RISK AND UNCERTAINTY IN WATER MANAGEMENT

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Abstract

Risk and uncertainty are intrinsic in water resources decision making. This is hardly surprising when in water management the primary concerns are hydrological phenomena of essentially random nature. The estimation of flood and drought hazards present examples of application of mathematical methods in water resources practice. Water resources data are observational rather than experimental: there is no possibility to repeat an experiment of a particularly destructive flood or a prolonged drought. Series of observed hydrological data are in most cases relatively small, which leads to uncertainties in the results of statistical calculations. Consequently, water management decision has to be taken under uncertain circumstances. The following issues are discussed in the paper: (1) role of stochastic models in hydrological predictions, (2) uncertainties in assessing flood risks, and (3) sensitivity of droughts to climate change.

Keywords: hydrologic extremes, water management.

1. INTRODUCTION

Water-and-Economic System (WES) represents a set of elements and objects interconnected by physical, economic and technical relations. Natural sources of water, various elements of technical infrastructure, water users and ecosystems constitute WES objects. The WES boundaries, although stipulated, are usually identified with boundaries of river basins. Characteristic features of WES’s are their dynamic character and randomness of nearly all input variables. Most of the problems that water managers are trying to solve are characterized by hazards which arise from random climatic and hydrological processes. In addition, there is usually uncertainty about assessment of these hazards. Problems related to hydrological aspects of flood risk assessment are discussed in Chapter 3.
Due to dynamic properties of WES, any decision taken at moment $t_0$ will influence the system’s behaviour in the time period $t > t_0$. Two examples may illustrate such situation. The first one concerns storage problem, when any decision of discharging some part of stored water in a given moment is taken, due to random inflow to the reservoir, without a possibility of exact evaluation of its consequences on supplying water in the future. The second example concerns watering of cultivated crops, because a decision not to supply water in a critical moment of the vegetation period may essentially decide about a whole future process of vegetation. Also in case of designing flood protection schemes, various aspects of hydrologic uncertainty should be taken into account in a systematic way.

There is some evidence that most of the Earth physical and socio-economic systems may be affected by the climate change. In particular, changes in climate have a potential to alter drought and flood hazards. It is still not clear how important are different sources of uncertainty: in greenhouse gases emission, global climate scenarios, and basin-scale hydrological effects of climate change. Water managers have to make adaptation decisions on the basis of incomplete and uncertain information.

2. STOCHASTIC MODELS IN HYDROLOGICAL FORECASTING

In many cases, water management decisions are based on predicted values of hydrologic or/and demand data. Hydrological or meteorological forecasting means a process of inference about future occurrence of certain events or processes, based on relations among variables which are the objects of prediction (predictands), and variables which influence these objects (predictors). The forecasting techniques ought to be regarded as a final effect of hydrologic research, aimed on assessing future behavior of phenomena under consideration. In practice one cannot, in general, construct relations among predictors and predictands which would exactly reflect the quantitative characteristics of these phenomena at the time horizon $t_0 + \tau$, where $t_0$ is the moment when the forecast is formulated and disseminated. Consequently, the available information on future water supply and demand may be highly uncertain, which – even in case of sophisticated optimization procedures – may lead to wrong decisions.

The sources and magnitude of errors in hydrologic forecasting depend on many factors:
- Lack of stability of forecasting models, which leads to changes of relations between predictors and predictands. This is particularly important if model parameters are identified on the basis of data concerning some period of time $T < t_0$, and they may be not valid for $T > t_0$.
- Inadequacy of forecasting models due to oversimplified assumptions (e.g. assuming linear regression model among predictors and predictands), or due to omitting some important predictors.
Errors in measured or computed values of predictors.

These errors may become more pronounced when in place of unknown values of variables (e.g. precipitation), influencing directly the forecasted phenomena, one has to use “causes of causes”, like e.g. atmospheric circulation indices (e.g. North Atlantic Circulation index) or results of calculations based on global (or regional) meteorological models.

