between annual rainfall and annual runoff due to the effects of spatial and topographic variation. The authors concluded that this problem is evident for shorter (seasonally, monthly or daily) intervals. Nonetheless, they used the correlated annual runoff coefficients to generate the mean runoff coefficients for various catchments in the study area. The values 0.140, 0.044, 0.036 and 0.023 are assigned to Khor Gwob, Khor Odrus, Khor Arbaat and Khor Arab respectively as catchment runoff coefficients. In the second study, Musa ²³ has computed the actual annual runoff coefficient (by relating discharge to rainfall depth *e.g.*, ⁴¹) for Khor Gwob, Khor Odrus, Khor Arbaat (including Khor Odrus) and Khor Arab as 0.130, 0.051, 0.093 and 0.026 respectively. With regard to catchment characteristics, He included soil, slope and vegetation cover. Generally, he concluded that the ground surface is rocky, of low infiltration capacity, rainfall is of high intensity and of short duration, the slopes are steep, and the ground surface is bare. In a generalized statement, he suggests, "the conditions are highly favorable for runoff" in the Sudanese Red Sea Region, and this is supported by the fact that the region is intersected by numerous watercourses.

As for this study, the coefficients and the models from mapped and modeled climatic and physical factors are used

to quantify the monthly surface waters in the Khor Gwob catchment. The estimated runoff is compared with the observed discharge records from the catchment. The model is used to quantify monthly runoff in the whole catchment area and to estimate the regional monthly runoff in the whole study area. Problems of error (and estimation differences), model reliability and generalization (the regional context) are also considered.

3.3 The catchment and regional runoff quantification:

The weights generated are used as scalars in the construction (from slope, roughness, soil texture, soil moisture and plant cover images) of Geographic Runoff Capacity Index (GIRC) for Khor Gwob catchment. The index layers are coupled to monthly rainfall depth (Fig 5) in order to quantify the monthly areal runoff and infiltration magnitude in the catchment. Using the physical, stochastic (semi-distributed) and lumped (derived from 8 and 12 month flood contribution) models, the monthly areal runoff magnitudes (in m^3) in the Khor Gwob catchment are estimated. These models are linked in a GIS to the hydrological Rational Formula. Figure (3) shows monthly measured mean discharge (1961-1979) and estimated mean rainfall in the Khor Gwob catchment.

3.4 The performance of the Model

With regard to the predefined goals of the study, the question (in relation to the estimated and the observed) is which of the deterministic (or physical) and the stochastic models performs the best. Four models, however, are evaluated and one model is selected to quantify the runoff magnitudes at the catchment and regional scales. In hydrological research, model verification involves, for example, comparison of the observed values with the modelled or simulated ones. Respectively, the less the difference between the observed and the estimated values, the more valid is the model. Comparisons of runoff (annual, seasonal, daily and hourly flows) volumes and distributions have been recommended by the Stanford Watershed Model, as steps towards model verification⁴². This usually applies many types of goodness-of-fit measures such as:

$$F1 = \sum_{i=1}^n (Q_{obsi} - Q_{predi})^2 / n \quad (1)$$

where $F1$ is the objective error function, Q_{obsi} the observed discharge at time i and Q_{predi} is the predicted discharge at time i , while n is the number of observations.

A simple comparison between observed values and the model simulations (in the form of deviations (\pm) between observed and the modelled) using the general error method is a valid verification procedure. The general error term is an absolute difference between the observed and the predicted values. The magnitude of the total error e_r could be assessed as the difference between the observed value

(or true value), x_o , and the best estimate, x' , can be, according to Davidson⁴³, included in a simple formulation written (similar to eq. 2 when rewritten) as:

$$x' = x_o \pm e_r \quad (2)$$

Finally, the *Std* model is used to estimate runoff in the lower ungauged parts of the Khor Gwob catchment as well as in the estimation and the mapping of the monthly runoff magnitude in the whole Khor Gwob catchment (Fig 6). Furthermore, the *Std* model is applied to estimate the monthly regional runoff in the 26 catchments of the study area. (Fig 7, Fig 8).

Out of the four alternative physical and stochastic models, the *Std* model has been implemented in the Sudanese Red Sea region at both catchment and regional scales. The *Std* is a stochastic model, but strongly linked via class ranking system to the runoff relationships of the five physical attributes used in modelling the surface contribution to runoff in the region. Its inputs-outputs are spatially and temporally (monthly) dynamic. The *Std* model is spatially defined as a linear rainfall-runoff weighting model that is linked to the Rational formula. Hence, the Rational formula is better implemented in terms of spatial and physical characteristics of runoff coefficients.

Accepting the Lane and Nichols⁴⁴ evaluation, the uncertainty and complexity of the Rational Formula is considered reasonable. As for the model systematic error, the spatial modelling used to improve the estimation of runoff coefficients C from five surface attributes is regarded a further step toward the reduction of such an error.

To apply the model regionally, problems that may arise from generalization need consideration. The spatial units and their resolution levels range from grid cells (e.g., 500 m^2) to regions (e.g., $n \text{ km}^2$). The arrangement of units shows that every individual unit has the likelihood to be hydrologically characterized.

