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January 2012

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HYDROLOGIC EFFICIENCY IN WATER CONSERVATION

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Introduction

The hydrologic cycle can be subdivided into three phases: 1) Humidity is transported within the atmosphere and becomes precipitation, and 2) Water moves downhill until eventually reaching the sea while all the time 3) Evapotranspiration returns exposed moisture to the atmosphere. During its movement, flowing water transports suspended sediments and dissolved minerals to reshape landforms and redistribute the mineral composition of the earth's surface throughout geologic time.

It is during the second phase that flowing water can be diverted for uses that generally add to evapotranspiration (through consumptive use) and transport (through waste disposal). The water resources development that serves these uses adds a humanly managed phase to the hydrologic cycle.

For simplification in our initial analysis, we will index the size of a water development project by the amount of dependable flow diverted into the water use system. Optimization of the diversion design involves computing facility costs and estimating benefits for a range of sizes and identifying the project size that maximizes benefits minus costs as illustrated on Figure 1.

The seeming simplicity of the process disguises a multitude of forecasting assumptions in forming the cost curve and need assumptions in forming the benefits curve. In both cases, a conservative, empirical approach in the face of uncertainty reduces the needs that can be fulfilled by a given water project. The theme of this paper is that scientific approaches to hydrology and to needs estimation can be used to increase water supply efficiency greatly. Conversely, the research needed to accomplish these increases defines the mixture of contributions required from the traditional

sciences to develop hydrologic sciences for water supply and water use. Both aspects are assessed individually below.

Water Supply Analysis

<u>Deterministic:</u> The deterministic approach to water supply analysis is to run a monthly water balance analysis based on inflows during a design drought and associated precipitation on and evaporation from the reservoir surface, annual demand pattern, water rights, and reservoir geometry. If the water balance were to be continued over the duration of monthly inflows used for the study, one would encounter a critical drawndown period at the end of which the reservoir storage would reach the minimum value. The yield that causes this minimum storage to just reach zero (Figure 2) is considered the firm yield. The analysis can be repeated for a range of reservoir sizes to derive a yield storage curve as shown in Figure 3. Estimates of costs for developing different storages can then be combined with Figure 3 to establish the cost curve in Figure 1.

Once a reservoir is constructed, actual operations will produce many drawdowns that could be plotted on the axes of Figure 2. Most of the time, the plot would fall above the critical drawdown curve. If one only knew for sure that a following wet period would prevent the reservoir from emptying, one could withdraw additional water, develop secondary yield, for added benefit (perhaps achieved through reduced groundwater pumping). Other times, the plot would fall below the critical drawdown curve, should this happen well down the curve, reservoir operation receives a signal to reduce deliveries below the design firm yield in order to prevent the storage from going dry and leaving users completely without water. Thus reservoir operation requires a secondary yield curve and a hedging curve.

The secondary yield may be estimated as:

$$Y_s = S_t/(T_c - t) \qquad (1)$$

where S_t is the difference between the reservoir storage in month t and the storage in month t of the critical drawdown period containing T_c months. If S_t is negative, hedging is suggested, and <u>stochastic</u>: Yield depends on inflow during the remainder of the critical drawdown period as well as current storage. Total inflow includes precipitation, evaporation, and seepage, but we will consider only river inflow for our first pass. If one knows the current monthly inflow (Q_t) and the inflow (Q_h) associated months t through T_c of the critical drawdown period, Equation 1 can be refined. A stochastic flow generation model provides an estimator of the form:

$$Q_{t+1} = Q_{i+1} = b\,(Q_t - Q_i) + \varepsilon\, V_i\ \ 1 - r^2 \qquad (2)$$

where t is the monthly counter through the critical drawdown period, i is the monthly counter over a year, Q is a flow, Q is an average flow, V is the standard deviation of the flow, b is the regression coefficient and r the correlation coefficient of flows between months i and i + 1, and ε is a random value taken from the distribution of residuals. Alternatively one might use an annual flow disaggregation model, but direct monthly flow generation is used here because month to month correlations are of primary interest. Equation 2 can be applied over the remainder of the critical drawndown period to estimate

$$Q_c = T_c \Sigma j{=}t\ Q_t \qquad (3)$$

Refinement of Equation 1 then gives:

$$Y_s = (S_t + Q_c - Q_h)/(T_c - t) \qquad (4)$$

where Q_c and hence Y_s are random variables. Multiple flow generations with Equation 2 can supply data for equation 4 to derive a probability distribution

for Y_s so that a value can be selected given an acceptable risk of the reservoir going dry.