Stochastic (probabilistic) methods of hydrological forecasting play an important role in water management. According to Krzyżtofowicz (1999): Rational decision making requires that the total uncertainty about a hydrologic predictand (such as river stage, discharge, or runoff value) be quantified in terms of a probability distribution. Relations between predictors and forecasted hydrologic variables may be expressed either in the form of a set of regression surfaces, or in the form of conditional probability distribution of predictands. Assuming that both predictors and predictands are random variables one may denote by \( X \) a vector of \( k \) variables \( X_1, \ldots, X_k \), whose values are given at \( t_0 \), and by \( Y \) a vector of \( r \) predictands \( Y_{k+1}, \ldots, Y_{k+r} \). The density function of conditional probability distribution of predictands is

\[
f (y | x) = f (y | X_1 = x_1, \ldots, X_k = x_k) ,
\]

where lower case letters denote values of predictors given at the moment \( t_0 \) of forecast estimation.

Random properties of hydrological and meteorological phenomena may differ considerably, and may therefore be subject to various probability distributions. This restricts the usefulness of function (1) as a workable prognostic model unless one may assume that the joint vector \(<XY>\) can be transformed into multivariate normal probability distribution function. The application of normalizing transformation has been recommended by many authors in analyzing multivariate geophysical events.

Let’s assume that the marginal distributions of predictors and predictands have the form:

\[
f (x) = Nrm (x, \mu_x, \Omega_{xx}) , \tag{2a}
\]

\[
f (y) = Nrm (y, \mu_y, \Omega_{yy}) , \tag{2b}
\]

where \( \mu_x \) and \( \mu_y \) are the vectors of mean values of predictands and predictors, while \( \Omega_{xx} \) and \( \Omega_{yy} \) are the sub-matrices resulting from partition of a joint variance-covariance matrix of predictors and predictands:

\[
\Omega = \begin{bmatrix} \Omega_{xx} & \Omega_{xy} \\ \Omega_{yx} & \Omega_{yy} \end{bmatrix} . \tag{3}
\]
The conditional probability distribution of predictands is

\[ f(y|x) = \text{Nrm}(y, \mu_x, \Omega_x) , \]  

(4)

with conditional matrices of predictands:

\[ \mu_x = \mu_y + \Omega_{yx} \Omega_x^{-1} (x - \mu_x) , \]  

(5a)

\[ \Omega_x = \Omega_{yx} - \Omega_{yx} \Omega_x^{-1} \Omega_{xy} . \]  

(5b)

Details of calculations, including procedures used for normalization of variables, are given in Kaczmarek (1973).

The forecasting model (4) describes all important stochastic properties of predicted variables. One should select a method to present forecasting results, which contains information about random properties of forecasted phenomena but at the same time, satisfies criteria of practical usefulness of prediction for water managers. Such forms may comprise point prediction or some kinds of interval prediction. We may demonstrate this by a very simple example.

Let \( V_X \) and \( V_{XI} \) be the inflow to a storage reservoir in October and November. Let us further assume that random variables \( X = \ln V_X \) and \( Y = \ln V_{XI} \) have a bivariate normal distribution with parameters:

\[ x = 4.675, \quad \bar{x} = 4.726, \quad \sigma(x) = 0.682, \quad \sigma(y) = 0.659, \quad r_{xy} = 0.771 , \]

estimated based on hydrological data. The conditional mean and conditional standard deviation are:

\[ \bar{y}_x = 4.726 + 0.771 \frac{0.659}{0.682} (x - 4.675) = 1.154 + 0.745x , \]

\[ \sigma(y_x) = 0.659 \sqrt{1 - 0.771^2} = 0.419 . \]

After simple calculations one may obtain conditional (predicted) expected values of inflow (in million cubic m) to reservoir in November:

\[ V_{XI} = 72.4 \quad \text{for} \quad V_X = 60 , \quad \text{and} \quad V_{XI} = 210.0 \quad \text{for} \quad V_X = 250 . \]