3.5 The Surface water allocation in the study area:

Within a geographical hydrological framework, the thesis' main concern is to examine and compare the different viewpoints about surface water *sufficiency* and *deficiency* in the Sudanese Red Sea region. The implementation of the research methodologies at both the catchment and regional scales reveal the following:

1. The study-estimated total annual runoff in the study area approximates 100 million m^3 and ranges from $0.39 \cdot 10^6 m^3$ (minimum) in catchment No. 26 to $13.9 \cdot 10^6 m^3$ (maximum) in catchment No. 12.
2. The daily human and animal water need in the Sudanese Red Sea region is estimated as $0.035 m^3$ and $0.030 m^3$ ²³. With regard to the size of human and

animal population the annual amount of water required would be 2299500 m³ and 1916250 m³ respectively. According to Musa ²³, one acre (0.96 feddan or 0.40469 hectare) in the study area requires about 300 m³ for cultivation purposes. Considering these figures, the following can be stated:

- a. Catchments No.8, 11, 13, 20, 9, 3, 1 (or Khor Gwob), 10, 7, 14, 5, and 12 contribute annual runoff that can support either estimated human or animal water needs. Only catchments No. 9, 3, 1 (or Khor Gwob), 10, 7, 14, 5, and 12 contribute annual runoff that can support both the human and the animal requirements in a year.
- b. Considering agriculture water requirements only catchments No. 3, 1 (or Khor Gwob), 10, 7, 14, 5, and 12 contribute to runoff that can support, in addition to human and animal water supply, the cultivation of land that ranges from 3000 to 30 000 acres (1214-12140 hectares). Nonetheless, the whole region contributes annual runoff that supports both the human and animal water requirements with a surplus that can irrigate about 300000 acres (121407 hectares).
- c. The area of potentially arable lands (of fine alluvial, coarse alluvial and alluvial sands) may total about 2131.6 Km² (526716.7 acres or 213157 hectares). If we assume that only half of this area can be utilized, the annual runoff in the region can support small scale agro-pastoral schemes.

Finally, it is concluded that the study area in particular and the Sudanese Red Sea region in large, contribute annual surface runoff that exceeds the human and animal requirements with a considerable surplus that can be used in agriculture (*i.e.*, the region is water sufficient). Nonetheless, this sufficiency may face the problem of spatial distribution and related storage problems and feasibility. With regard to human, animal and agriculture water supply, only few catchments can support the proposition of water sufficiency in the region.

4. Discussion

4.1 Hydrological research and modelling in aridlands:

Hydrology is a multi-disciplinary research field that investigates and manages water in different forms at different positions near or on the land surface for different purposes. This definition is incorporated in many views provided in e.g., ⁴⁵⁻⁴⁶⁻⁴⁷⁻⁴⁸⁻⁴⁹⁻⁵⁰⁻⁵¹⁻⁵². Irrespective of the growth of hydrology as a specialized science, hydrological research reflects different theoretical-empirical, pure-applied, micro-macro, systematic-operational, and geographical-non-geographical interests.

Generally, hydrological research and modelling are interrelated. For reasons, most of hydrological research concentrates on modelling as an approach for a simplified,

representative and logical presentation of hydrological system/s. As well, most hydrological modelling processes depend mainly on the knowledge drawn from available measurements and experimental results. Hydrological models are often referred to as 'hydrological systems' ⁵⁰. Models of hydrological systems may be designed to explain and represent the behavior and relations of the input and output of the system in many ways.

The typology of these models is broad and varying due to many reasons such as the type of modelling approach. Hydrological models can be parametric (e.g., statistical regression technique), analytical (systems analysis) or mathematical (physical analysis). Further, these models can be either stochastic conceptual, stochastic empirical, deterministic conceptual or deterministic empirical. The models can be systematically sorted as linear or non-linear models, or spatially classified as lumped models or distributed (probability or physical) models. ⁵³⁻⁵⁴⁻⁵⁵.

The large number of variables and complex interactions in hydrological systems makes no one modelling approach as absolutely superior over the others. Deterministic models ⁵⁴ are complex and their physical mechanism and relations are fixed. Alternatively, the randomness of hydrological processes and the uncertainty about hydrologic systems or their very complex behaviour are sometimes handled by using stochastic modelling. Nonetheless, these approaches involve an 'averaging' of the behaviour of a simply represented system ⁵⁶. The empirical and analytical approaches to modelling catchments, may offer better solutions to some of these problems. Nevertheless, the implementation of results from catchment A for example, in catchment B may not be possible without altering original terms of a model.

Another type of hydrological modelling which has been recently emphasized (also computer-based), is distributed modelling. Distributed models explicitly describing the hydrological problem as a function of location in a continuous manner. The "word 'distributed' implies that the hydrological status varies significantly over the land area in question" ⁵⁷. Distributed models are time dependent and require rare data (particularly in ungauged catchments). Anderson and Rogers ⁵⁸ argued that the potential turning point in research has been provided by distributed catchment hydrology.

Most of the distributed models are physically based catchment scale models in which the catchment can be analysed and the variables and parameters defined in the field ⁵⁸⁻⁵⁹. Catchments are treated as spatially variable systems with input variables, parameters and predictions dependent on their location (Anderson and Rogers, 1987). Different semi-distributed and distributed approaches have been developed. For example, to simulate soil moisture depletion and spatial variation, Beven and Kirkby ⁶⁰ used basin morphological characteristics, while Quinn *et al.*, (1989) used terrain analysis to derive a topographic parameter.

DeVries and Hromadka ⁶¹ reviewed some computer-based single-event models (CSEM) and computer-based continuous models (CCM) of surface water. The review covers model development and purpose, required input, computer demands and how to access these programs. The CSEM group includes the HEC-1 flood hydrograph package of the Hydrologic Engineering Centre of the US army Corps of Engineers, the TR-20 rainfall-runoff model of the US Soil Conservation Service, and the DRM3 rainfall-runoff model of the US Geological Survey (USGS).

On the other hand, The (CCM) group include PRMS precipitation-runoff model of the USGS, the physical distributed-parameter SHE model of the joint Danish Hydraulic Institute, the UK Institute of Hydrology and France's SOGREAH. Bergström ⁶² describes the Swedish Meteorological and Hydrological Institute HBV runoff (CCM) model. For more theoretical descriptions and examples of distributed models, one may refer to Beven and O'Connell ⁶³, Beven ⁶⁴ and Anderson and Rogers ⁵⁸.

