

Hydrological Impact Assessment of Ensembles of Small Reservoirs

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Scope

This tool helps assess the hydrological impact of an ensemble of small reservoirs with regard to evaporative losses, spillage, water used for irrigation, and irrigation excess drainage. Once the tool has been made operational for a certain region, it can be used to predict what may happen when the number of reservoirs is increased. The tool uses stochastic simulation and assumes that the main statistical properties of the ensemble do not change when new reservoirs are added. The advantage of this approach is that it is not necessary to precisely define the location of each new reservoir as it is added.

A set of ensemble characteristics is needed as an input for this tool, in particular the statistical distribution of reservoir surface area, and the relationship between surface area and volume (which can be obtained with the Small Reservoir Capacity Estimation Tool, described elsewhere.) Additional assumptions that are needed include values for rainfall/runoff relations and water use efficiencies. Reasonable default values can be used initially, but these should be critically assessed and improved based on local research and local conditions. This tool should be seen as an analytical framework or algorithm, not as a global ready-to-run model.

Target group

On the basis of the information provided here, a technically schooled person with introductory knowledge of hydrology and water resources management should be able to assess the likely hydrological impact of an ensemble of small reservoirs. Once the tool is operational, it should be able to interactively provide answers about the hydrological impact of reservoir ensembles to non-specialists, such as regional planners and donor agencies working at regional/provincial, national, or sub-continental scales of analysis.

Requirements for application

Minimum requirements for this tool include an inventory of existing reservoirs (see the Reservoir Inventory Mapping Tool, described separately) and a regionally-relevant estimate of the relationship between reservoir surface area and reservoir volume (see the Small Reservoir Capacity Estimation Tool, described separately). In addition, access to a reasonably good computer is needed.

Access to local and/or global databases, such as Hydrosheds (<http://hydrosheds.cr.usgs.gov>) and CRU climate data (<http://www.cru.uea.ac.uk>), is facilitated through a good internet connection. The code provided here is Matlab code but can easily be transcribed into any other programming language by any person with computer programming skills.

Description and application

Ensembles and hysteresis

This tool is based on the notion that an ensemble of small reservoirs has certain statistical properties (such as probability distributions, area/volume relations) that are relatively constant, even when the number of reservoirs is increased. By randomly drawing from established distributions, one can increase the number of reservoirs and simulate the total impact of the (enlarged) ensemble. The scaling laws of ensemble impacts are governed by these statistics. The major alternative to this approach would be to site and design individual new reservoirs and simulate their behavior. This would be feasible for a small number of new dams but not for larger numbers. For example, if the government of Burkina Faso wished to know the likely impact of doubling the number of small reservoirs from 2000 to 4000, the tool described here would be more appropriate.

Small reservoirs are typically found in smaller headwater streams. It is convenient to think of an ensemble of small reservoirs as one larger reservoir, perhaps situated at a higher order stream downstream from the headwater streams. Unfortunately, there is a little snag. An ensemble of differently sized reservoirs fills and empties along different trajectories (such a phenomenon is called hysteresis). This is illustrated in Figures 1A&B.