If, however, one wants to present the result of forecasting by means of an interval, then in case of \( V_X = 60 \times 10^6 \text{ m}^3 \) the inflow to reservoir in November is expected to be, with probability \( P = 0.8 \), within the limits \( 38.7 \times 10^6 < V_{XI} < 113.0 \times 10^6 \). If \( V_X = 250 \times 10^6 \text{ m}^3 \) the inflow is expected to be between \( 112.0 \times 10^6 \text{ m}^3 \) and \( 329 \times 10^6 \text{ m}^3 \).

The point predictions are useful in cases when the error of prediction is small. They also are applicable when one is interested in the average trends in phenomena under consideration. A forecast based on mode (most probable value) of the condi-
tional probability of predictors, over information based on conditional expected values should be preferred. In all other cases, the interval prediction is recommended. One may distinguish several sources of forecasting errors:

- Lack of stability of model in time, which leads to changes of relations between predictors and predictands;
- Inadequacy of the forecasting model due to oversimplification of assumed causal relation among variables, or due to omitting certain important predictors;
- Errors in estimation of parameters of probability distribution (1) based on small samples of hydrometeorological data.

From the utilitarian point of view, the ultimate measures of performance of a hydrologic forecasting system are the *ex ante* socio-economic effects of water management decisions based on predicted hydrologic data. Forecasting future behavior of hydrological processes and incorporation of prediction errors is invaluable in operation of water systems under uncertainty (Liu et al., 1998). But as De Mare (1980) observed, when judging the efficiency of a forecasting system, it is more important to detect extreme situations (catastrophes) than to know “how close the prediction is to the actual process”.

### 3. UNCERTAIN ESTIMATION OF FLOOD RISK

The stochastic nature of flood events is a main reason of uncertainties in designing flood control projects, and in flood management. In spite of a bunch of scientific literature devoted to flood assessment (Klemes, 2000; Singh and Strupczewski, 2002) the existing models and procedures are still not satisfactory from the point of view of engineering practice. The major sources of uncertainty are imprecision of maximum discharge measurements, selection of an appropriate probability distribution allowing low probability flood assessment, and statistical estimation errors due to short data samples. Also the impact of global change on flood events is subject to professional disagreement. Watershed development, climatic trends and other factors are extremely difficult to predict.

Nevertheless, with increasing welfare and population density in some water districts, the protection against flooding becomes a necessity. In parallel with advancement of traditional probabilistic assessment of flood disasters, some less conventional methods may be recommended. Some examples of such methods are discussed below.

Several years ago Gumbel and Schelling (1950) analyzed the probability that the $r$-th observation in an ordered (decreasing) sample of $N$ years of observations – taken from an unknown probability distribution of a continuous variable $X$ – may be exceeded $m$ times in $K$ future trials (years). This probability may be calculated by means of the hypergeometric distribution:
\[ P(A_{N,K,r,m}) = \frac{r \binom{N}{r} \binom{K}{m}}{(N+K) \binom{N+K-1}{r+m-1}}, \]  

(6)

where

\[ \binom{a}{b} = \frac{a!}{b!(a-b)!}, \]  

(7)

denotes a totality of combinations of \( b \)-element sets, which may be obtained based on \( a \)-element set. In the cited paper one may also find formulae for calculating the mean number of exceedances, as well as other statistical moments, of the event \( A_{N,K,r,m} \) in the future \( K \) years.

As an example, the maximum yearly discharges of the Odra river in Wroclaw will be analyzed. In the years 1901-2000 the flood of \( Q_{\text{max}} \geq 1500 \text{ m}^3/\text{s} \) occurred 4 times. By means of formula (6) it may be calculated that the flood of such magnitude may, with probability \( P(A_{100,30,4,1}) = 0.329 \), happen at least once in the period 2001-2030.