Scientific: Equation 4 improves obtainable yield from information on current streamflow conditions based on statistically averaged associations. If we were able to develop a better understanding of the weather and runoff phases of the hydrologic cycle, we could improve on Equation 2 by reducing the variability expressed in ε. For this purpose, consider the relationship:

$$Q_c = Q_b + Q_r + \varepsilon_2 S \tag{5}$$

where Q_b is an estimate of baseflow (from past precipitation) and Q_r is an estimate of direct runoff (from future precipitation), ε_2 is a random value from the residuals using this predictor, and S is the standard error. Q_b estimates drainage from water currently stored in the catchment, and Q_r estimates runoff from precipitation yet to fall. One can envision:

$$Q_b = f\ (H_p, G_e, \ .\ .\ .) \tag{6}$$

recognizing that the baseflow depends on the history of precipitation on the basin and basin geology.

$$Q_r = f\ (F_p, F_e, R_m, \ .\ .\ .) \tag{7}$$

recognizing that the estimate of future runoff depends on the spatial and temporal distributions of future precipitation, the same characteristics of future evapotranspiration, and the available estimator for calculating runoff from precipitation. One might use the Stanford Watershed Model for R_m or go to a more sophisticated distributed model.

Advances in estimating Q_b and Q_r will reduce ε_2, reduce the variability in estimating Q_c from Equation 5, and consequently increase the value estimated for Y_s given an acceptable risk. At this point, it is difficult to suggest the forms that the improvements to Eqs. 6 and 7 should take to reduce ε_2; we will only note that substantial improvements can be achieved by:

1. Research for characterizing catchment storage and subsequent drainage rates for better estimating G_e.

2. Research for identifying and tracking precipitation patterns in ways that give better base flow predictors for H_p.

3. Research for more reliable precipitation forecasting for estimating F_p.

4. Research for better evapotranspiration forecasting and spatial characterization for estimating F_e.

5. Research to improve R_m for better precipitation-runoff modeling.

These areas of research generally fall into the disciplines of meteorology, soil physics, and geology and collectively comprise a research direction for hydrology. In fact, one can consider hydrology as a combination of these disciplines. If one were to represent research in these three disciplines along three axes in Figure 4, one can picture research in hydrology as progressing along a line through three dimensional space for the origin. The direction is determined by how best to integrate inputs from the three disciplines to reduce ϵ_2. If the scope of this overview were broadened to include the chemical determinants of water quality and the biological contributions to catchment response and runoff quality, Figure 4 could be expanded to 5 dimensions. Of course the basic research represented contains many pitfalls, and one might better represent the line in Figure 4 by a streamtube.

Prospects: Several parting observations should be made on the above structure for defining hydrologic research needs. The nature of the discipline, the importance of interdisciplinary activity (a reminder to hydrologists to keep in contact with contributions from the basic sciences), and showing how advances can be made in water supply management.

1. The improvements will become harder to achieve with longer periods T_c -t.

2. The uncertainties are greatest in long-term weather forecasting, F_p. Nevertheless, the following possible opportunities can be pursued.

3. At some point in the more distant future one may revert to the model of Eq. 2.

4. Some positive actions to influence R_m through watershed management may be possible. These actions could increase runoff (or reduce flood peaks) or reduce sediment or pollution production.

   a. Can be expanded from storage to include reuse concepts too.

5. Promising research directions for decline with the achieveability issue are the weather processes that increase or decrease precipitation probabilities over various time horizons, their precursors, global weather patterns, external causality, etc.

