Recommending the IHACRES model for water resources assessment and resolving water conflicts in Africa

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Abstract: The International Association of Hydrological Sciences (IAHS) recognized the lack of hydrological data as a world-wide problem in 2002 and adopted the Prediction of Ungauged Basins (PUB) as a decadal research agenda during the period of 2003 to 2012. One of the objectives is to further develop methodologies for prediction in ungauged basins and to reduce uncertainties in model prediction. Estimation of stream flows is required for flood control, water quality control, valley habitat assessment and water budget of a country. However, the majority of water catchments, streams and valleys are ungauged in most developing countries. The main objective of this paper is to introduce the IHACRES (Identification of Hydrographs and Components from Rainfall, Evaporation and Stream) model into African hydrological planning as a methodology for water resources assessment, which in turn can be used to resolve water conflicts between communities and countries and to study the climate change issues. This is because the IHACRES model is applied for the estimation of flows in ungauged catchments whose physical catchments descriptors (PCDs) can be determined by driving variables (i.e. rainfall and temperature); and also in gauged streams but whose gauging stations are no longer operational but historical data are available for model calibration. The model provides a valuable insight into the hydrologic behaviour of the upper water sources for valleys as well as provides a useful methodology for water resources assessment in situations of scarce financial resources in developing countries. In addition, it requires relatively few parameters in its calibration and has been successful applied in previous regionalization studies. It will also make possible the equitable distribution of water resources in international basins and rivers' catchments. This paper does not apply the model anywhere, but recommends it as a methodology for water resources assessment in order to cure water conflicts on the African continent.

Keywords: ungauged catchment; water resources assessment; rainfall; runoff; lumped models; Nile Basin; Africa

1 Introduction

Hydrological data are required for sustainable water resources planning and management to enable quantification of water quantity and quality (Oyebande, 2001). River flow measurements are necessary for water resources planning and conservation, pollution control and for solving many environmental problems. The required data can be obtained through measurements at river gauging stations. However, most water catchments in most African countries (Fig. 1) are ungauged, i.e. without adequate recorded data in both quantity and quality or spatial and temporal distribution and hence such data may be unavailable when needed. Furthermore, the changes of land use make past stream flow records difficult to use for future assessment of water resources. Data's inadequacy occurs not only in ungauged catchments but also in gauged catchments because of data's inconsistency, inaccuracy in measurements, short duration of recorded data or low network density, while some gauging stations are sometimes located in remote areas and become inaccessible during rainy season hindering acquisition of data and maintenance of equipment. Although the availability of measurement data for stream flow is restricted tempor-

Received 2010-09-29, accepted 2010-11-12
doi: 10.3724/SP.J.1227.2011.00040
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ally and spatially, the needs of data are inevitable. Water supply, storage, distribution and hydraulic structures all require stream flow data, and the needs for stream data flow are increasing due to rising water demand, declining finance, technology and human capacities for data collection and monitoring.

Hydrological models are substantively a set of mathematical equations based on theoretical principles that link inputs to outputs and are important tools in watershed management. They are used to study complex problems and synthesize different kinds of information necessary for planning and decision making in water resources management and development (Woolhiser *et al*., 1982). In stream flow prediction they provide the water resources planning and disaster management tool. Models are either lumped or distributed and have been classified into statistical, black box, lumped parameter and physically based models (Vertessy *et al.* 1993). Each model is related to itself predictive power, utility, accuracy and use.

Generally, basic models represent producing mechanisms of individual run-off and spatial variations in catchment characteristics (e.g. soil properties and vegetation cover). Beven (1989) indicated that models require large amount of input data, which is difficult to be obtained. The models are poorly used, unless the input data are of very good quality (Refsgaard *et al*., 1992). Statistical models are based on regression relationships and have been widely used in catchment runoff predictions since they are relatively simple to be constructed (Stoneman *et al*., 1989). The major limitation to these models, however, is that they need to be based on long-term rainfall-runoff records and that statistical association on catchment characteristics or planned treatments is different (Bosch *et al*., 1982). Most black-box models are lumped and have good agreement between observed and predicted daily stream flow using their time series analysis function method (Jakeman *et al*., 1993). These models are incapable of predicting the hydrological impact of catchment disturbances unless stream flow data collected after the disturbance are first calibrated.