4.2 Spatial hydrology

The area of spatial hydrology may cover different elements such as developing a Spatial hydrology model, time and spatial domain, modeling procedure, processing Digital Elevation Data, standardized approach to watershed delineation, time averaged hydrologic modeling mean annual flow, non-point source pollution assessment, time varying water balance models, atmospheric water, soil water, groundwater, surface water, and water Utilization ⁶⁵ ⁶⁶. Briefly, GIS can perform several levels of hydrological modelling such as follows:

- a. Parameterized and indexed intermediate layers. .
- b. Integrating different hydrological models by linking of different sub-systems (or micro models). For the environmental modelling (including hydrology) should start with simple 'micro models' where few input variables are incorporated. These micro models are efficient enough to generate relevant data for research
- c. Regional hydrology. Regional hydrological assessment is a growing interest (EosSSC, undated) and ⁶⁷ that gives GIS another link to hydrological modelling. Besides encouraging independent regional models,
- d. Within GIS, polygonal areal hydrological models can be constructed. This may incorporate some steady flow and areal models where the unit areas are given weights according to the associated determined hydrological parameters ⁶⁸. Moreover, the system analysis, structured as a 'rule-based' procedure ⁶⁷ might serve as a framework for a hydrological expert system and can be a powerful future tool in regional hydrological research.

4.3 Errors in GIS data, analysis and hydrological models

Errors due to the observer, instrument, measurement conditions, nature of the observed phenomenon and sampling ⁴³ can be traced into scientific evaluations. Errors exist or arise in spatial data as a result of the quality and quantity of observations, the effect of natural and spatial variations and the nature of data processing such as classification, interpolation, overlay analysis etc. ¹¹. Some contributions for assessing and modelling these kinds of errors have been made (i.e., ⁶⁹). Assessing error in spatial databases, Hunter and Goodchild ⁷⁰ point out that due to the growing diversity of applications and the number of spatial processes, "there can be neither a single all embracing error model for spatial data, nor any one optimum method for presenting error".

With respect to inherent errors in spatial databases and their manipulation, two issues should be considered. The first is that it is beyond the interest of this research to question the problem with the availability and appropriateness of the original spatial data. Nonetheless, much has been done to reduce such a problem. Errors concerning geomorphometric, classification, interpolation and DEM analysis has been dealt with. Nonetheless errors that arise due the multilayer analysis have been considered insignificant or ignored ⁷⁰. Lane and Nichols ⁴⁴ address complexity, uncertainty and systematic errors in mathematical hydrologic models (e.g., rainfall-runoff models). They evaluated three infiltration models (Phi Index, Runoff Curve Number and the Green-Ampt Infiltration equation) and the Rational Formula and the coupled Green-Ampt Kinematic Wave Model (for discharge estimation).

4.4 Conclusions

4.4.1 Concerning Aridlands' hydrology

- a. Rainfall analysis can be modelled stochastically.
- b. The partitioning of the input rainfall is highly determined by the surface.
- c. Thus the Horton's overland flow concept (which is mainly dependant on rainfall conditions) can be checked with regards to the fundamental hydrologic system equation ($input = output + \square storage$). Respectively, the Rational Formula ($D = CR_iA$) can be applied if the runoff coefficient C is spatially (xy) and physically (input attributes) distributed (i.e deterministic approach).

4.4.2 Concerning the model

- a. It fulfils the above arguments.
- b. It improves the systematic representation of the RF.
- c. It gives the ability to generalize from small surface units (i.e. $500^2 m$) via sub-catchment and catchment to regional levels.

- d. It reduces the demand for i.e. discharge data (which is either incomplete or not available).

4.4.3 Concerning the region's surface waters:

- a. Sufficiency/deficiency is proportional to use. On regional level there is considerable amount of water. Nonetheless the sufficiently of surface water cannot be separated from the subsurface storage.
- b. On regional level there is good potential level, but it is bound to spatial and temporal distribution in relation to particular demands.

4.4.4 Concerning the region's surface waters:

- a. With reference to section 6.6, it is concluded that the study area in particular and the Sudanese Red Sea region at large, contributes an annual surface runoff that exceeds the human and animal requirements with a considerable surplus that can be used in agriculture (*i.e.*, the region is water sufficient).
- b. Conversely, this temporal sufficiency is faced with the problem of spatial distribution and related storage problems (such as evaporation and silting). With regard to human, animal and agricultural water supply, only few catchments can support the proposition of water sufficiency in the region.

4.5 Recommendations

What future research is expected to do:

Water balance models have been used to compute the geographic and seasonal patterns of soil moisture and streamflow/runoff predictions *etc.* at different time steps and areal delineation *e.g.*, catchments⁷¹. No attempt is made by this research to construct a water balance for the region because of the problem of estimating the actual evaporation from the PET estimated earlier. For PET, the study estimate (spatial modelling) is very matching to the observed than those produced by Awadalla²² and Hobler *et al.*,¹⁸ (who applied aerodynamic methods)⁷²⁻⁷³.

Secondly, evaporation estimates, whatever their accuracy is, represent the potential not the actual evaporation, with the later being of much direct concern to hydrological studies. Evaporation estimates, whatever their accuracy is, represent the potential not the actual evaporation, with the later being of much direct concern to hydrological studies.

Being the idealised upper limit of evaporation, potential evapotranspiration can not be compared to rainfall when the adequacy of rainfall is evaluated in arid and semi-arid regions. Generally, the actual evaporation can be obtained by either by subtracting runoff and infiltration from the estimated rainfall or by applying available empirical figures. The use of remotely-sensed data (*e.g.*, from NOAA-AVHRR, and METEOSAT) in modelling evaporation is also hindered by the lack of ground based

measured energy elements that are necessary for solving the relevant aerodynamic equations.

