Drought Storage Allocation Rules for Surface Reservoir Systems

Jay R. Lund[1]

Abstract: This technical note develops a simple drought storage allocation rule to minimize evaporative and seepage water losses from a system of reservoirs. Such a rule might have value during a prolonged drought, when the value of lost water is likely to be particularly high. Typically, concentrating water storage in one or a few reservoirs reduces overall water losses compared to "balancing" storage among reservoirs. Paradoxically, concentrating storage during a drought tends to minimize reservoir surface area available for recreation, increasing recreation losses even as it minimizes water losses.

DOI: 10.1061/(ASCE)0733-9496(2006)132:5(395)

CE Database subject headings: Droughts; Reservoirs; Seepage.

Introduction

Reduction in evaporative and seepage losses from reservoirs is particularly important and valuable during a drought (Kelley 1986). For a multireservoir system, can storage rules among reservoirs be devised to minimize such physical losses? Would such rules tend to distribute water among reservoirs or concentrate water storage in a single reservoir? This technical note explores this problem and finds that for some fairly general circumstances, water losses are lessened if water storage is concentrated in a single reservoir depending, of course, on local constraints. Some potential socioeconomic losses from this water conservation strategy are also discussed.

Reservoir Losses during a Drought

The major losses of water from a reservoir during a drought are evaporation to the atmosphere and seepage to groundwater. These losses can be estimated for a reservoir in a valley with a very regular geometry, having valley side slopes of a and a longitudinal valley slope of b (Fig. 1). Here, H=deepest depth of water in the reservoir (at the dam); W=half width of the triangular water surface (at the dam), and L=longitudinal length of the water surface. While no single reservoir will ever have these characteristics, this shape is similar to that of many surface reservoirs. The surface area of this reservoir is $A=LW$, and its storage volume $S=1/3LWH$. We later compare this reservoir shape with those of several actual reservoirs.

Evaporation

Evaporative losses from a reservoir are generally taken to be proportional to the surface area of the reservoir, $E=eA$. By substitution, Eq. (1) is the evaporative loss from a reservoir with storage S

$$E = eab\left(\frac{3S}{ab}\right)^{2/3} \tag{1}$$

Seepage

Many seepage "losses" are eventually regained downstream in the form of streamflows or groundwater. However, during a drought,

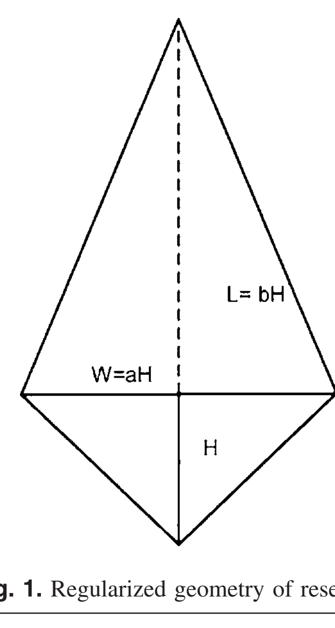

Fig. 1. Regularized geometry of reservoir

[1]Professor, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, Davis, CA 95616. E-mail: jrlund@ucdavis.edu

Note. Discussion open until February 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this technical note was submitted for review and possible publication on June 2, 2005; approved on September 14, 2005. This technical note is part of the ***Journal of Water Resources Planning and Management***, Vol. 132, No. 5, September 1, 2006.

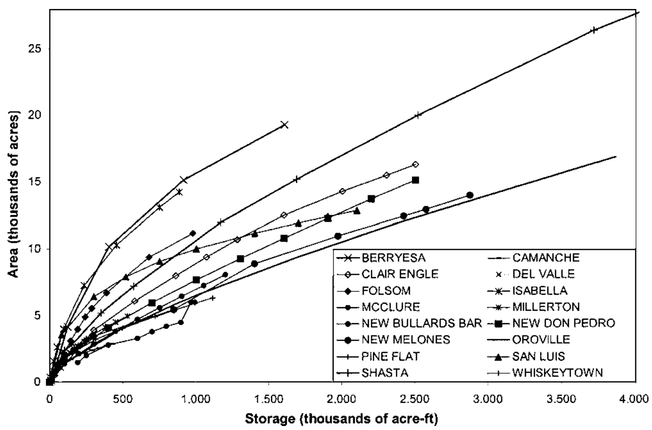

Fig. 2. Area–storage curves for 16 large reservoirs in California

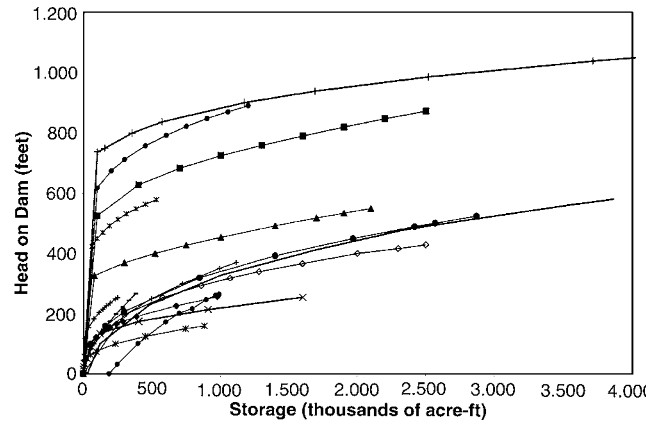

Fig. 3. Head–storage curves for same 16 large reservoirs in California

seepage is a loss of water available during a critical time. Seepage losses from the reservoir will need to flow under the dam or hillsides, and should be proportional to the head on the dam (by Darcy's law). With some algebra, this gives an approximate representation of seepage loss as a function of storage in the following equation:

