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Prediction in ungauged basins—a systemic perspective

ZBIGNIEW W. KUNDZEWICZ
Research Centre for Agricultural and Forest Environment, Polish Academy of Sciences, Bukowska 19, 60-809 Poznań, Poland and *Potsdam Institute for Climate Impact Research, Telegrafenberg, 14 412 Potsdam, Germany*
zkundze@man.poznan.pl, zbyszek@pik-potsdam.de

Abstract One gathers hydrological data in order to assess the water resources and to understand the variables characterizing hydrological processes (fluxes) and the states (storages) of hydrological systems (drainage basins). It is likely that most catchments of the world are ungauged or poorly gauged—even available estimates of water budgets for continents are considerably discrepant. There is a whole spectrum of cases, which can be collectively embraced by the term "ungauged basins", some of which are genuinely ungauged, others are poorly gauged, or were previously gauged, where monitoring discontinued. If there are no data from a catchment, one has to use methods of estimation of model parameters, which do not require the availability of a long time series of hydrological records. One option is to develop models for gauged catchments and link their parameters to physical characteristics, so that the approach can be applied to ungauged basins in the region, whose physical characteristics can be determined. One can try to express parameters of conceptual hydrological models in terms of physical system parameters.

Key words hydrological data; hydrological modelling; ungauged basins; water resources assessment

INTRODUCTION

Hydrological data are indispensable for assessment of water resources. Information on water level in rivers and lakes, discharge, sediment and water quality is necessary for a range of projects, in some of which, information on time series, maxima or minima of the variable may be needed. Among examples of areas for which hydrological information is essential, are: water supply planning, water engineering works (dams, reservoirs, spillways, canals, diversions, hydropower, etc), zoning, insurance, and legislation. Moreover, availability of hydrological data in real time is needed for management of water resources, reservoir operation, and in particular, flood forecasting and control. Without adequate knowledge of water resources, uninformed decisions are likely to be made, which are not adequate to the rising water stress on the "thirsty planet".

It is likely that most catchments of the world are ungauged or poorly gauged. Therefore, one cannot really assess the global water resources in detail. Available estimates of water budgets for continents (in particular, South America) are considerably discrepant. As phrased by John Rodda we have been "guessing rather than assessing" the water resources. Eminent international organizations have issued numerous calls: to collect hydrological data, to enhance observation networks and data centres, to make data freely available (e.g. Resolution 25 on free exchange of hydrological data, taken by the 13th WMO Congress in 1995). Yet, these calls have not been ubiquitously heeded. In fact, the hydrological networks have been shrinking and are largely inadequate for the purpose. This corroborates the *raison d'être* of the PUB project. What can be done if there are no adequate hydrological data in the basin of concern?

There is a whole spectrum of cases, which can be collectively embraced by the term "ungauged basins". There are different grades of being "ungauged". Some basins are genuinely ungauged, others are poorly gauged. In some basins, which had previously been gauged, monitoring may have discontinued. But even in gauged catchments, gauges may be overtopped and destroyed by a high flood and the maximum flood levels need to be sought indirectly, e.g. via tracking the maximum water level on walls. If gauges survive and continue operating, there is still no reliable rating curve for determination of extreme floods. In this range, flows are notoriously ungauged.

HYDROLOGICAL DATA FOR ASSESSMENT OF WATER RESOURCES

In order to preclude gross mistakes in decision-making and to minimize the chances of inadequate design, construction or operation of water systems or other hydrological projects, an adequate level of basic data collection is required. Hydrological observations provide the basis for essential early warnings of cases where sustainable development is threatened.

Hydrological data are also indispensable for enhancing understanding of variables characterizing hydrological processes (fluxes) and the states (storages) of hydrological systems (drainage basins).

Before launching a freshwater-related project it is essential to know how much water and of what quality has been available in the past-to-present. Yet, even major projects have been launched with meagre hydrological background, the typical excuse being the lack of time for data collection programmes. Some dam failures may have been due to the inadequacy of the available data used for prediction of design conditions. If dam design calculations are based on a short time series with particularly high flows, the overdesign is likely and the nominal design power cannot be reached.

The numbers of hydrological stations in operation worldwide, as reported by the WMO Member countries, are very impressive. The INFOHYDRO Manual (WMO, 1995) estimates that there are nearly 200 000 precipitation gauges operating worldwide. At over 64 000 stations discharge is being observed, at over 12 000—evaporation, at nearly 38 000—water level, at 18 500—sediment, at over 100 000—water quality, and at over 330 000 stations—groundwater characteristics. Despite the apparently high global aggregate numbers of operating hydrological observation stations, the situation is not uniform, being deficient over large areas.

Already the UN Water Conference in 1977, and many other meetings and bodies since, have recognized the inadequacy of hydrological networks. Recent studies in Africa have demonstrated that the phase of expansion of networks of hydrological observing stations that took place in the 1970s has long passed. Hydrological data collection and analysis worldwide are not keeping pace with actual water development and management needs. Despite the increasing demands for water and the growing water stress, calling for improved and scientifically-based water management, the largely inadequate funds available for maintenance and operation of hydrological services are being further reduced. Many millions are invested in projects with fragile hydrological data foundations, but there is no willingness to spend sums smaller by several orders of magnitude, to ensure that data are collected to meet the needs adequately. Table 1 shows WMO recommendations on minimum network density or maximum area per station (WMO, 1994) for selected hydrological variables and for different physiographies. By comparing these recommendations with the actual figures for particular countries one can see how inadequate hydrological observation networks are in tropical Africa.