The research is able to partition the rainfall into runoff and 'loss to infiltration and evapotranspiration'. In the future similar studies of actual evapotranspiration and sub-surface storage and moisture conditions might be a further step to construct a water balance for the region. Though it is not in a position to recommend, future research is much needed in land surface characterisation and empirical parameterisation. In addition, the preparation of detailed high-resolution remote sensing and map data is regarded necessary.

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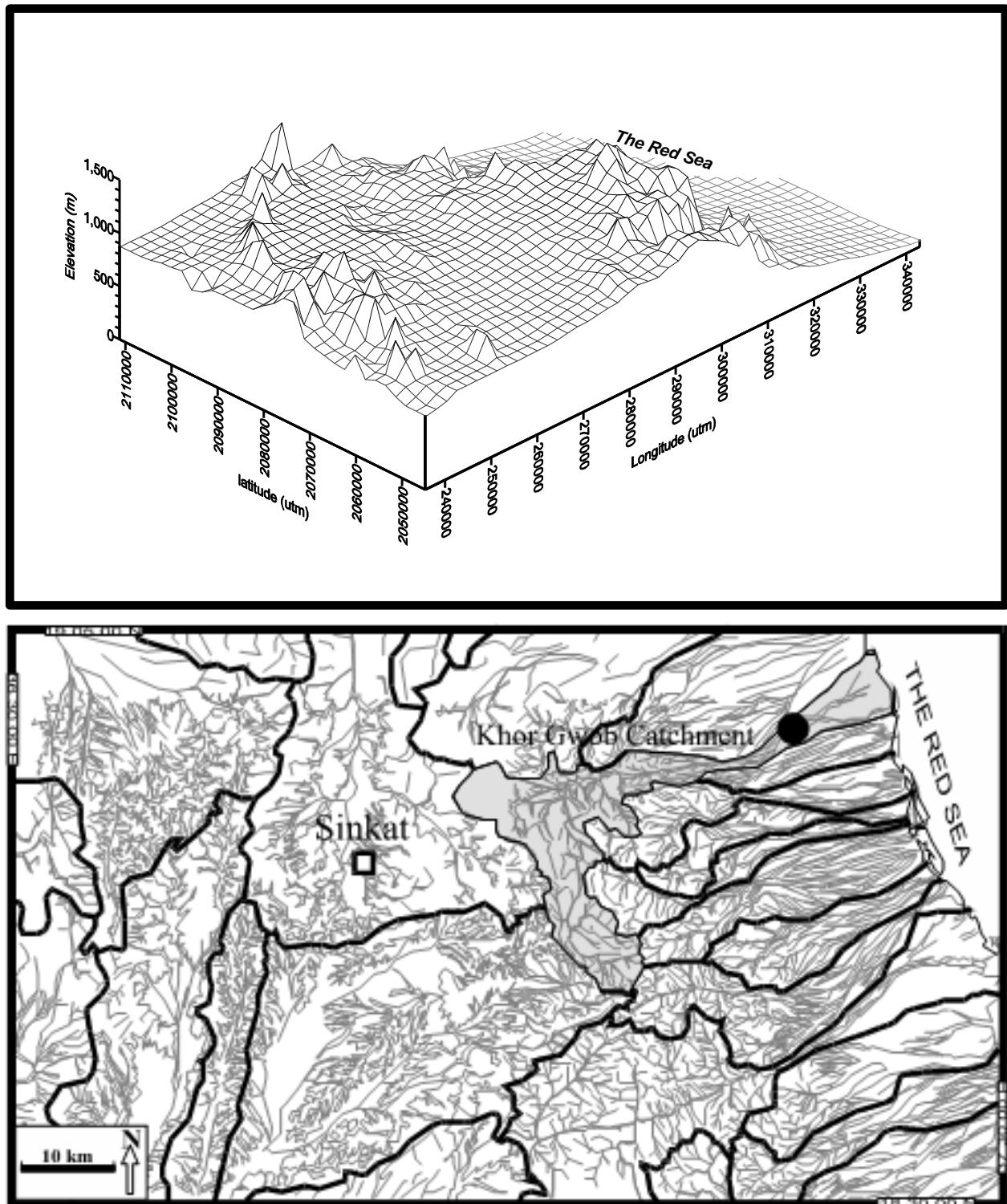


Figure (1). The Khor Gwob catchment (shaded) and the adjacent water systems (2-D and 3-D). The location of the Gwob gauging station (A and B) is shown by the dark circle

