RIVERS AND HUMAN DEVELOPMENT

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Contents

Summary

Rivers adjoining sites or human settlements have, since time immemorial, been utilized as sources of water supply. Rivers were also used since the earliest times as sinks for the disposal of waste material and effluents. The ever-increasing pressures placed on river water by these demands in recent times call for better strategies for managing river water if it is to continue to adequately meet the demands.

To assess the amount of river water that can be safely abstracted for water supply and other consumptive uses, river flow data began to be scientifically analyzed by statistical methods or earlier methods such as the *mass curve analysis*. Rivers, as sources of hydro-electric energy, had to be analyzed from the *firm yield* and *surplus yield* points of view - by means of flow duration curves, mass balance determinations and sequential flow routing. On the other hand, concerns about pollution gave rise to the need for monitoring and maintaining river water quality, and the setting up of standards for effluents and the introduction of in-stream water quality management.

Contemporary issues affecting river water development relate to conservation, urban run-off control and integrated water resource management. The issue of having dams and reservoirs as essential parts of river water supply projects is considered in detail, emphasizing the environmental objections to dam construction and the need to control evaporation losses. Controlling urban run-off at source can help to reduce river flow variability, thus increasing net yield, and also reduce incidents of river water flooding and pollution. Ground water used conjunctively with river water may realize considerable savings, as is the integrated management of multiple reservoirs which has been reported to realize water savings of up to six percent.

The importance of rivers as water supply sources for humankind cannot be emphasized enough. However, coping with rising demands, pollution and climate change impact, requires better management and more conscientious use and conservation of combined water resources.

1. Introduction

Rivers have been the backbone for nearly all human settlements for generations. Indeed, the development of many major cities in the world has been close to rivers which have been used by communities for meeting their essential needs for drinking water, irrigation, agriculture and the assimilation of their waste. Rivers can also be a source of human misery, particularly during floods when they overflow their banks and cause damage to anything in their course. This article will only concentrate on the beneficial effects of rivers, and takes the view that by proper management, the negative effects of rivers can be minimized or eliminated. In discussing the benefits of rivers to humankind, particular attention will be given to the technical and engineering aspects of river water development. The article will end with a brief outline of contemporary issues affecting further development of river sources.

2. Rivers as Sources of Water Supply

Although water in rivers constitutes only 0.0001% of the total amount of water available on the earth’s surface, according to Maidment, rivers are still very strategic for human development. River water is vital for human existence. It is used in various domestic activities, in agriculture, irrigation and industry. All of these uses are regarded as consumptive uses because the return flow from such activities is more often less than the original abstraction. However, unlike the water in groundwater aquifers, river water is also valuable for non-consumptive uses such as hydroelectric power generation, navigation, and wastewater treatment plant effluent dilution.

While river water serves the above consumptive and non-consumptive purposes, its availability for the various uses is highly variable, both temporally and spatially. As a consequence, it is often not possible to rely on river water in its natural occurrence to meet these needs without one form of human intervention or another. Human intervention in the form of constructing dams has been used since the earliest historical times to regulate river water, thereby storing the excess water during periods of high rainfall and runoff for later release during periods of low rainfall and run-off. The combination of water in rivers, dams with their reservoirs and natural lakes increases the contribution of surface water sources to the world’s water budget to 0.014%, according to Chow.

As will be expected, the main factor determining whether or not river water conservation by dams_and reservoirs will be required for meeting water supply needs, is the demand. Demand is used in a purely economic sense here and represents what consumers actually desire. It is different from the notion of water demand used in less developed regions where, due to limitations posed by available water resources and/or supply infrastructure, the amount of water actually supplied is well below that desired. In sections 2.1. and 2.2. respectively, demands for water supply and irrigation are examined, paying particular attention to models for their estimation. Section 2.3. details the river data analyses required to establish whether river water in its natural state is sufficient to meet demands or whether a dam with its reservoir will be required.

2.1. Demand for Water Supply

Estimating water demand for the various domestic and industrial uses is a very difficult process. For the purpose of planning and management of water supply infrastructure, the situation is further compounded by the fact that not only must the present level of demand be known, but also its forecast level for the future must be known. Municipal (i.e. domestic and industrial) water consumption varies with a number of factors such as the water price, household income, the weather situation as revealed by the temperature, and the general standard of living. Leakage from distribution networks and consumer taps is also an important factor since this can mean that the total amount of water put into supply is much higher than the demand. Leakage rates vary from one water supply area to another depending on a number of factors not least of which are the age and integrity of the network and the management experience of the water supply undertakers. However, in recent times most water supply undertakers have realized that reducing leakage rates can partially meet increasing demands and delay investment in the development of new resources.