Table 1 WMO recommendations of minimum density of hydrological networks (maximum recommended areas per station).

Physiography Hydrological variable	polar/arid	coastal	hilly	interior plains	mountain
Precipitation (non-recording gauge)	10 000	900	575	575	250
Precipitation (recording gauge)	100 000	9000	5075	5075	2050
Evaporation	100 000	50 000	50 000	50 000	50 000
Discharge	20 000	2750	1875	1875	1000
Water quality	100 000	7500	7500	7500	3000

According to WMO (1995), there are only three stations in Chad (area of 1 284 000 km^2), where water levels are monitored. There are no discharge/level stations with longer time series of records (≥30 years) in Botswana, while Burkina Faso has only one water level and three discharge stations.

The results of the Basic Network Assessment Project, BNAP (Perks *et al*., 1996) show that many countries in Africa are inadequately gauged. The area per one precipitation station is 7855 km^2 in Senegal; 6429 km^2 in Chad; 3381 km^2 in Mali; 2745 km^2 in Rwanda; and 1918 km^2 in Cote d'Ivoire, i.e. far below the minimum density recommended by WMO. For water quantity observations (water level and discharge) the areas per station read: 17 450 km^2 in Chad; 6379 km^2 in Namibia; 6323 km^2 in Guyana; and 5292 km^2 in Mali. In Namibia, Senegal, Chad, Guyana, Ghana, Rwanda and Mali the densities of evaporation stations are among the lowest worldwide, as reported by Perks *et al*. (1996), with areas per station in excess of 20 000 km^2. The area per water quality station is, on average, 10 318 km^2 in Senegal.

Striving to ensure better areal data coverage at the global level was the rationale for undertaking further multi-disciplinary large-scale research and monitoring programmes and experiments concentrated on energy and water fluxes. Rise of understanding of the availability of water is a pre-requisite for prediction of changes of the hydrological cycle and their impacts. In order to gather high quality uninterrupted data on freshwater resources at the global scale, the World Hydrological Cycle Observing System (WHYCOS) has been launched jointly by the World Meteorological Organization and the World Bank, where reference stations (hydrological observatories) sited on major rivers monitor more than a dozen variables such as flow, water chemistry and on-bank meteorological variables, and then transmit the data through satellites to national, regional and global data centres.

Institutional issues play an extremely important role. Typically, water data collection is fragmented among several institutions. At the national level, the existence of one central water office, such as the Ministry of Water Resources, dealing with all aspects of water management is rare. Usually several ministries (e.g. of environment, agriculture, forestry, industry, navigation, construction, interior, etc.) hold responsibilities for a portion of water issues. Frequently, the coordination between these national players is very limited to non-existent. Due to the multi-faceted nature of water issues, it is necessary, though difficult, for an agency to operate across disciplinary and jurisdictional lines.

In the WMO's survey (1995), 175 countries reported on hydrological data collection activities. However, among the respondents were 480 agencies, that is, on average, nearly three agencies per country, while for some countries, many more. This illustrates the fragmentation at the national level. A similar illustration also holds at the international level. No powerful intergovernmental water agency exists. There are two dozen or so agencies of the United Nations family dealing with water. However, water-related units in most of these agencies are outsiders—appendices of secondary (at best) importance.

Is there a hope for the rather gloomy area of global hydrological data and databases? One possible source of hope is remote sensing as the method to extend the database. Yet, despite the considerable achievements, there are still limitations, as remote sensing "cannot see through Earth". Furthermore, ground truth data are still needed to verify the remotely sensed information.

HYDROLOGICAL DATA FOR MODELLING

Several informed decisions related to water resources in a basin require mathematical models, to convert the measured (or postulated) values of some variables into the relevant variables of interest. In order to simulate the behaviour of the drainage basin, time series of observations (e.g. precipitation over the basin area and river flow in a terminating cross-section) are first used to identify the system's model (an impulse response in the linear case). Once this has been done and the system's response is identified, one can model the response of the system corresponding to an arbitrary input (from some class of input values). In ungauged basins, where precipitation or river flow, or both, are not measured, the models have to be developed without the access to a long time series of gauge records. Yet, urgent practical problems need to be solved in both gauged and ungauged basins. How then to model an ungauged basin?

Let us take a simple physical analogy. It is not necessary to measure mass, force and acceleration of every moving object, since the formulation of the general Newtonian law makes us understand any motion. Does one have general hydrological laws of comparably universal validity, which could be of use in ungauged basins? One could say that drainage basins are so very much different from each other. Yes, but so indeed are the objects obeying Newton's laws of dynamics. Certainly, one obvious and essential law ruling hydrological systems is the principle of conservation of mass (continuity rule), valid at any spatial and temporal scale.

