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Use of small reservoirs in West Africa as remotely-sensed cumulative runoff gauges

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Throughout the semi-arid to sub-humid tropics, people have built thousands of small reservoirs to overcome dry periods. The social value of water in such regions as West and Southern Africa, South and South-East Asia, and central Brazil, is very high. Small reservoirs, with volumes from 10^4 to 10^7 m^3, provide the rural population of these areas with water for households, cattle, fisheries, and small-scale irrigation. Besides positive socio-economic impacts, small reservoirs may also have negative impacts on human health and aquatic ecology. The general thinking is that construction of reservoirs at village level has less negative impact than the construction of large dams. As such, many governmental and non-governmental development programs promote further construction of small reservoirs.

One obvious question with respect to this development is if an optimal density exists, beyond which further construction of reservoirs shows diminishing returns due to limited total water availability, market saturation, or negative health and environmental impacts. Within the CGIAR's Challenge Program on Water for Food, the Small Reservoirs Project[*] addresses these research questions concerning the overall behavior of reservoir ensembles in the Volta, Limpopo, and Sao Francisco basins. The work presented here also builds on field work done within the framework of the GLOWA Volta Project[†].

Hydrological knowledge of the semi-arid and sub-humid tropics is very limited and the observation network in these parts of the world has been declining rapidly since the hydrological decade. Remote sensing still holds great promise to fill gaps in ground-based observation networks but scientific progress has been slower than anticipated. One added problem is that the regions considered here are under almost permanent cloud cover during the rainy season. This makes microwave-based (radar) remote sensing the main source of data with respect to the hydrological state of the land surface, whereby, unfortunately, the luscious vegetation tends to obscure any soil moisture signal during the wet season. There is, however, one well-established application of radar satellite imagery and that is the mapping of open water. Clearly, (changes in) volumes stored in the thousands of small reservoirs contain imperfect but hydrologically relevant information. The question now is to what extent we can use reservoir states, as derived from radar images, to calibrate and validate hydrological models.

In the remainder, we first briefly sketch the different components of the water balance of the reservoirs, and how different parts of the balance can be observed or modeled. This sketch includes a simple accounting scheme that allows keeping track of remotely-sensed runoff estimates, consisting of most likely runoff, and, under specific conditions, minimum and maximum discharges that constrain possible model output. Finally, the limitations and potential of using remote sensing of

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[*] `http://www.smallreservoirs.org`

[†] `http://www.glowa-volta.de`

reservoirs for model calibration is demonstrated by a simulation, showing the effects of model and measurement errors and of the use of constraints.

Reservoir Water Balance The basic reason why we want to examine the usefulness of satellite-observed reservoirs for runoff estimation and model calibration is that a survey showed a very good correlation between surface area and storage volume in the Upper East Region of Ghana. According to a bathymetric survey of sixty reservoirs, 97.5% of the observed variability in volume could be explained on the basis of surface area. This was especially remarkable because the basic shapes of the reservoir surfaces were extremely diverse. The relation found, and used here, was $\mathrm{Vol} = 8.52 \cdot \mathrm{Area}^{1.437}$ ($10^{-3}\,\mathrm{m}^3$). The surface area of reservoirs that are larger than one hectare can be observed with good accuracy with ERS-PRI images, as shown in Figure 1.13.

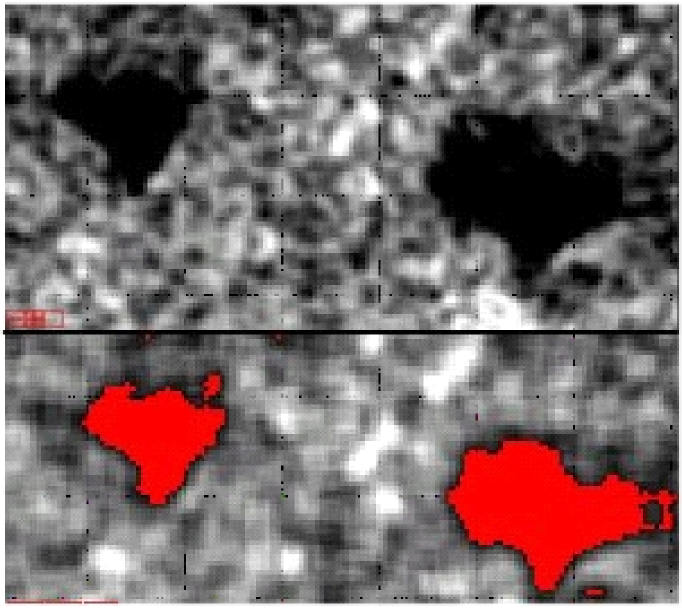

Figure 1.13: Two small reservoirs in the Upper East Region of Ghana as observed by ESA's ERS2. The classification was based on density slicing of the mean band from the co-occurrence measure analysis.

On the basis of satellite images, we can calculate surfaces and thus volumes. ERS2 covers the area of interest on a monthly basis. By subtracting the volumes from two subsequent overpasses, we obtain a measure of how much water has run off into the reservoir during that particular month. The accuracy of this volume estimate is about 95%. One still needs to account for losses through evaporation, seepage through dam and bottom, and water use for irrigation and other purposes. All these elements of the water balance are subject of an on-going intensive field measurement campaign. It is expected that evaporation can eventually be modeled with standard meteorological observations with an error of 10% on a monthly time scale. Seepage and water use will be much more error prone and can probably not be modeled within less than a 30% error.