McMahon discusses a number of models for forecasting future levels of domestic and industrial water demand, using the above factors - although it should be stressed that some of these factors, albeit germane, may be difficult to quantify. In the discussion McMahon distinguishes between static forecasts, in which time is not a parameter, and dynamic forecasts in which time is a parameter. The use of dynamic models is recommended for short-term forecasts or in situations where current water use is influenced by past water use. Static models are recommended for long-term forecasts. Example_s of either class of models are, according to McMahon:

$$Q = a_0 + a_1 P + a_2 D + a_3 Y + a_4 W + u \quad \text{(Static model)} \qquad (1)$$

$$Q_t = c_0 + c_1 P + c_2 D + c_3 Y + c_4 W + c_5 Q_{t-1} + u \quad \text{(Dynamic model)} \qquad (2)$$

where, Q is the monthly water consumption of the average household;
P is the water price charged to the average household;
D is the difference between what the typical consumer actually pays for water and what would be paid if all the water were purchased at the marginal rate;

Y is the personal income per household;
W is the evapotranspiration less the rainfall
u is the random error term
t is the time; and
$a_{i,\ i=0,1,..,4}$ and $c_{j,\ j=0,1,\ldots,5}$ are empirical coefficients obtainable by least squares regression techniques.

Another common approach for forecasting future demand levels is by linearly extrapolating past trends. However, the danger of such an approach is that past trends may not be an accurate indication of the future trend, particularly where societies have reached a level of saturation regarding living standards. This is clearly demonstrated by the United Kingdom (UK) example illustrated in Figure 1. Indeed, where changes in the economy imply a shift in emphasis from heavy industry to the less water intensive service industry, as happened in the UK during the 1980s, future water demand increase can be much less than that of the past.

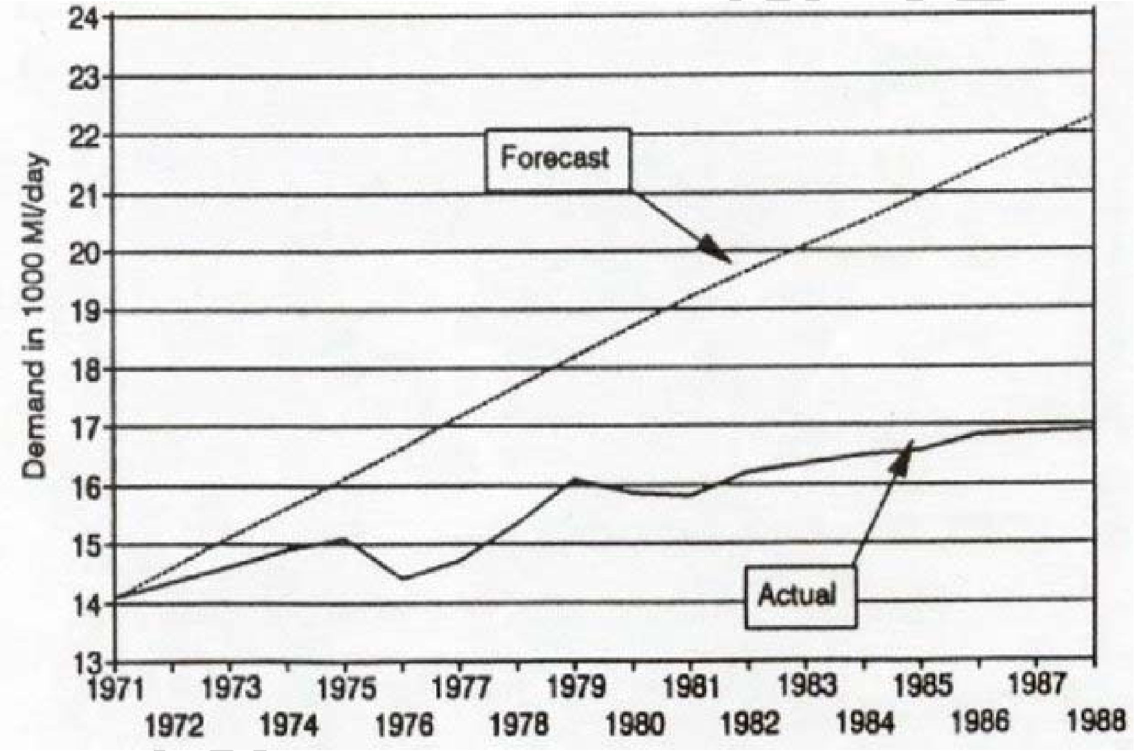

Figure 1: Example of possible error in forecasting future demand in England and Wales using the past trend (Source: Gray, 1994)