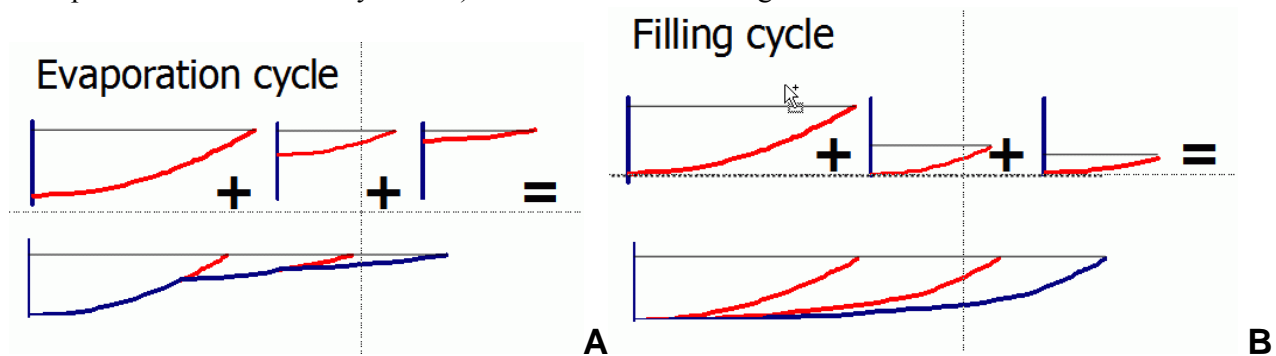


Figure 1 A: Evaporative cycle of three differently sized reservoirs, starting with completely full reservoirs. B: Filling cycle of three differently sized reservoirs, starting with completely empty reservoirs.

When all reservoirs are full, such as at the end of the rainy season, and losses are entirely due to evaporation, all reservoirs begin to empty (because of evaporation) but the smallest one will empty first. In order to sum all reservoirs into one larger reservoir, one would align the tops and add them up, as in Figure 1A. When all reservoirs are empty, such as at the end of the dry season/ beginning of the rainy season, all reservoirs begin to fill as runoff commences – but the smallest reservoir will be the first to completely fill up. To combine the reservoirs into one larger reservoir, one would now line up the bottoms and add them, as in Figure 1B. In one large reservoir, the parts that would empty out first through evaporation will be the last parts to fill back up again. In an ensemble, the reservoirs that fill up first, also empty out first. This causes the hysteretic behavior within reservoir ensembles.

An important implication is that the complete history of filling and emptying has to be taken into account to determine the complete state at a given moment. One might hope that this is not significant and that average large reservoir behavior is good approximation. Simulations show, however, that in general, hysteresis cannot be ignored. The approach taken here simulates

hundreds of reservoirs in parallel to obtain summary states such as total amount of water stored or spilled. The speed of even modest computers allows for simulation of hundreds of reservoirs for a hundred years, taking a few minutes at most.

To set up the simulation, several statistical distributions and correlations need to be collected. Once these are in place, it is merely a matter of bookkeeping to obtain ensemble behavior.

Information needed

The following sets of information are needed:

1. Distribution of reservoir sizes (surface areas)
2. Surface area – volume relationship
3. Reservoir size – watershed size correlation
4. Climate data (rain, potential evaporation, rainfall/runoff relation)
5. Cropping information, including water use efficiencies

1. Distribution of reservoir sizes

The Reservoir Inventory Mapping Tool (described separately) shows how the areas of small reservoirs can be mapped with satellite images. The result for Ghana's Upper East Region is shown in Figure 2.

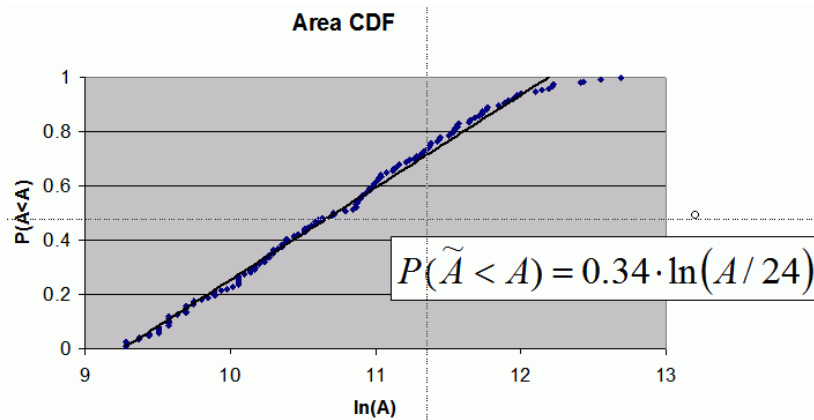


Figure 2: Cumulative Distribution Function for reservoir area size in square meters for Ghana's Upper East Region (Liebe et al, 2005)