In addition to errors in the water balance, one also has to deal with the facts that reservoirs may spill unknown amounts during months with large runoff, and that such spills may cascade into a reservoir below. Cascades with a length of up to five reservoirs are known to occur in neighboring Burkina Faso. To keep track of possible spills, a matrix-based accounting scheme was developed that keeps track of the connectivity under spilling conditions. When a reservoir is close to being full during an ERS2 overpass, this reservoir is marked as such and no runoff estimate will be available for that month. When a reservoir is observed to be almost full, a constraint is used instead that simply states that the actual runoff must exceed the runoff based on the observed area differences. When such a reservoir cascades into a downstream reservoir, this information can be taken into account. In the remainder of this extended abstract, it is, for the sake of simplicity, assumed that no cascading takes place.

Calibration of hydrological model In order to assess how useful satellite observed reservoir areas can be, we developed a simple hydrological model that was first run in forward mode to predict observable reservoir areas. Subsequently, model parameters were fitted on the basis of the information that would be available from satellite images. The fitting was repeated for four error levels, 0%, 10%, 20%, 30%. For each level, a uniformly distributed random error within the range of plus/minus the given percentage of the error-free observation was imposed. Runoff into each reservoir was derived from the difference in storage in two successive months, plus modeled evaporation and water-use. When observable reservoir areas were close to maximum capacity, no discharge estimate for that month was used. For those months, only minimum runoff could be used to constrain the model.

The hydrological model used is simple but covers the main hydrological processes at work in small watersheds in West Africa, as observed through detailed field work over the past decade. The model consists of a Thornthwaithe-Mather (TM) module, which simulates regional recharge, and a watershed-specific runoff coefficient (RO). The TM module uses only one regional parameter, S_{max}, which represents the maximum storage in the soil that needs to be filled before recharge takes place. All recharge is assumed to runoff via the groundwater. In addition, direct runoff occurs from built-up, degraded, and saturated areas. RO represents the fraction, varying between 0.5% and 3%, of each watershed that is covered by such runoff generating areas. The forward model is run on a daily time step. Runoff then accumulates in the reservoirs from which evaporation and water-use are extracted. The predicted areas are, after addition of errors, used as input for inverse runoff calculation and parameter fitting. It is recognized that such simulated observations are somewhat removed from the often unforeseeably more complicated reality, but this is the only way in which effects of error in otherwise non-observable variables can be assessed. In this case we are particularly interested in three aspects:

- To what extent does the fact that only cumulative monthly observations are available limit the fitting accuracy?
- For months in which reservoirs may have spilled, only constraints on the minimum discharge can be used. How does this affect the fitting?
- What is the effect of the large errors in, especially, the modeled water-use?

The setting is that of the Upper East Region of Ghana, where 154 reservoirs have been identified on the basis of remote sensing and for which monthly ERS coverage is available since October 2003. For the purpose of this extended abstract, the built-in solver of Excel was used to estimate model parameters through (constrained) error minimization. With the given model complexity, only up to eleven parameters (S_{max} and ten individual RO's) could be calibrated reliably with this solver. The intention is to do a more advanced optimization for all 154 reservoirs for the final article and presentation. The results are shown in Table 1.3, which compares original and fitted parameter values for different input error levels.

Two things become clear from the table with fitted model parameters. First, even with relatively high errors in estimated water-use, the fitted parameters are close to the original model values. This close fit bodes well for using small reservoirs as runoff gauges as observed by satellites. Clearly, the proper processes still need to be captured in the models, so hydrological field work in

Table 1.3: Effect of input errors (0%, 10%, 20%, 30%) and those of the use of constraints on the ability to retrieve the original model values using the observable changes in storage and modeled evaporation and water-use.

		Constraints used				No use of constraints			
	Original	0%	10%	20%	30%	0%	10%	20%	30%
S_{max}	350.0	347.9	347.4	347.8	342.7	360.5	360.6	360.4	360.9
RO_1	2.40	2.42	2.51	2.85	3.06	2.42	2.51	2.31	3.06
RO_2	1.40	1.40	1.47	1.33	1.60	1.41	1.47	1.47	1.60
RO_3	1.70	1.69	1.60	1.95	2.09	1.69	1.60	1.86	2.09
RO_4	1.30	1.30	1.27	1.12	1.72	1.30	1.27	1.37	1.72
RO_5	2.00	1.99	2.01	2.03	2.01	1.99	2.01	2.03	2.01
RO_6	0.50	0.51	0.53	0.29	0.55	0.51	0.53	0.51	0.55
RO_7	1.20	1.20	1.25	1.46	1.33	1.20	1.25	1.46	1.33
RO_8	1.80	1.80	1.86	1.80	2.19	1.80	1.86	1.83	2.19
RO_9	0.70	0.67	0.69	0.87	0.75	0.67	0.69	0.76	0.75
RO_{10}	0.50	0.48	0.45	0.80	0.56	0.48	0.45	0.55	0.56
Avg Error		0.01	0.05	0.19	0.24	0.01	0.05	0.08	0.24

the region of interest remains very important. Second, using reservoirs that spilled as constraints on the minimum flow amount only improved the fit of the regional variable, S_{max}. The reason for this is simply that reservoirs spilled during months with high flows when the rainfall to be stored in the soils exceeded S_{max}. By using the minimum flow constraint, the model was “forced” to spill at the right time by adjusting S_{max}.

In general, the proposed method of runoff observation and model calibration is promising. Observing water stored in small dams with radar satellites can contribute to the on-going hydrological research on Prediction in Ungauged Basins (PUB), especially in parts of the world where the value of water is high and hydrological observations scarce.