2.2. Irrigation Water Demand

Irrigation water demand, also termed the consumptive use, depends on the type of crops grown, the area under cultivation and the efficiency of the water conveyance and water application facilities. The consumptive use is often approximated by the actual evapotranspiration, which in turn is factored from the reference crop evapotranspiration. The reference crop evapotranspiration is a theoretical concept, which assumes that water for crop growth is non-limiting. It is defined by Doorenbus and Pruitt: *“the rate of evapotranspiration from an extensive surface of 8 to 15cm tall, green grass cover, actively growing, completely shading the ground and not short of water”.*

The reference crop evapotranspiration can be estimated using the Penman-Monteith equation as recommended by the United Nations Food and Agricultural Organization, FAO as given by Doorenbos and Pruitt. The Penman-Monteith equation uses weather measurements - wind speed, solar radiation, humidity, temperature, sunshine hours - to estimate the reference crop evapotranspiration. The associated calculations are relatively complex and are as outlined by Shuttleworth. However, once the reference evapotranspiration becomes known, the actual crop evapotranspiration can then be factored using:

$$ET_{\mathrm{crop}} = k_{\mathrm{c}} ET_0 \tag{3}$$

where ET_{crop} is the actual evapotranspiration, k_{c} is the crop coefficient and ET_0 is the reference crop evapotranspiration. The crop coefficient k_{c} varies from one crop to another, and for a given crop, varies with the stage of development within the growth cycle. Other factors which affect k_{c} are according to McMahon sowing and planting dates, rate of crop development, the frequency of rain or irrigation and climatic conditions.

Apart from the consumptive use, additional water has to be provided for the leaching out of excessive salts from the root zone of crops, and to compensate for the water lost during conveyance and application. In general, only about forty percent of the water released at head works actually goes into consumptive use according to McMahon. In addition, the leaching requirements vary with the type of irrigation system, the salinity of the irrigation water and of the root zone, and the soil texture. Doorenbos and Pruitt provide practical guidance on making allowances for leaching requirements and losses in water conveyance and application, during irrigation planning. If all these factors are taken into account, then the total monthly irrigation water requirement can be obtained using the Eq. (4) below, due to McMahon:

$$V_{\mathrm{irr}} = C \frac{f}{\eta_{\mathrm{p}}} \sum_{i=1}^{n_{\mathrm{c}}} \left(\frac{A I_{\mathrm{n}}}{1 - L_{\mathrm{R}}} \right)_i \tag{4}$$

where V_{irr} = total irrigation requirement (m^3/month)
η_{p} = the project irrigation efficiency (fraction)
f = flexibility factor, typically 1.2
A = area under a given crop (ha)
I_{n} = net irrigation requirement for a given crop (mm/month)
L_{R} = leaching requirement (fraction)
i = crop type counter
n_{c} = number of crop types
C = conversion factor = 10

2.3. Meeting Water Demands: Analysis of River Flow Data

With the demands known, it is then necessary to determine whether or not a dam with reservoir_storage will be required. This will require analyzing the record of river flow data at the potential abstraction site. To be reliable, the available record must be relatively long, usually at least twenty years of continuous daily or monthly flow measurements according to Adeloye. For direct abstraction from rivers, daily flows are required because abstraction decisions are made on a daily basis. If the decision is made to build a dam, then monthly data will be adequate for obtaining the relevant information.

One rule of thumb commonly used is that, when the demand is less than five percent of the average daily flow, according to Twort and Law, there is no need for a reservoir. In such a situation, the required water can be obtained by direct abstraction from the river, subject to constraints imposed by environmental considerations. In many countries, specifying a minimum residual flow in the river, below which abstraction is not permitted, caters for environmental needs. The determination of the minimum residual flow to be maintained at the abstraction site is a difficult exercise involving considerations of downstream riparian requirements, the need of migratory fish, and the impact of low flows on river ecology and habitats. However, once determined, it is important that the limit is rigorously enforced. Twort and Law give examples of residual flows for some UK rivers in which it is apparent that the residual flow, expressed as a ratio of the average daily flow, can vary widely.