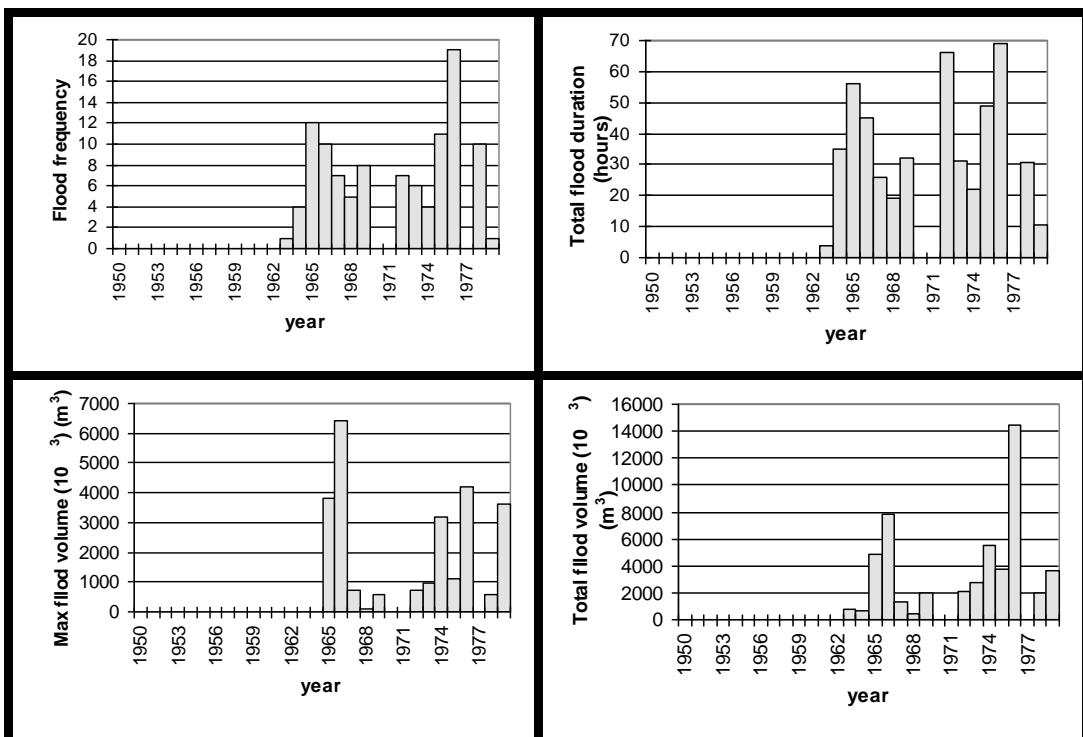


Figure 2: Annual flood frequency, duration and volumes in the Khor Gwob catchment 1958-1979

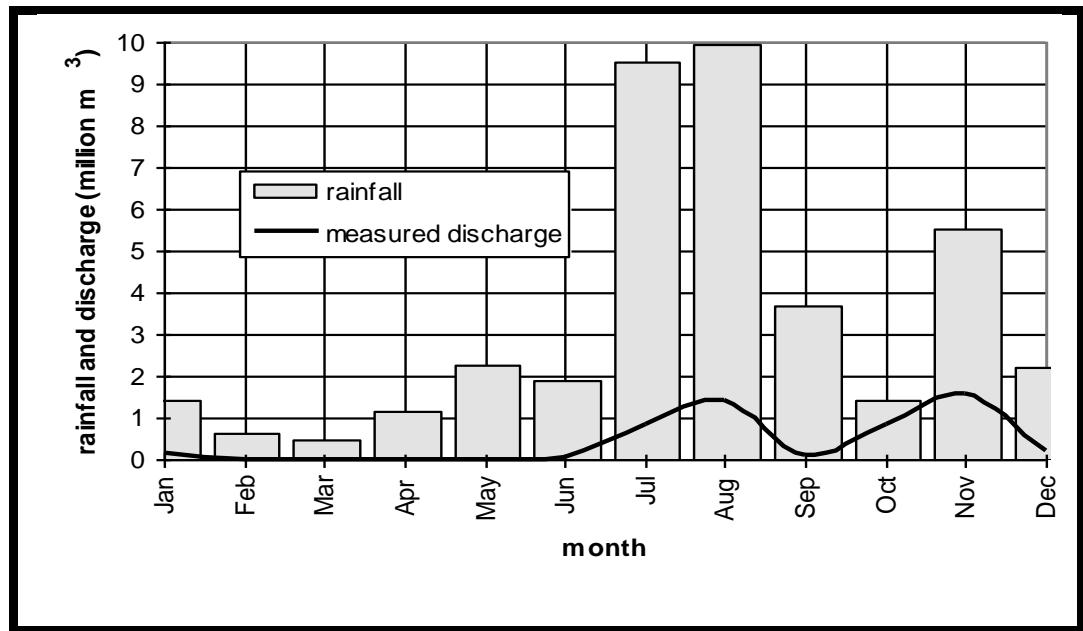


Figure (3). Monthly measured mean discharge (1961-1979) and estimated mean rainfall in the Khor Gwob catchment. *Discharge data from SRWC records