$$D = d\left(\frac{3S}{ab}\right)^{1/3} \tag{2}$$

Marginal Losses

In developing an operating rule that minimizes losses, we would like to compare the additional loss from an additional unit of water placed in each reservoir (the marginal water loss). These marginal losses are merely the first derivatives of Eqs. (1) and (2), appearing as Eqs. (3) and (4), respectively

$$\frac{dE}{dS} = 2e\left(\frac{ab}{3S}\right)^{1/3} \tag{3}$$

$$\frac{dD}{dS} = \frac{d}{3^{2/3}(ab)^{1/3}}S^{-2/3} \tag{4}$$

Concave Loss–Storage Relationships

The above geometric reasoning indicates that while reservoir surface area and seepage head increase with storage, they increase at a diminishing marginal rate (second derivative is negative). Surface area (and evaporation) and head on the reservoir are therefore concave functions of storage. This geometric result is generally confirmed for the storage–area relationships of 16 large reservoirs in California, illustrated in Fig. 2. Fig. 3 plots head–storage curves for the same reservoirs. This relationship is similarly concave. Reservoir losses generally tend to be concave functions of storage.

Drought Storage Rule

Since marginal losses from additional storage (second derivative of losses as a function of storage) generally decrease with increasing storage, losses will be minimized if, to the extent practicable, water is stored in one reservoir, rather than distributed among many. The particular reservoir(s) chosen for concentrating storage should be those with the least loss potential. Stated simply: "to minimize water losses during a drought, water storage should be concentrated in reservoir(s) with the least loss potential."

Balancing storage among reservoirs, a common practice where each reservoir is filled to a similar percentage of its overall capacity, does not minimize water losses. Indeed, if all reservoirs in a system had the same loss–storage relationship, balancing storage among reservoirs would maximize water losses during a drought. The particular reservoirs where storage should be concentrated to minimize water losses is likely to be driven by the combined effects of reservoir geometry and local surface evaporation and seepage rates. Only in systems where loss functions are convex would it make sense to balance water storage among reservoirs to minimize water losses. For mild or moderate droughts, where most reservoirs remain in the relatively linear portion of the relationships between surface area, head, and storage, the reductions of water loss from concentrating storage might be relatively small. Under severe drought, when storages tend to be in the more concave portions of these relationships and water is much more scarce, water loss reductions are more likely to justify operating rule modifications.

Rule Implications

In the course of a prolonged drought, it is often possible to shift some storage among reservoirs, whether directly (from upstream to downstream reservoirs) or by indirect means (such as wheeling releases among reservoirs in parallel or making all releases from downstream reservoirs while allowing upper reservoirs to fill, to the extent of available inflows). For systems where it is difficult to move water among reservoirs during a drought, then perhaps it is worthwhile to arrange for carryover storage in a reservoir system to be distributed more according to loss minimization than according to spill minimization.

Paradoxically, this rule for minimizing water losses by concentrating drought storage in one or a few reservoirs will tend to exacerbate the appearance of drought, in terms of pictures of dry reservoirs on the evening news, and worsen some drought impacts, in terms of potential lost reservoir recreation benefits (which, like evaporation, also tends to be positively related to reservoir surface area). Economic losses and political controversies arising from recreation loss might mean that while concentrating storage in the fewest number of reservoirs is physically optimal, it might not be economically or politically optimal.

Similar difficulties can arise for hydropower, environmental, or other operating purposes. In addition, changes to normal storage operations to reduce evaporative or seepage losses are likely to require prearranged agreements with water-right holders, regulators, and other interested parties in a system. This points to the importance of having contingency plans and agreements in place before the occurrence of a drought.

Conclusions

This technical note develops a simple drought storage allocation rule to minimize evaporative and seepage water losses from a system of reservoirs. Such a rule is likely to be valuable during a prolonged drought, when the value of lost water is likely to be highest. Typically, concentrating water storage in one or a few reservoirs minimizes overall water losses compared to "balancing" storage among reservoirs. Paradoxically, concentrating storage during a drought tends to minimize the overall reservoir surface area, which tends to minimize reservoir area available for recreation, and increase recreation losses, even as it minimizes water losses. Such rules are likely to require advance agreements to accommodate multiple water uses and right holders.

Acknowledgment

Three anonymous reviewers are thanked for their suggestions for improving this technical note.

References

Kelley, K. F. (1986). "Reservoir operation during drought: Case studies." *Research Document No. 25*, Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, Calif.