Needs Analysis

Deterministic: The long-practiced approach to estimating water diversion requirements is to extrapolate from data on past use and delivery losses. One can extrapolate from a past record on uses made, expand the numbers proportional to growth factors, and proportion the estimates over an annual use cycle. Economists have long complained over the high cost of the "requirements approach" to water supply planning stemming from the fact that it projects water use habits developed in a setting of low water costs and exaggerates water uses with projections far higher than they will occur under future conditions of reduced water availability and higher cost. This analysis goes further by suggesting that the water inputs required to achieve given outputs can be estimated by scientific analysis of the contribution that water performs in production.

Irrigation Efficiency: The scientific analysis of the productivity of water

has been advanced furtherest in irrigation. There, field plots have been used

to derive crop production functions that show crop yield to increase with

water deliveries to a maximum yield (U_m) and then decrease thereafter as shown

in Figure 5. From a curve of this form, one can use the principles of

marginal economic analysis to identify the point on the rising limb of the

curve where the value added by a marginal increase in yield just equals the

marginal cost of supplying additional water (U_E). Actual use (U_a) exceeds

this amount for a variety of reasons that can be combined in the relationship:

$$U_a = U_e/\eta_e\eta_m\eta_f\eta_c = U_e/\eta_t \qquad\qquad (7)$$

where

η_t = The overall efficiency of the use process defined as the ratio of

amount shown to be required to maximize the efficiency of water use to that

actually used. The overall efficiency can also be defined as the product of

four component efficiencies.

η_e = The component efficiency representing the fraction of the use

required to achieve maximum yield associated with the economically optimal

use. This efficiency is less than unity because farmers lack the economic

incentive to cutback water use given the complexity of the additional

management care required.

η_m = The component efficiency representing management losses associated

with needed nonuniformity associated with soil variability over the field

while irrigating to match the needs of the point requiring most, incorrect

estimation of the water requirements or the amount actually applied and

irrigating extra to make sure, etc.

η_f = The component efficiency representing losses from the farm headgate

to the point of use. The farmer tries to completely fill the soil root zone

to its field capacity (the volume of water that can be held in the root zone against the downward percolating force at gravity). In trying to achieve this filling losses occur because of nonuniformity in spreading water over the field, deep percolation below the root zone, operating losses at the end of the field or the field distribution system, and seepage or evapotranspiration from field ditches.

η_c – The component efficiency representing losses from the water source to the farm headgate as caused by canal leakage, evapotranspiration from the canal surface, and operating losses from the end of the canals.

As the price of water increases, farmers have incentives to increase these efficiencies by, respectively, η_e) reducing targeted water use based on the principle of deficit irrigation, ηm) more careful estimation of true crop water requirements and their distribution of over the fields, η_f) field losses (generally achieved by going from flooding to furrow, sprinkler, or drip systems), or η_c) conveyance losses (generally achieved by canal lining or converting to piped systems). Our primary concern in needs assessment is η_m. Several observations can be made:

1. The primary contribution to greater efficiency through better management comes through better estimation of current water requirements and the variability of these requirements over the field. Irrigation generally targets application to the maximum requirement.

2. Irrigation does not supply water precisely as it is needed for evapotranspiration but rather provides water to fill the soils to field capacity at various time when the soil moisture drops close to the point where further drying would reduce yield. Thus irrigation is something like filling a terminal storage.

3. The scientific goal in water use estimation is to determine the requirements of given plants, how these requirements vary over the plant population, and how to vary the water deliveries to have a supply always available where needed. Thus the goal in irrigation, as in other uses, requires estimation of volume and rate requirements and of the variability in both. Also, scientific needs estimation can be combined with supply analysis to determine the extra benefits from secondary yield by moving up the crop production function and the losses from hedging during periods of shortage forcing downward movement.