Unlike statistical and black-box models, lumped models assume that system inputs and dynamics are uniform in space and are realized when rainfall-runoff models are aggregated spatially and temporally over the entire catchment. The models simulate catchment response well although some accuracy may lose as the scale of lumping increases (Kirkby, 1999). The models require less input data, pose little computational burden, hence, their use is widespread. Unlike statistical and black-box models, lumped model can not be applied to the conditions not reflected in the calibration data set. This is because the lumping of processes is often over-simplified. A key factor in the application of lumped models is the stability of the catchment system, stable spatial distribution of precipitation, vegetation and soil characteristics. According to the study of Refsgaard *et al*. (1996), when the objective is to simulate time series of stream flow, only lumped conceptual model gives best results compared with other models.

2 Study area

The African continent (Fig. 1) is a rich mosaic ecosystem ranging from the snow and ice field of Kilimanjaro to tropical rainforest to the Saharan desert. Although it has the lowest fossil energy use per capita compared with other regions, Africa may be the most vulnerable continent to climate change because widespread poverty limits country's capabilities to adapt

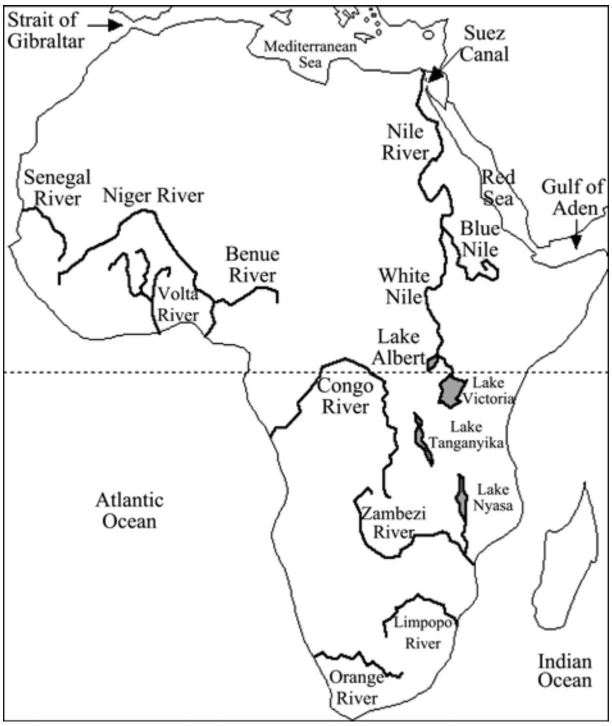

Fig. 1 River basins and lakes in Africa

the change. Signs of changing climate in Africa have already emerged including melting glaciers in the mountains, warming temperatures in drought-prone areas, and sea-level rise and coral bleaching along the coastlines. The surface area of the Chad Lake has decreased from 25,000 km^2 in 1963 to 1,350 km^2 in 2008. Periods of severe drought led to large-scale environmental degradation, population displacement and urbanization.

In addition, post independence Africa has witnessed very violent conflicts over water resources (Smillie, 2000). In western African, sub-region water conflict involved sedentary farmers and mobile pastoralists (Shatima and Tar, 2008). Pastoralists have interacted with sedentary farmers for millennia, but water scarcity increased tension and conflicts between these groups in many parts of the world (Fratkin, 1997). Traditionally, resource-based conflict has been represented by the old competition between farmers and pastoralists over water and land resources (Assal, 2006). Sub-Saharan Africa is more vulnerable to water stress than any other regions where about 64% of Africans rely on the water that is limited and highly variable; croplands inhabit the driest regions of Africa where some 40% of the irrigated land is unsustainable; roughly 25% of Africa's population suffers from water stress; nearly 13% of the population in Africa experiences drought-related stress once each generation (Tatlock, 2006). The conflict in Darfur, Sudan was over water and grazing rights (Schanche, 2007) where many sedentary tribes became targets for displaced groups from Northern Darfur and various camel pastoralists (Ayoub, 2006).