In conclusion of their article these two eminent mathematicians noticed that: “These methods may be of interest for forecasting floods if, instead of the size of the flood, we are interested only in the frequency. The same procedure may also be applied to other meteorological phenomena such as droughts, the extreme temperatures (the killing frost), the largest precipitation etc., and permits to forecast the number of cases surpassing a given severity within the next \( N \) years” (Gumbel and Schelling, 1950). It is really strange that this promising approach was never applied in the water resources practice and in other geophysical studies.

Returning to classical flood frequency theory it should be stressed that three research problems seem to have a great importance in developing a useful model: selection of right probability distribution, testing the conformity of observations with the model within the areas of particularly large floods, and cumulative probability of flood disasters in coming years in the face of possible non-stationarity of geophysical and watershed processes. The first two questions were discussed in Kaczmarek (2003) and will not be repeated here. The problem of cumulative risk assessment is treated below.

In case of stationary hydrologic processes, the probability of exceeding at least once a critical discharge \( Q_{cr} \) in floods occurring in the next \( K \) years is, according to Bernoulli theorem, equal to

\[ R_k = 1 - \left[ 1 - P(Q_{\text{max}} \geq Q_{cr}) \right]^K. \]  

(8)

For example, a risk that the so-called “hundred years flood” \( Q_{cr} \) will be exceeded at least once in the coming 30 years is \( R_{30} = 0.260 \). In case of non-stationary hydrology, the probability of exceeding \( Q_{cr} \) in following years will change in time, therefore:
\[ R_i = 1 - \prod_{j=1}^{k} \left[ 1 - P(Q_{\text{max}} \geq Q_{cr}) \right] = 1 - \prod_{j=1}^{k} P(Q_{\text{max}} < Q_{cr}) . \]  

(9)

For known (assumed) probability distribution function of annual maximum discharge, eq. (9) may be presented in the form:

\[ R_i = 1 - \prod_{j=1}^{k} \int_{0}^{Q_{\text{cr}}} f(Q_{\text{max}}, G_i) \, dQ_{\text{max}} , \]

(10)

where \( G_i \) is a set of parameters of the probability function, depending on time.

For example, a cumulative probability of maximum annual discharges of Vistula River at Warsaw, exceeding at least once the value of 8000 m\(^3\)/s in years 2001-2050, will be calculated by means of formula (10). The function \( f(Q_{\text{max}}, \mu(Q_{\text{max}}), \sigma(Q_{\text{max}})) \) was assumed to be the two-parameter gamma (Pearson III) probability distribution. Let us further assume that the expected changes in the mean and standard deviation of annual maximum discharges in consecutive years are for \( i = 1, ..., 50 \):

\[ \hat{\mu}_i(Q_{\text{max}}) = 2910(1 + i \cdot \delta_1), \quad \hat{\sigma}(Q_{\text{max}}) = 1190(1 + i \cdot \delta_2) . \]

The results, shown in Table 1, indicate that assumed variations in statistical properties of the investigated variable may have a significant impact on the cumulative risk of the critical flood.

<table>
<thead>
<tr>
<th>( \delta_1 )</th>
<th>( \delta_2 )</th>
<th>( R_{50} )</th>
</tr>
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<tr>
<td>-0.005</td>
<td>-0.005</td>
<td>0.0035</td>
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<tr>
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<td>0</td>
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<tr>
<td>0</td>
<td>0</td>
<td>0.010</td>
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<tr>
<td>+0.005</td>
<td>0</td>
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</tr>
<tr>
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</tr>
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</table>

### 4. SENSITIVITY OF DROUGHTS TO UNCERTAIN CLIMATE CHANGE

Drought is a recurrent feature of climate and hydrology, originated from a deficiency of precipitation over an extended period of time. It should be considered relative to the long-term condition of balance between precipitation and evapotranspiration in a par-
ticular river basin. To hydrologists, drought is present when water balance variables, like streamflow and soil moisture, are at the lower end of their frequency distributions. Managing water in a face of supply scarcity is a challenge confronting water managers in many countries.