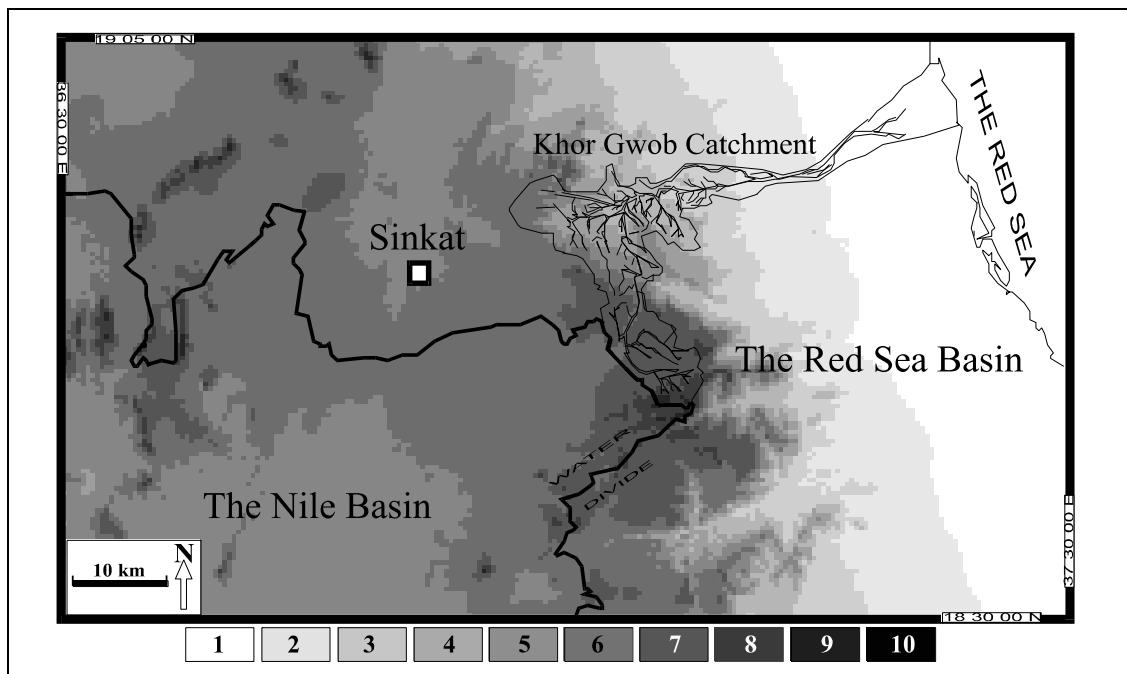


Figure (4-a). 100m grid DEM of the Study area: Legend: No. 1 = 0-150m, No. 10 = 1350-1500m, interval =150m

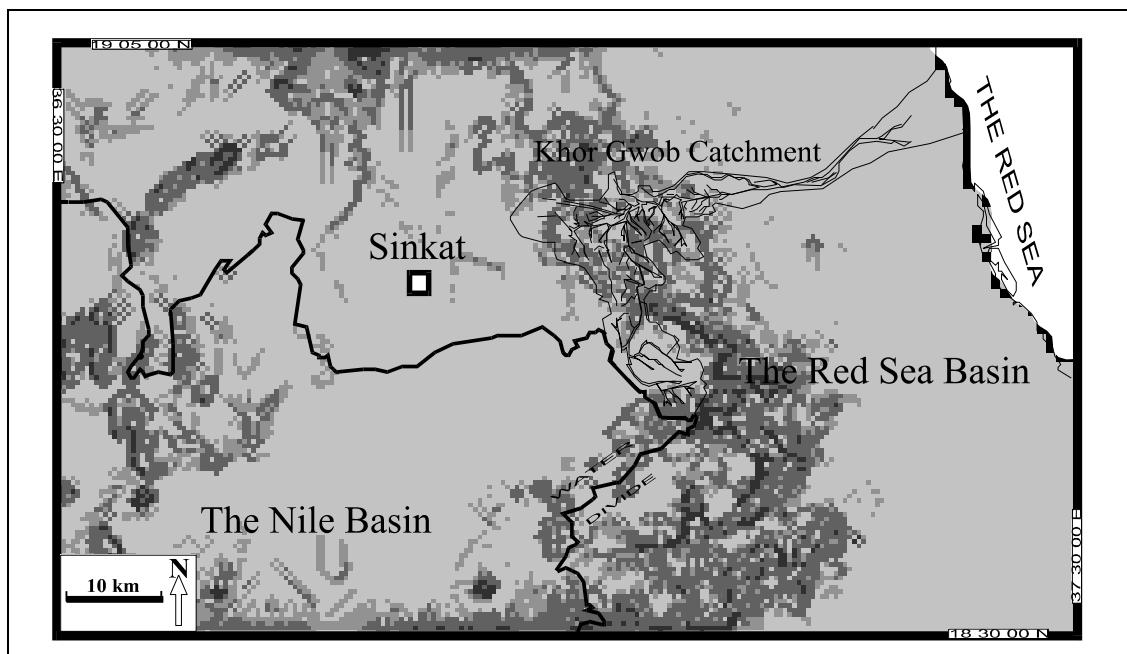


Figure (4-b). Slope map of the study area: Very light grey (gentle slope = 0-5%), Light grey (moderate slope = 5-10%), dark grey (steep slope =10-30%), and Very dark grey (very steep slope = > 30%)