Extended Efficiency: The principle followed in the above analysis was to conduct 4 agricultural experiments to determine how crop yield varies with supplied water and how consumptive use rates vary spatially (largely with soil conditions) and temporally (largely with weather conditions). Have the water serve a biological function, and its productivity is determined by the weight of saleable crop produced. Generalization to other water uses can be done by determining the function water serves, productivity in each function, and the value produced. The principal water applications are:

1. Landscape vegetation. Landscape productivity, but the desired result is an appearance of lushness and beauty rather than maximum weight of vegetable matter produced. While crop productivity and beauty may maximize for the same water application, the curves of increasing mass yield and attractiveness with additional supplied water are probably quite different.

2. Animal biology. People and animals, like plants, require water for good health and growth. Amounts can be estimated from activity levels and the weather. While human requirements are largely satisfied by drinks other than tap water and are hard to meter out in units exactly matching drinking

desires, the concept η_e probably makes little sense. The other component efficiencies dc as will be presented in the attached table.

3. <u>Cleansing.</u> Because of the properties that cause it to be called the universal solvent, water is used for a variety of functions in industry and around the home that involved dissolving some substance for transport elsewhere. Most of these applications are for cleansing, but diverse other uses also exist. For example, sugar syrups may be used in home or commercial canning.

The typical cleansing operation mixes a cleansing agent (soap) into the water, places the mixture in contact with a dirty surface, and applies mixing or scrubbing energy until the dirt or grime is taken up. Dirty surfaces may be cleaned in stages with some variation in cleansing agent, mixing energy or timing.

If one takes the actual cleansing of the dirty surface as the critical unit process, one can view the dissolution rate as

$$R = k(C_m - C) \ E \hspace{4cm} (8)$$

where C increases as dissolution occurs over time, where k increases with soap content and varies with the land and soap and E increases with the rate of energy use and probably varies with the energy form. Should the rate, R, fall too low, the originally cleanser can be released with fresh water.

One can then examine a surface for the nature and volume of grime to be removed and calculate the water requirements from dissolution chemistry based on Eq. 8. Energy and soap inputs can be traded for water saved. Water needs can be calculated from the volume of grime that must be removed per unit time, the surface area over which it is spread, and the frequency of cleansing.

4. <u>Thermodynamics.</u> Because of its high specific heat, latent heats at freezing and boiling, and the temperature-pressure volume properties of steam,

water is used for a variety of heating, cooling, and steam cycle applications, principally conveying heat for heating or cooling, for temperature control by preventing rapid fluctuations, or in steam engines.

Heating or cooling depends on a similar equation to Eq. 8. A temperature control water requirement must be based on the central volume to be managed. One can then compare the control capacity of the water with the maximum allowable temperature change.

Steam cycle equations are also available. The typical heating or cooling water requirement can be calculation from:

$$H - CW \tag{9}$$

where the heat transport rate capacity equals the specific heat of water times the water flow rate. Loss coefficients are needed to account for extra heat that must come from the source to accomplish desired warming. A transport equation can also be applied to carrying any water after cleansing.

6. <u>Aesthetics.</u> Water also possesses considerable value as an agent for enhancing site esthetics whether flowing or ponded. Recreational swimming can also be included here. The principal uses here are 1) to restore evapotranspiration losses, either directly from the water surface or indirectly from associated vegetation, 2) to provide for a minimal level of outflow circulation to prevent stagnation (possibly calculated from the volume of incoming salinity and outflow to prevent salt buildup), 3) possible biological stagnation, 4) space required for swimming.

<u>Efficiencies by Use:</u> At this point we should also consider the scientific limits to efficiency terms in Eq. 7. Full 100 percent efficiency is limited because of 1) the scientific responsibility of preventing all losses, 2) economic and social factors limiting the affect that people devote to

increasing efficiency, 3) human preferences for something less than the fully efficient state, and 4) other?

One can approach estimation of the component efficiencies in Equation 7 either empirically based on observations of actual water use (an exercise that would give quite low values) or from the scientific limits (quite high values). The approach at this point then becomes one of determining whether the low empirical values are the consequence of some socio-institutional constraint or whether the scientific analysis shows the way to water conservation.