2.3.1. Meeting Water Demands from a River: Estimating the Unregulated Yields of Rivers

The water that can be abstracted from a river after making allowance for the residual flow is known as the *net yield*. One way of obtaining this is to examine the daily flow record for the minimum and then to deduct the specified residual flow. However, rather than using the minimum flow on record, the daily flow having some specified *p*% probability of exceedance is used. In the UK and other countries, *p* is generally taken to be 98% but it could be any prescribed value.

To determine the net yield with a *p*% probability exceedance for a direct abstraction scheme, the starting point is the construction of the one-day low flow frequency curve. In some rivers large variations may occur in the daily flows within any given week, particularly where there are large industrial users who do not operate during weekends. In such situations, Twort and Law recommend using the total weekly flows instead of daily flows in the flow frequency analysis. A flow frequency curve relates the flow magnitude of a given duration, here one-day, to its probability of exceedance. The probability of exceedance is evaluated on the basis of the theoretical probability distribution function which best describes the flow data. For example, assuming the commonly used *normal distribution function,* the probability of exceedance can be estimated using:

$$\Pr(X > x) = \int_x^\infty f(x) \tag{5}$$

where X is the random variable, x is a flow of a given magnitude and $f(x)$ is the probability density function for the normal distribution given by:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}; \qquad -\infty < x < \infty \tag{6}$$

where μ is the mean flow and σ is the standard deviation of the flow. The expression $\frac{(x-\mu)}{\sigma}$, which we denote by z, has a mean of zero and variance of unity and is known as the *standard normal variate*. Equation (5) is difficult to evaluate analytically; hence its values for different values of z have been obtained numerically and tabulated in most statistical tables. Such tabulated values have also been used to develop empirical relationships between z and the exceedance probability p, such as given by Stedinger et al:

$$z = \frac{p^{0.135} - (1-p)^{0.135}}{0.1975} \tag{7}$$

Once the value of z corresponding to a given probability of exceedance is known, the corresponding value of x, namely x_p, can be found by inversion, i.e.

$$x_\mathrm{p} = z\sigma + \mu \tag{8}$$

Thus the analysis to obtain the flow frequency curve proceeds as follows:

1. Extract the minimum daily flow in each year of the record;

2. Sort the extracted minimum flows in ascending order of magnitude, then assign ranks to the sorted flows, giving rank 1 to the lowest and rank n to the highest, where n is the total number of years of record;

3. Assign probability to the ranked events using an appropriate plotting position formula such as that proposed by Cunnane:

   $$P(X > x) = 1 - \frac{r - 0.4}{n + 0.2}$$

   where r is the rank of an event of magnitude x.

4. Plot x (ordinate) against P (abscissa) on an appropriate probability grid paper. Often, the normal probability paper is used, and a better fit may be obtained by using the log-transformation of x rather than x itself.

If the data follow the normal or log-normal distribution, then the plotted points should indicate a straight line distribution when plotted on the normal or log-normal probability paper respectively in step 4 above. The theoretical straight line can then be superimposed, based on the normal (or log-normal) probability distribution function (see Figures 2 and 3 as examples). This theoretical straight line is the flow frequency curve from which flows corresponding to any desired probability of exceedance can be read off.

Then the net *p*% yield at the abstraction site, taking into account the residual flow, becomes:

$$Y_\mathrm{p} = Q_{1\text{-}day,\,p\%} - Q_\mathrm{res} \tag{9}$$

Where Y_p is the net yield, $Q_{1\text{-}day,p\%}$ is the one-day flow with a p% probability of exceedance and Q_res is the prescribed residual flow at the abstraction site.