Reservoirs tend to follow a Pareto Distribution: The chance of finding a reservoir of a certain size or smaller increases with the logarithm of that size. This is shown in Figure 2, where the Cumulative Distribution Function (CDF) based on satellite images is given. The way to construct such a curve is to order them from small to large and to plot the logarithm of the size (x-axis) against the chance of finding a smaller reservoir (y-axis). The chance of finding a smaller reservoir is simply the rank divided by the total number of reservoirs in the survey: The chance of finding a reservoir that is smaller than or equal to the largest reservoir is equal to one. In Figure 2, the chance of finding a reservoir with an area of which the logarithm is 11 or less (area = $\exp(11) \approx 60,000 \text{ m}^2$), is about 0.6. Once the individual reservoirs are plotted, a straight line can be fitted, which in this case can be described by the equation:

$$P(\tilde{A} < A) = 0.34 \cdot \ln(A/24)$$

Once the CDF is known, as many reservoirs as are needed can be drawn following this same distribution. A random number is drawn between zero and one from the uniform distribution. This number is plotted on the y-axis and a horizontal line is drawn from this point. The size of the reservoir can be found on the x-axis where this horizontal line crosses the CDF.

2. Area – volume relation

Satellite images are good in delineating surface areas but volumes are usually more interesting. Fortunately, good regional correlations can be found between surface area and volumes (Liebe 2002, Liebe et al, 2005, Sawunyama et al 2006). Ways to establish such correlations are shown in the Small Reservoir Capacity Estimation Tool, described elsewhere. The result for the Upper East Region of Ghana is shown in Figure 3.

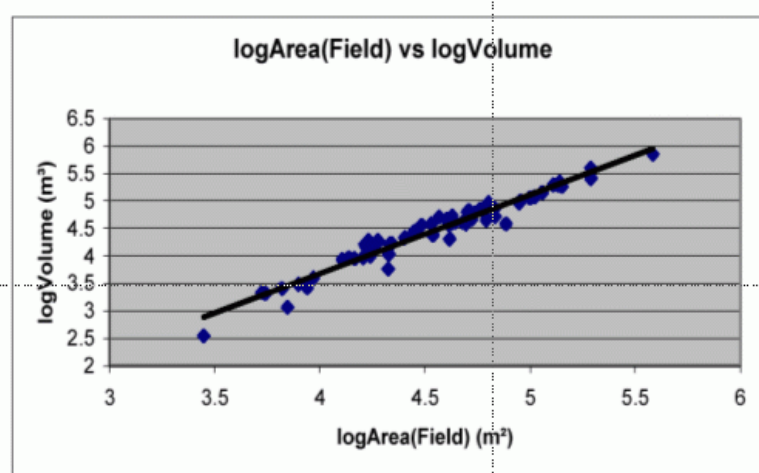


Figure 3: Correlation between reservoir areas and volumes (Liebe et al, 2005).

A power relation can be observed which for triangular reservoirs (half a pyramid) has an exponent of 1.5. Once surface areas are known, volumes are readily derived from the fitted curve. In Ghana, 98% of the variation in volume can be explained by the variation in surface area. In such a case, one may simply use the relation and neglect the noise, basically taking the relation as deterministic.

If the correlation is not as strong as found in Ghana, it is advisable to construct a stochastic relation consisting of a deterministic and a “statistical part”. The deterministic part is obtained from a curve that best fits the data. This part is then subtracted from the actual data. These differences are more or less random. By fitting a statistical distribution to these differences, one obtains the statistical part. Usually, a normal distribution characterized by a mean of zero and a standard deviation comes pretty close to this statistical distribution. For the simulation, one subsequently draws from this statistical distribution and adds the deterministic parts. In a formula, this may appear as:

$$\text{Volume} = 0.00567 \cdot \text{Area}^{1.43} + \varepsilon$$

with ε a random variable drawn from a normal distribution with zero mean.

3. Input: Reservoir size – watershed size correlation

Steps 1 and 2 are used to produce estimates of the most relevant physical properties of the actual reservoirs in the ensemble. What is needed next is the water balance, consisting of inflow, evaporation, seepage, spillage, and water used for irrigation. Expert judgments are used here: relevant local knowledge can be readily included when available.