3 Methods

3.1 Conceptualization of rainfall-runoff relationship

Rainfall-runoff models are mathematical expressions of various rainfall-runoff processes. Some models have conceptual parameters only, while others have both conceptual and physical parameters. Although the majority of these models were developed for humid temperate regions, they need to be adapted to local conditions through calibration and validation before being applied locally. This is done by using rainfall, stream flow, and physiographic data. The data needed for the determination of physical parameters are available from topographical sheets, soil maps or remote sensing and are derived using GIS. Conceptual parameters require rainfall, stream flow, and temperature data for their calibration, which is achieved through optimization algorithms (Sorooshain *et al*., 1995). This involves systematic search for parameter values that yield computed runoff hydrographs that best match observed hydrographs. With model parameters determined, the model can be used to improve data records in gauged catchments, if rainfall data for missing stream flow is available.

In ungauged catchments, rainfall-runoff models can be used in data generation after regionalization, which involves correlating the conceptual parameters to catchment characteristics from several gauged catchments (Nathan *et al*., 1990; Shaw, 1996; Funke *et al*., 1999). Therefore, the data to be obtained by rainfall-runoff models with regionalized parameters are possible for use. Regionalization of model parameters is the calibration of the model to representative catchments scattered across the basin and assigning the parameters from these catchments to other catchments around them with assumed similar characteristics. However, the description of hydrological characteristics in terms of physical catchment descriptors (PCDs), allows for the estimation of the Unit Hydrograph (UH) for any catchment within the region. The resulting relationships are then used to derive model parameters for the ungauged catchments in the same geographical and climatic region making it possible to simulate stream flows in ungauged catchments.

3.2 The IHACRES model

The IHACRES model identifies the rainfall-runoff behavior from data in its parameters at a catchment scale. To present physical feature, it incorporates the conceptualization of the relevant large scale catchment process. It is comprised of two modules in series (Fig. 2), a nonlinear and a linear. The first one is a non-linear loss module that links rainfall and air temperature (R_k and T_k) to effective rainfall (U_k) with parameters C, T(w) and F (Fig. 3). It uses temperature and rainfall data to estimate the relative catchment moisture index which determines the proportion of rainfall that becomes effective rainfall. The second is a linear unit hydrograph (UH) module that links effective rainfall U_k to stream flow X_k with parameters T(q) , T(s), and V(s) (Fig. 3). It routes the effective rainfall through any configuration of stores in parallel and/or in series, which is identified from the time series of rainfall and stream data but is typically either one store only, representing ephemeral streams or parallel two of both slow and quick flows to be represented (Croke *et al*., 2005). In the IHACRES application, it was shown that the parameters in the non-linear module (C, T(w) and F) had significant direct effects on the volume and the peak of flow hydrograph, while the parameters in the linear module (T(s), T(q) and V(s)) had an effect on the peak of flow hydrograph, but not on its volume (Taesombat and Sriwongsitanon, 2010).

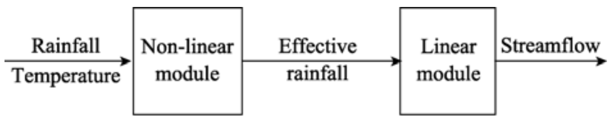

Fig. 2 Two modules of the IHACRES

The IHACRES is a lumped conceptual model, which simulates rainfall-runoff response of catchments to total stream flow, with calibrated parameters prior to simulation by comparison with observed stream flow data (Jakeman *et al*., 1993). It assumes that there is a linear relationship between effective rainfall and stream flow (effective rainfall U_k for time step k is that part of rainfall which eventually leaves the catchment as stream flow X_k). This assumption allows the application of the Unit Hydrograph (UH) theory which conceptualizes the catchment as a configuration of linear stores acting in series and/or in parallel. The non-linearity normally observed between rainfall and stream flow is therefore accommodated in the module, which converts rainfall to effective rainfall (Fig. 3).

The simultaneous identification of UH for both high and low flows by the IHACRES model extends the utility of the UH approach to include a large portion of the whole flow regime. The underlying conceptualization is that the catchment wetness varies with antecedent rainfall and evapotranspiration. Therefore, a catchment wetness index S_k (ideally, $0 \le S_k \le 1$) is computed at each time step on this basis. The percentage of rainfall, which becomes effective rainfall in any time step, varies linearly (between 0 and 100%) as the catchment wetness index S_k (between 0 and 1).