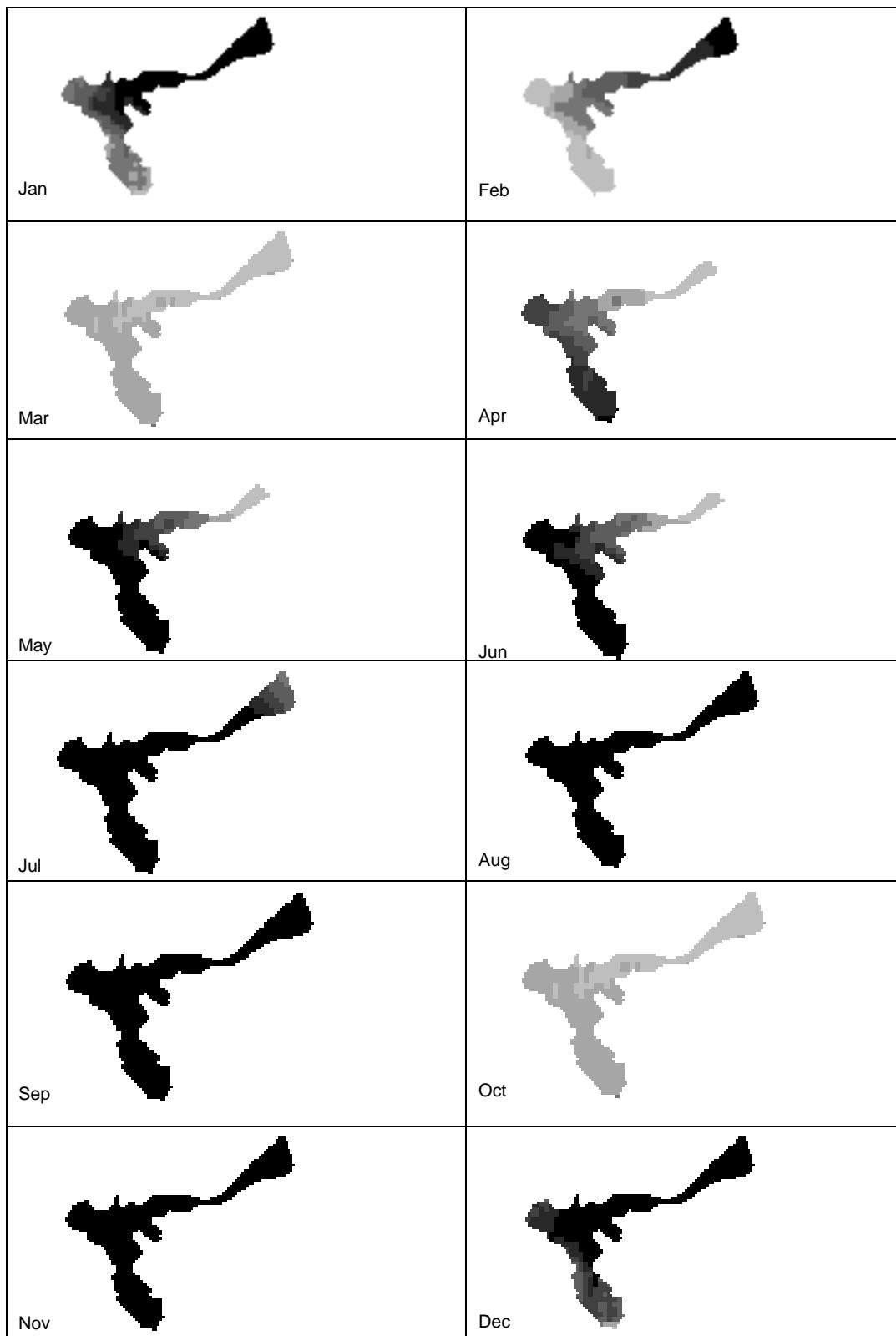


Figure (5). The monthly pattern of rainfall in the Khor Gwob catchment. The magnitude ranges from 0.0 (white) through 0.5 (light grey) to >10.0 (10^6 m^3)

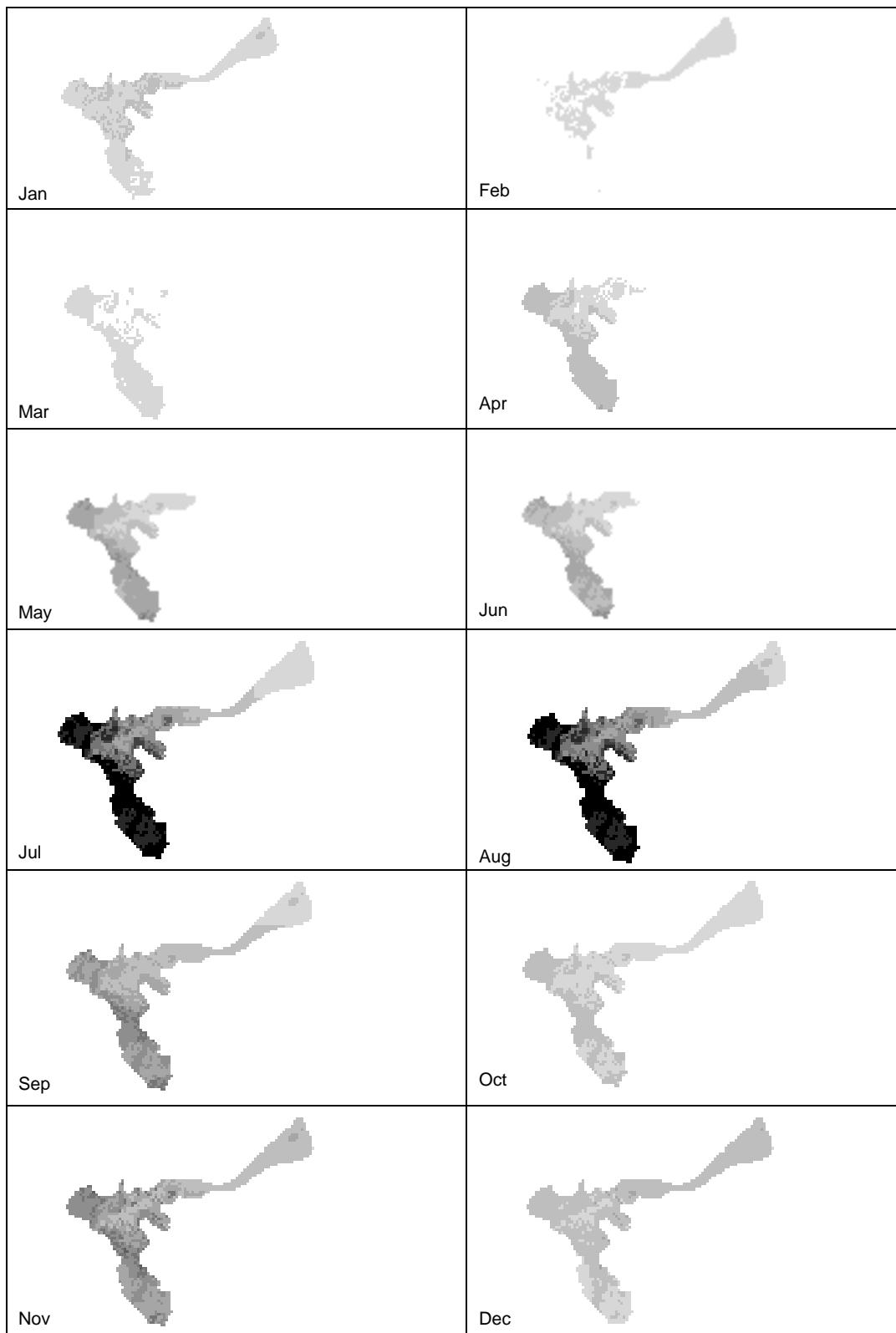


Figure (6). The *Std* modelled monthly pattern of runoff in the Khor Gwob catchment. The magnitude ranges from 0.0 (white) through 0.06 (light grey) to > 1.4 (10^6 m^3)