Inflow is determined by watershed size, rainfall over the watershed (and reservoir) and the way rainfall is transformed into runoff. Watershed size can be determined on the basis of topographic data whereby the watershed surface area is assumed to be roughly equal to the runoff generating area. For this tool, Shuttle Radar Topography Mission (SRTM) data were used. These data are available globally through <http://srtm.usgs.gov>. Watersheds can be outlined in any standard GIS package. An improved SRTM dataset with built-in watershed delineation capacity is available through: <http://hydrosheds.cr.usgs.gov>. The result for a number of reservoirs is shown in Figure 4.

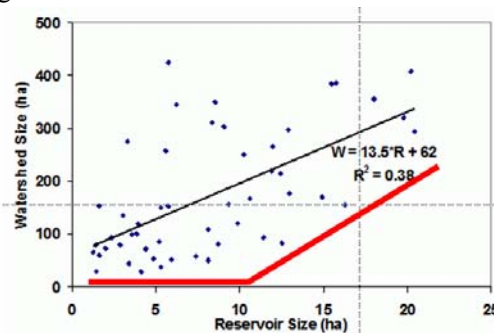


Figure 4: Correlation between reservoir size (ha) and watershed size (ha) in Ghana's Upper East. The black line gives the linear correlation. The thick red line is the lower envelope used to model size/watershed distribution.

Figure 4 shows that there is not a very strong correlation between reservoir size and watershed size. This correlation is important in helping understand the siting of reservoirs. It generally makes good sense to build small reservoirs (5-10 ha) in large watersheds. When built with a good spillway, this is no problem. Reservoirs fill up quickly and provide water during the dry season. Siting is best determined by proximity to a village, favorable valley/dam geometry, and presence of roads and/or building materials. Hydrology does come into play for the larger (>15 ha) reservoirs. It does not make sense to build a large reservoir in a small watershed because it would never fill up. This binary correlation was modeled by drawing a lower envelope under the graph and fitting the remaining distance with a beta distribution. Other distributions can also be used as long as the main characteristics of the stochastic distribution between reservoir and watershed sizes are captured. On the basis of this, a watershed size can be assigned to each reservoir based on its size and a (random) drawing from the distribution.

The hydrological model used here is very simple and based on observed large-scale behavior in the Volta Basin. Better hydrological models are available but are not needed to merely demonstrate the functioning of this tool. The model assumes 9% of the rain falling on the watershed runs off, following an average monthly distribution.

4. Climate data (rain, potential evaporation))

Monthly time steps are used here coarse climate data are sufficient. These can be obtained through the Climate Research Unit of East Anglia University (<http://www.cru.uea.ac.uk>).

5. Cropping information, including water use efficiencies

A cropping calendar is needed, together with K_c values and water use efficiencies. Most difficult to estimate is total irrigated area. Here, a learning algorithm is used that extends the irrigated surface area from year to year until the number of failures (no more water at the end of the rainy season) is reached. Local information should be used where available.

Simulation model

All information is now in place to simulate the behavior of an ensemble of reservoirs by simple accounting of the volume of water flowing in, evaporating, spilling, and being used for irrigation.

The file '`SRC_Sim5.m`' contains a sample code that keeps tracks of the flows. The code can be found with this tool in digitized form. If you received this tool without '`SRC_Sim5.m`', please contact the author at n.c.vandegiesen@tudelft.nl. The code also contains a learning routine to adjust irrigated area based on previously available water. The code is annotated and an attempt has been made to use meaningful names for the variables, so it should be readable without too much trouble. Figure 5 shows a typical simulation result whereby average depth is plotted against average stored volume. All other terms, such as evaporation, spillage, irrigation water, and inflows, are also available.