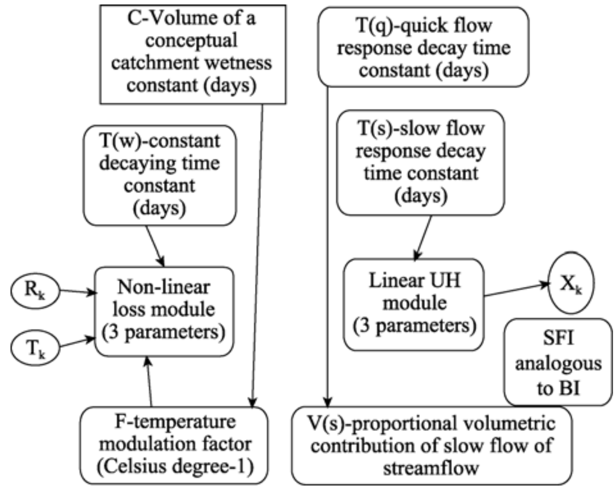

Fig. 3 IHACRES model structure and dynamic response characteristics (DRCs). Source: Littlewoods *et al*., (1992)

The advantage of the spatially 'lumped' approach is that it requires only a few (six) parameters, three in the non-linear module from model rainfall to rainfall excess and three in a linear module from rainfall excess to stream flow. A model with a few well-defined parameters gives better statistical relationships between those parameters dynamic response characteristics, (DRCs) and the selected physical catchment descriptors, (PCDs). The parameter T(w) is the rate at which the catchment wetness declines in the absence of rainfall. Hence a large T(w) gives more weight to the effect of antecedent rainfall on catchment wetness than the smaller one. The value of parameter C (Fig. 3) is set such that the volume of rainfall excess is equal to the total stream flow over the estimated period. It is the increase in catchment wetness index per unit rainfall in the absence of any decrease due to evapotranspiration. The parameter F (Fig. 3) is a temperature modulation factor, which determines how T(w) (T_k) changes with temperature for a constant S_k. The parameter A_q (or α_s) describes the rate of decay, or equivalently the time constants T(q) (T(s)) of the quick (slow) flow hydrograph following a unit input of rainfall excess. The volume V(s) is the proportional volumetric contribution of slow flow to total stream flow. The quantities C, F, T(q), T(w), T(s), V(s) are DRCs of the catchments (Fig. 3).

Generically, the IHACRES is the "data based mechanistic" (DBM) type (Young, 2002) and hence is able to make efficient use of existing data set. For calibration, the model requires time series of rainfall, stream flow and temperature data. Its parametric efficiency makes it easy to link its DRCs to PCDs making it useful in regionalization studies. Despite its structural simplicity, the IHACRES model has been applied successfully to a wide range of catchment types and for regionalization studies (Post *et al*., 1996, 1999, 2002; Kokkonen *et al*., 2003). In practice, the selection of the 'best' IHACRES model is based on performance in both calibration and simulation (Littlewood *et al*., 2002).

Physical catchment descriptors of slope area, soil type, elevation, stream density and land cover at a catchment scale can be determined using ArcView GIS and the available physiographic data. Stepwise regression can be used to quantify the relationship between DRCs and PCDs and to identify those PCDs with the strongest statistical relationship with the DRCs in order to draw in PCDs overlooked in correlation analysis. The PCDs that change with time allows hydrological response to be affected by changing land use or climate. An implicit assumption is that the relationships between PCDs and DRCs are constant and the change in land use or climate will not alter the hydrologic response of a catchment or processes governing the losses.

The relationships between DRCs and PCDs can be derived by using a progression of techniques from inspection, correlation analysis, stepwise regression and multiple regression analysis. The derived relationships should have some meaning in the context of the individual parameter conceptualization and are not simply mathematical abstractions. Stepwise regression can be used to identify those PCDs with the strongest statistical relationship with DRCs and these can be combined in a multiple regression model that expresses each DRC in terms of PCDs. The validity of the relationship can be tested by re-calculating DRCs for all calibration catchments and two other catchments that were not used in the derivation of the relationships.

Using regionalized parameters to estimate flows is a way of validation of the relationships, and the derived parameters can be used to simulate flows and carry out the sensitivity analysis in two ungauged catchments and comparison between observed and simulated flows using visual and numerical methods, and an objective appraisal can also be carried out.