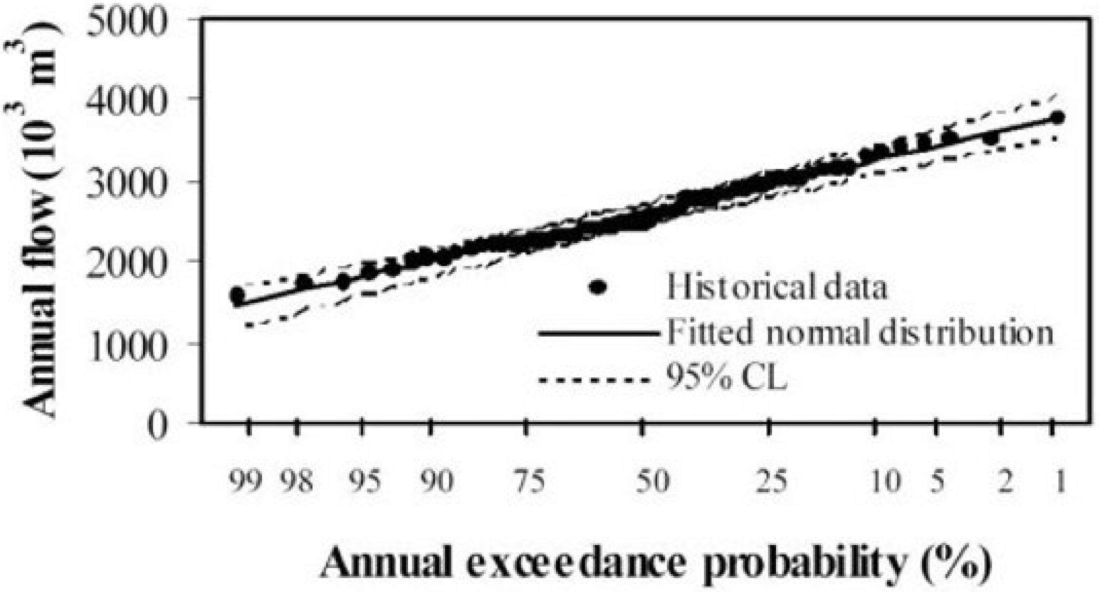

Figure 2: An example of a Flow Frequency Curve based on the Normal Distribution

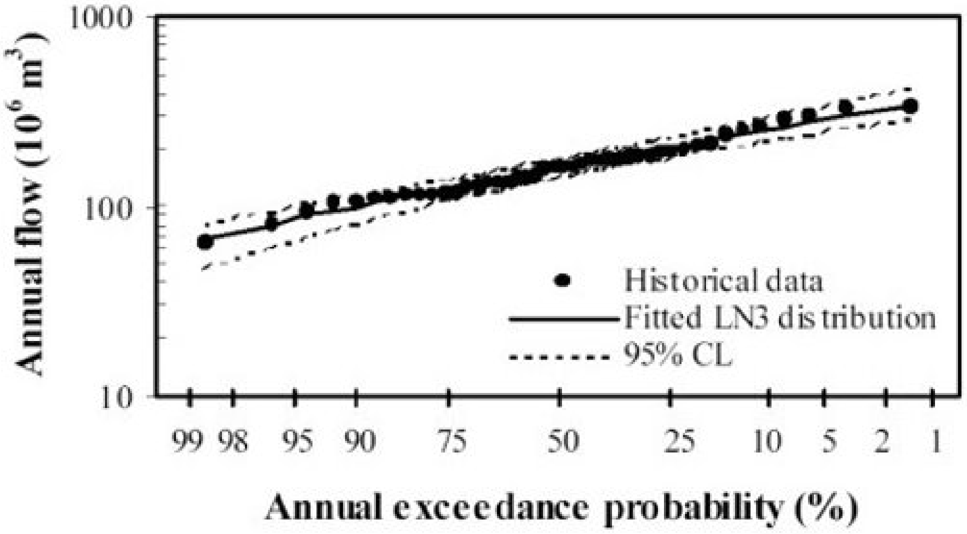

Figure 3: Another example of a Flow Frequency Curve, but based on the Log-normal Distribution

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Biographical Sketch

Adebayo Adeloye was born in Nigeria, Africa, and currently lectures courses in water resources and environmental engineering in the Department of Civil and Offshore Engineering at Heriot-Watt University in Edinburgh, UK. He holds the B.Sc. (First Class, First Position Honors) degree in Agricultural Engineering from the University of Ife (Nigeria), and the M.Sc. and Ph.D. degrees in Water Resources Engineering from the University of Newcastle upon Tyne, England.

He is a chartered engineer, (UK), member of the Chartered Institution of Water and Environmental Management (CIWEM) and a member of the British Hydrological Society. Dr. Adeloye is a recognized specialist and authority in the field of hydrology, specifically surface water resource assessment. Recently, he has developed graphical techniques allowing for evaporation losses in reservoir yield assessment. He has also guided studies on reservoir capacity determinations by critical period techniques using new algorithms developed by him.

His other research interests include the estimation of the economic value of hydrometric data, environmental flow analysis, rainfall-runoff modeling and the assessment of the impacts of climate and land use changes on water resources assessment. He participates in IAHR activities, mainly those of the African Division and attended recent international congresses in that respect. He is the author of several technical papers in various journals.