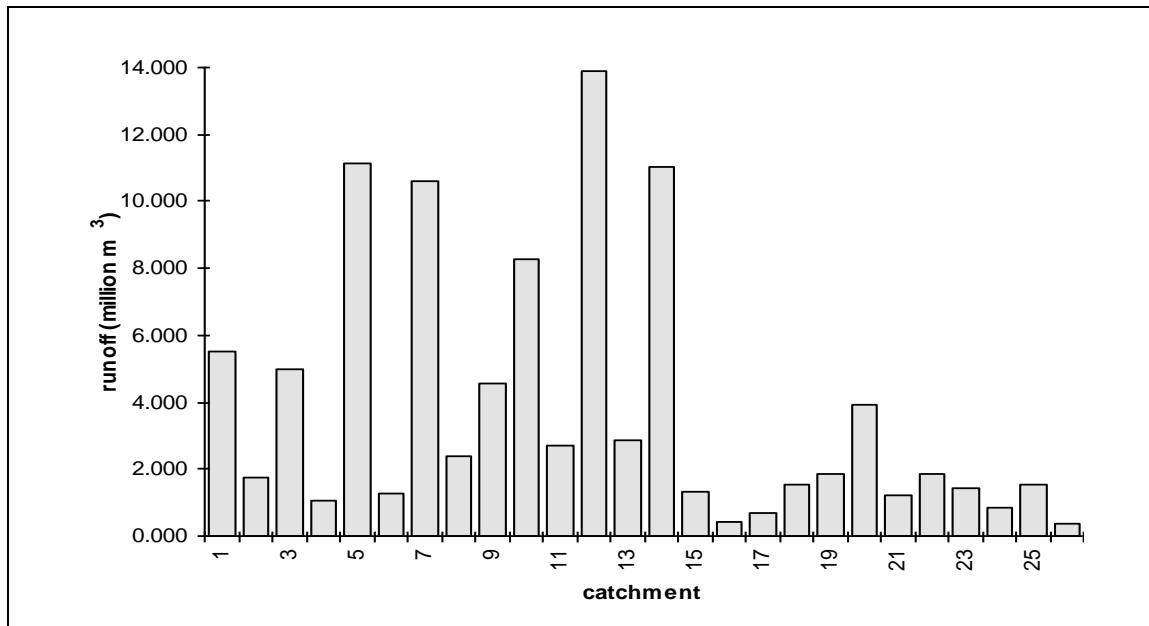


Figure (7). Mean annual runoff magnitude (million m³) in 26 catchments in the Sudanese Red Sea region.

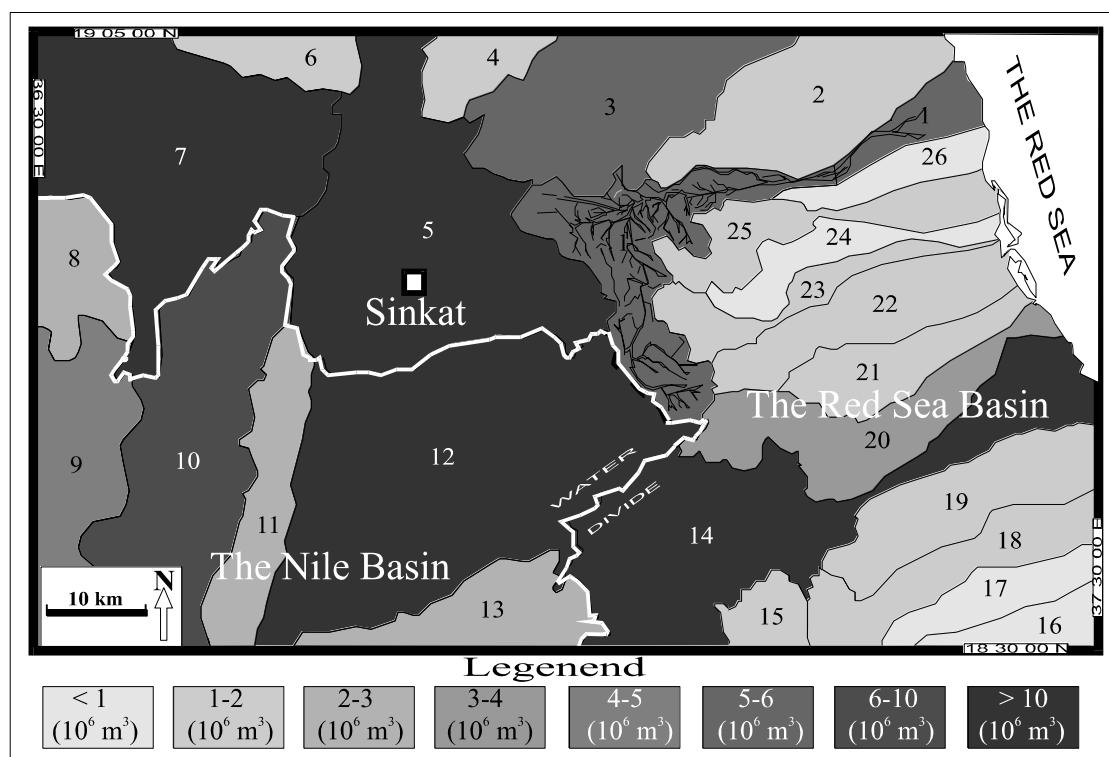


Figure (8). Classified annual regional runoff magnitude (million m³) in 26 catchments in the Sudanese Red Sea region.