Due to uncertainties regarding climate change scenarios and their impact on watershed environment, sensitivity analysis may help water planners to undertake necessary strategic measures to respond to expected water deficits, and therefore to reduce vulnerability of water systems to droughts. As Parry (2001) concluded in an overview of the recent report of the Intergovernmental Panel on Climate Change, the quantitative assessment of possible changes in environmental and social systems due to climate variations should be treated as a priority research area. Also the European Union Sixth Framework Programme encourages international cooperation to achieve common strategies to respond to global change issues.

For the purpose of sensitivity analysis, monthly values of a Hydrologic Drought Index (HDI), based on an altered Palmer model (Kaczmarek and Jurak, 2003), were calculated for three Polish river catchments. Time series of $HDI$ may be calculated by a recurrence formula:

$$HDI_1 = \frac{z_1}{3}, \quad HDI_k = 0.897 \cdot HDI_{k-1} + \frac{z_k}{3}, \quad (11)$$

where

$$z_k = \mu \Delta_k. \quad (12)$$

Variable $\Delta_k$ is defined as the difference between monthly precipitation $P_k$ and precipitation “climatically appropriate for existing (moisture) conditions” (Palmer, 1965). In our model this difference has the form

$$\Delta_k = P_k(1-\phi_{2j}) - \phi_j PET_k - \left(\frac{\phi_{1j} S_{\text{max}}}{30.4} + \alpha \phi_{2j} \right). \quad (13)$$

In the above equation, $PET_k$ denotes average monthly potential evapotranspiration, which may be calculated by means of widely used Penman method. The soil holding capacity $S_{\text{max}}$ and $\alpha$ are parameters of a water balance model CLIRUN, developed by Kaczmarek et al. (1998). Both parameters have to be identified (calibrated) based on hydrologic and climatic data for at least 10 years. Formulae for calculating coefficients $\phi_{1j}, \phi_{2j}, \phi_{3j}$, depended on runoff, actual evapotranspiration and catchment storage in the $j$-th month are given in the cited paper of Kaczmarek and Jurak (2003).

PC software is available for calculating these coefficients. Then weighted $\mu$ are determined, and finally a time series of $HDI$ values may be obtained by means of eq. (11) for all months of $N$ years of available input data. Calculations implemented at several watersheds in Poland show that $HDI$ values are highly correlated with catchment moisture, and therefore may well represent the severity of hydrologic drought conditions.
In an earlier study drought projections for Central Poland in the first half of 21st century were assessed, based on three Global Climate Models, developed by Hadley Climate Center (Reading, U.K.), Geophysical Fluid Dynamic Laboratory (Princeton, U.S.A.), and Max-Planck Institute for Meteorology (Hamburg, Germany). The results differ significantly depending on climate scenario and seem to be uncertain and largely conjectural. The conclusion was that the direct outcomes from the recent GCMs – although providing representation of large-scale aspects of future climate – are not well suited for assessing climate impacts on water resources at the watershed spatial scale. In order to formulate a robust drought management policy under hydrologic uncertainty, a sensitivity analysis allowing assessing a frequency of drought-related risk for assumed changes in climatic variables is required.

Sensitivity analysis has been implemented for three river catchments in Central Poland of various physical and socio-economic features (Fig. 1). The Narew River is the largest tributary to the Vistula River, with the catchment area equal to 21,860 km². The watershed is to great extent covered by lakes and forests. The only important

Fig. 1. River catchments selected for sensitivity analysis.
man-made hydrotechnical structure influencing hydrological regime is the Siemianówka reservoir located in the upper part of the catchment. Annual precipitation in the Narew watershed is 650 mm, and the annual potential evapotranspiration is 640 mm. Mean annual discharge is in range from 50 to 190 m$^3$/s.