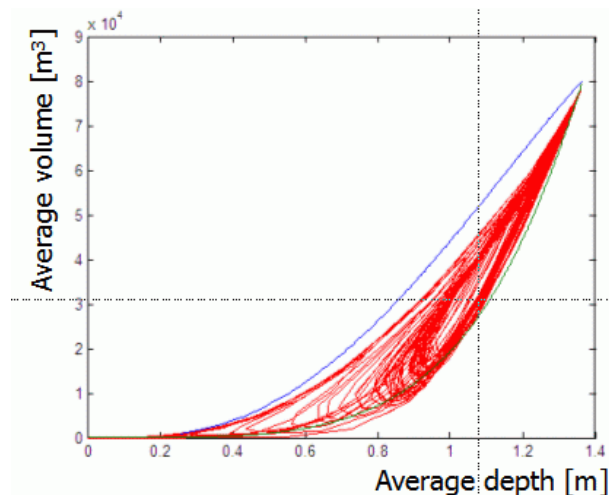


Figure 5: The thin red line shows the evolution of the average depth and volume of one thousand reservoirs over on hundred years. The blue line is the theoretical upper envelope that would be followed if the reservoirs are filled completely with average runoff (no losses), starting from being completely empty. The descending green line is the lower theoretical enveloped for the case the completely filled ensemble empties out completely through evaporation only.

Figure 5 shows that, in general, hysteresis cannot be neglected. At every point in time, the average behavior of, say, one thousand reservoirs is now known. One can either adjust the number of reservoirs and run the program again, or simply assume that the averages will not change. Then, by multiplying average reservoir states and flows with the total number of

reservoirs for which one want to know the impact, total impact can be calculated. This method is easy to use in the context of decision making or a WEAP application.

Lessons learned, recommendations, and limitations

This tool can be developed further, especially where local circumstances and information availability differ from those described above. It should, in first instance, be seen as an analytical framework that guides users through the steps necessary to assess the hydrological impact of ensembles of small reservoirs. However, it has not been tested extensively. Validation of the tool with respect to the development of total storage over time in an existing ensemble is the recommended next step. A possible way towards regional validation would be through radar based monitoring (see the tool on Reservoir Radar Monitoring, described separately).

References

- Annor 2007: Delineation of small reservoirs using radar imagery in a semi-arid environment: A case study in the Upper East Region of Ghana, Master thesis, UNESCO IHE, Delft, Netherlands (http://www.smallreservoirs.org/full/publications/reports/Annor_FO.pdf).
- Liebe 2002: Estimation of Water Storage Capacity and Evaporation Losses of Small Reservoirs in the Upper East Region of Ghana. Diploma thesis, University of Bonn, September 2002. (http://www.glowa-volta.de/publications/printed/thesis_liebe.pdf)
- Liebe et al 2005: Estimation of Small Reservoir Storage Capacities in a semi-arid environment. A case study in the Upper East Region of Ghana. J. Liebe, N. van de Giesen, M. Andreini. *Physics and Chemistry of the Earth*, 30: 448–454, 2005 (doi:10.1016/j.pce.2005.06.011, <http://dx.doi.org/10.1016/j.pce.2005.06.011>).
- Liebe et al 2008: Monitoring small reservoirs' extent and volume in a semi-arid area with ENVISAT ASAR. Jens R. Liebe, Nick van de Giesen, Marc S. Andreini, Tammo S. Steenhuis, submitted for publication, under review, available through SRP.
- Sawunyama et al 2006: Estimation of small reservoir storage capacities in Limpopo River Basin using GIS procedures and remotely sensed surface areas – Case Study of Mzingwane Catchment, Zimbabwe. T. SAWUNYAMA, A. SENZANJE and A. MHIZHA, 2006, *Physics and Chemistry of the Earth*. Vol.31, Issues 15-16:935 – 943. <http://dx.doi.org/10.1016/j.pce.2006.08.026>
- Tiger project AO2871: <http://tiger2871.shorturl.com>

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Free GIS software: <http://www.itc.nl/ilwis/>

Free modeling software: <http://www.python.org>

Data sources

Watershed topography: <http://hydrosheds.cr.usgs.gov>

Climate data: <http://www.cru.uea.ac.uk>