If there are no data observed in a catchment, one has to use methods that do not require the availability of long time series of hydrological records. If among many similar and adjacent catchments, some are gauged, and others are not, one can try to establish regionally valid laws. One can develop models for gauged catchments and link their parameters to physical characteristics (e.g. by not-very-illuminating linear regression). Once this is done, the regional approach can be applied to ungauged basins, whose necessary physical characteristics can be (at least approximately) determined. This holds both for prediction (flood frequency analysis, regionalization of annual maximum flood, and then determination of floods with return period of interest, such as 100-year flood, Q_{100}, etc.):

$$Q_{100} = f(\underline{p}_1, t)$$

and for forecasting of an individual flood event, e.g. via synthetic unit hydrograph approach, i.e.:

$$h(t) = g(\underline{p}_2, t)$$

where $\underline{p}_1$, $\underline{p}_2$ are vectors of parameters.

One can also try to theoretically express parameters of conceptual hydrological models in terms of physical system parameters, and this avenue was pursued 20–30 years ago (Kundzewicz, 1986). Among the drivers were computational constraints, which do not exist anymore (Kundzewicz *et al*., 1987). Examples of applicable methodologies for physical interpretation of conceptual parameters are: comparison of finite difference schemes or matching impulse responses by moments (Kundzewicz, 1986). This latter methodology examines similarity of two different linear models—a physically-based one and a conceptual one.

Conceptual flood routing models have some physical sense, as they are based on physical premises and strictly obey the law of conservation of mass. Under the assumption of a semi-infinite broad uniform channel, conceptual parameters (e.g. of the Kalinin-Miljukov method–series of linear reservoirs, or of the Muskingum model) can be related to physical parameters of linearized hydrodynamic (St. Venant) equations, such as the roughness coefficient, channel length; and reference velocity or water depth. However, there are a roster of problems. Hydrological systems are nonlinear, so linear models can be valid, at best, to a limited extent (e.g. for small departures from the linearization level). Furthermore, it is not possible to justify physically the reference values (and the assumption of small departures) for extreme flood amplitudes. Determination of effective (aggregated) parameters for a non-uniform real case of river discharge also constitutes a serious problem. How to aggregate, if an arithmetic mean is not necessarily the appropriate characteristic of a whole nonlinear system?

Since hydrological processes and systems are distributed rather than lumped and nonlinear rather than linear, another methodology for PUBs has to be sought. It definitely needs to be combined with remote sensing and GIS. If a model is distributed, one also needs distributed precipitation (available via remote sensing) without the need to arrive at a (problematic) estimate of an aggregate precipitation over a basin, as in the case of lumped models. Also the distributed initial conditions (state of the basin) are necessary.

It remains to be seen how to determine the most essential, first-order characteristics, based on scarce information about an ungauged catchment. What methodology to use and which physical descriptors to deploy? They may refer to topography, geomorphology, geology, climate and land use. Catchments can be seen as nested in a broader forcing, e.g. teleconnections of the ocean–atmosphere type—ENSO, NAO. Geomorphoclimatic unit hydrograph-like methods, raising considerable interest in ungauged basin studies, e. g. in climate impact assessments, have been holding promise over decades (cf. Rodriguez-Iturbe & Valdes, 1979), but are still not satisfactorily operationalized. Similarly, broad applicability of the fractal geometry of nature and chaotic dynamics to PUBs has not yet materialized.

The hydrological sciences are not well suited to tackle the problems of ungauged basins in ungauged regions, i.e. where no adequate data transfers are possible. The *Flood Estimation Handbook* (Reed, 1999, volume 1, page 5) gives a number of useful maxims for determination of flood frequency distribution. Some of them read:

- Flood frequency is best estimated from gauged data.
- While flood data at the subject site are of greatest value, data transfers from a nearby site, or a similar catchment, are also very useful.
- Estimation of key variables such as the index-flood (QMED–median annual flow) or unit hydrograph's time to peak (TP) from catchment descriptors alone should be a method of last resort, some kind of data transfer will usually be feasible and preferable.

So, in the ungauged case, data transfers from a gauged "donor" basin are seen as superior to the estimation from catchment descriptors alone. A donor or analogue basin (e.g. close to subject catchment, of similar size, physiography, land use, soil, etc.) must offer gauged data of good quality. In the absence of flood peak data, QMED should be estimated from catchment descriptors based on digital data rather than manually from maps. FEH (1999) supplies catchment descriptors for ungauged basins in the UK on CD ROM, for basins greater than 0.5 km^2, including parameters characterizing the rainfall depth–duration–frequency.

CONCLUDING REMARKS

Why is the PUB project needed? Ungauged basins are ubiquitous. Yet, burning water problems—too little, too much, too dirty—have to be solved in both gauged and ungauged basins. It is worth continuing to strive towards adequate monitoring of the hydrological cycle worldwide. Yet, as covering the whole World by an adequate hydrological network is not realistic, development of methodology is needed, which works in ungauged and poorly gauged basins and could help improve our assessment of water resources and our understanding of the hydrological cycle, including its interactions with other systems. This is extremely important in our "thirsty planet" on the eve of the "age of scarcity".

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