3.3 Flow estimation in ungauged catchments

When data on stream flow are unavailable to support model calibration, other catchments' data become very valuable (Kokkonen, 2002). To estimate stream flow from ungauged catchments for existing or forecasted future conditions, model parameters may be extrapolated from gauged catchments within the same region, a transfer of information known as regionalization (Bloschi *et al*., 1995). This effective transfer should form a relatively homogeneous group (Post *et al*., 1996). According to Bates (1994) a successful regionalization of rainfall-runoff model depends on accurate estimation of model parameters for the gauged catchments, selection of PCDs with significant influences on catchment response to rainfall, proper identification of homogeneous regions and the degree of correlation between model parameters and catchment descriptors. Regionalization is an attempt to relate flow characteristics at gauging stations to physical and climatic characteristics of their drainage basins (Riggs, 1990). It is the transfer of information in the form of characteristics describing the hydrological data or models from one catchment to another (Bloschi *et al*., 1995). These characteristics, obtained from maps and weather records, can be used for ungauged catchments from the derived relationships to estimate their stream flow.

Sefton *et al*. (1998) and Funke *et al*. (1999) respectively indicated that step-wise regionalization methodology is applicable in the situations where the number of gauged catchments is limited. Most regional predictive studies focus on a certain flow regime. In particular estimation of flood indices for ungauged catchments has received a lot of attention. Vandewiele *et al*. (1995) reconstructed monthly flows for basin considered ungauged, while Post *et al*. (1996, 1999) and Sefton *et al*. (1998) predicted daily flows by developing relationships between the parameters of a daily time step rainfall-runoff model and PCDs. In such studies, the models should be parsimonious in order to capture efficiently the hydrological behavior of the catchment. The consequences of over-parameterization are well document in literature (Pilgrim, 1983, Jakeman *et al*., 1993).

Regionalization approach needs data from many catchments in the same region (Kokkonen, 2002), and the limited number of gauged catchments is usually available, and using large regions increases the number of available gauged catchments but also increases the variation of climate and physiography between these catchments leading to introduction of more variables in the regression analysis (Seibert, 1999). The regionalization process is usually accompanied by loss of accuracy due to optimization error, adjustment of boundary conditions and use of transfer functions. To determine the overall regionalization efficiency, simulations should be carried out using the regionalized parameters and the efficiency is determined by comparing with that of optimization. The transfer functions should be tested in separate catchments in the same climatic regions in order to verify their validity.

That the model can be calibrated for any period and a 3-year period is sufficient to capture the diverse weather conditions. Selection of a 3-year calibration period (Jakeman, 1993) helps to balance problems of variance and bias. Each period can be selected to start and end on low flows because the model assumes an initial catchment wetness peak index (S_k) of zero. Model calibration can be performed on daily rainfall stream flow time series during a common period, for example the period of 1970 to 1978, for all the number of catchments selected. The period of record can be divided into non-overlapping calibration periods. Transfer function parameters can be optimized using an instrumental variable technique (Jakeman *et al*., 1990), while the parameters of a nonlinear loss module can be selected by a semi automatic parameter. Optimal combination of loss characteristics can be chosen using objective guidelines based on maximizing R^2 and minimizing average relative parameter error (ARPE) and bias. The parameters can be considered to represent the dynamic response characteristics (DRCs) of the catchments.

Validation can be cited to a specified number of gauged valleys within a chosen area in order to obtain a set of dynamic response characteristics (DRCs) describing their hydrologic behaviour. Physical catchment descriptors (PCDs) indexing topography, soil type, climate and land cover can be allotted and linked to hydrological model by overlaying catchment boundaries with GIS technique. For example, using multiple regression analysis, predictive equations can be developed that predict the calibration parameters of the gauged valleys as a function of measurable/desirable PCDs. The assumption is that the resulting predictive equations apply for valleys or streams other than those from the data that are drawn for their development. These equations can be validated on two additional valleys or streams and then used to derive DRCs of two other valleys. Using the derived DRCs and the available rainfall and temperature, the model can be used to simulate annual flows in gauged valleys but considered ungauged for the purpose and a comparison between simulated and observed flows using visual and numerical methods.