The Warta River is the largest tributary to the Odra River. Catchment area of 54,000 km$^2$ covers 17% of the territory of Poland. The region is home to the most productive cropland, and may be therefore significantly impacted by climate related alteration of soil moisture and flow regime. The annual precipitation is 610 mm, while the potential evapotranspiration is 690 mm. Mean annual discharge is from 120 to 350 m$^3$/s, with average value of 210 m$^3$/s. The Warta water district is inhabited by 6.4 million people, with available water supply in an average year of 1050 m$^3$/capita.

The third investigated region is the Upper Vistula River which heads in the Carpathian Mountains and drains 31,850 km$^2$. The flow is regulated by several reservoirs aimed on providing water supply to the densely populated industrialized area. Annual discharge is from 170 to 420 m$^3$/s, with the average value of 280 m$^3$/s. The annual precipitation is 840 mm, and the average annual precipitation is 660 mm.

Monthly values of hydrologic drought indices $HDI$ were calculated for the above water resources systems and for nine combinations of precipitation and potential evapotranspiration. For the background schedule (“scenario”) of input data measured $P_k$ and $PET_k$ values were used in the $HDI$ model for all months from the years 1961-1990. In case of eight other input schemes meteorological data were diversified by adding/subtracting some percentage of $P$ and $PET$, as shown in Tables 2 to 4.

Probability distribution functions of simulated $HDI$ values were fitted for each combination of input data. The lower 10% of $HDI$, calculated for the background scheme, are assumed to characterize risk of severe drought conditions in analyzed river basins. These threshold values are $HDI < -1.323$ for the Narew River, $HDI < -1.593$ for the Warta River, and $HDI < -1.472$ for the Upper Vistula River catchments.

Finally, frequencies of $HDI$ indices being less than the above threshold values were calculated for assumed combinations of precipitation and potential evapotranspiration. Results are shown in Tables 1–3.

The risk of severe drought in the investigated catchments, as presented in the above tables, was defined as the probability of $HDI$ being less than the threshold values. As can be seen, the risk depends highly on input meteorological data.

The climate change issue places new demands on water sciences to improve techniques and models. While water planners are accustomed to non-stationary water demands, most of methods were developed under the assumption that in the time-scale

$^*$ The word “scenario” is not used further in this paper in order not to identify the sensitivity approach with the climate impact analysis, used in reports of the Intergovernmental Panel on Climate Change.
5. CONCLUDING REMARKS

Risk and uncertainty research and water policy decisions should not be separated. Assumptions made by scientists may have direct relevance to the management decisions (Guidelines ..., 1992). The researcher’s role in dealing with risk and uncertainty is “to
identify the areas of sensitivity and describe them clearly so that decisions can be made with knowledge of the degree of reliability of available information”. Several questions may arise in a dialogue among scientists and decision makers. What does the risk and uncertainty mean for the latter in decision making? What is the accepted frequency of critical water situations?

When designing flood protection scheme for a highly populated agglomeration, the probability of the design level equal or higher to $p = 0.01$ may be seen as not satisfactory for the citizens. On the other hand, for a farmer a drought appearing, in average, once in ten years (i.e., with ten percent of probability of critical water deficit), may be not risky enough to spend money for assuring more sustainable water supply. The advantages and costs of reducing risk and uncertainty should be considered in any water management planning process.

The issue of climate change adds a new dimension to the old problem of water resources planning for uncertain future. Unfortunately, the ability of predicting future climate is still very limited. A number of factors determine the level of vulnerability of water systems to climatic processes. It should be expected to be particularly high in regions where the current level of water stress is high, as e.g. in some parts of the Polish Lowlands. Despite many uncertainties linked with future geophysical processes, legal, technical and analytical procedures used in water management should be from time to time re-evaluated in the light of possible non-stationarities of these processes.

References


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