An alternative to the regionalization of the parameters of a model is to regionalize aggregate measures of the hydrological response such as water yield and flow probability distribution, and use these methods to constrain the model parameters. Using the water yield from similar neighboring catchments has resulted in improved prediction of flows using a regionalization approach. This can be extended through regionalization of runoff coefficient, enabling prediction across a larger scale. If the model parameters are calibrated using the flow duration curve (FDC) rather than the time series of flow, the concept can be further extended to calibration of the model to the regionalized probability distribution, avoiding the need to determine the relationships between model parameters and PCDs (Littlewoods *et al*., 2002).

4 Discussion

Successful application of the IHACRES model will help the African countries to face development problems, growing population and demand for water resulting from climatic change, and to overcome water conflicts. The IHACRES model has been carried out in humid and arid environments and proved to be successful because it requires a few parameters in its calibration and regionalization. The study of Jakeman *et al*. (1993) confirmed the strong relationship between the lumped response parameters of the IHACRES model and its PCDs. Littlewood (2002) produced time series and flow duration curves (FDCs), respectively, for observed and modeled daily stream flow for the 894 km^2 catchment of the River Teifi to Glan Teifi in Wales. The model accounts for 88% of the variance of stream flow over its calibration period and has the following DRCs: T(w) = 22 days, F = 2.0°/C, C = 69 mm, T(q) = 1.91 days, T(s) = 39.0 days and V(s) = 0.36 (dimensionless). The FDCs confirm that the model performs well over the 5%–95% of flow range. The hydrological regime at Glan Teifi is characterized by the six DRCs described in Fig. 3 in our context here. Given similar models for other gauged catchments, statistical relationships can be sought that link DRCs and PCDs. The DRC–PCD relationships can then be applied to ungauged catchments (Littlewoods *et al.*, 2002). This research has proved that IHACRES can be effectively used for flood estimation and flood routing along the river course.

Dye and Croke (2003) applied the IHACRES model in two South African catchments. In many South African catchments, the water is an increasingly limited and highly fluctuating resource. Accurate prediction of low flows is especially vital if water resource managers are to successfully balance the growing needs of agriculture, industry and rural and urban populations, and to maintain the ecological health of aquatic and riparian ecosystems. The IHACRES shows great potential in linking proposed land-use change to altered flow regimes, and efficiently describing the flow characteristics within catchments. Jakeman *et al.* (1990) and Jakeman and Hornberger (1993) studied to determine whether uncertainty in daily river flow predictions using the IHACRES model in small to moderate size watersheds (50–400 km^2) in southern California would increase if URD gridded rainfall data were used in place of point rain gauge data to calibrate the model. This investigation was a part of a model regionalization project funded by NASA, Land Cover/Land Use Change (LCLUC) program (Hope *et al.*, 2005). The IHACRES model was selected for this project because it has a parsimonious, lumped-conceptual structure that avoids uncertainties associated with over parameterization and is well suited to parameter regionalization studies. Unlike distributed hydrologic models, lumped models such as the IHACRES do not require information on the spatial distribution of rainfall which would be problematic using URD gridded data in small to medium size watersheds (Hope *et al.*, 2008). The IHACRES model has been developed in the Messara catchment, Crete, with the results showing that the model is capable of capturing the key trends over time (Herron and Croke, 2009).

The IHACRES model is actually beneficial for water resources assessment in water conflict areas in Africa, such as the Nile Basin. The River Nile Basin is virtually important water catchment in Africa as it covers an estimated area of 3,254,000 km^2 representing 10% of the continent area. This basin support the lives for many centuries, but recent issues on the request of source countries for their share, declaration of historical right by downstream countries and the partial signing of Uganda, Tanzania and Rwanda on a separate agreement have shrunk future collaboration between the Nile Basin Countries. Political conflict on water resources is a facet of future wars on water resources. The Nile Water Treaty signed in the early last century is not convincing for many countries in the Nile Basin because of the challenging problems of population growth, desire for agricultural development, and so on. However, one of the methods that can increase knowledge about the actual amounts of water within the Nile Basin is the application of the IHACRES model. This will make database for equitable distribution of water resources within this basin and also, elsewhere for whole Africa, since the majority of catchments and basins are ungauged.

5 Conclusion

The general conclusions of this paper are as follows:

(1) The IHACRES model requires a few parameters in its calibration and was successfully applied in many regionalization studies.

(2) The IHACRES model is beneficial at the community and country level for water resources assessment.

(3) The IHACRES model can provide a solution for current water problems in Africa and provide database for future water resources planning and management.

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