Rain water harvesting and management of small reservoirs in arid and semiarid areas

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Small dams′ water balance: experimental conditions, data processing, and modeling

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Abstract

Within the HYDROMED program, to assess hydrological variables describing the water balance of small dams, each reservoir is equipped with a water level gauge, an evaporation pan, and two stations for automatic data collection. The first station is connected to a tipping bucket rain gauge (resolution of 0.5 mm rainfall), while the second is connected to a submerged probe that measures the water level, within 1 cm, and temperature each 5 minutes. The spillway is designed in such a way that the discharge can be estimated.

The bathymetry of each reservor is recorded at least once every hydrological year, and is compared with a detailed ground survey, making it possible to determine the silting rate of each erservoir, and to create level-volume and level-surface relationships. The water abstraction for main users around the reservoirs is observed daily.

A software package allows to take the data directly and store it in a single hydrological data bank:
- rainfall and evaporation,
- level-volume and level-surface curves for the reservoir,
- water level - spillway discharge curves,
- water level, spillway discharge, volume and surface area of water in the reservoir,
- water abstraction.

The software allows edititing tables of data and curves. Many different time steps can be choosen and various ways to present the data are possible.

For a certain time period t, the general water balance equation for a reservoir can be applied by using the principle of water volume conservation. The variation of the water volume stored in the reservoir is equal to the sum of water volumes entering minus water volumes exiting the system.

The instantaneous flow entering in the reservoir can be assessed at a time step of 5 min. Water balances can be computed at a daily time step.

Introduction

Management of surface water is inseparable from economic and social development (ICWE, 1992). In arid and semiarid regions, large rivers have been the object of numerous development projects to improve agriculture, produce energy, or favour navigation.

Micro improvements and on-site hydromechanical interventions are becoming important factors in rural development (Conac et al., 1984; Dumont, 1986; Rochette, 1989; World Bank, 1993). Predicting rainfall and flow and controlling the resulting water volumes are a constant concern here. Experimental watersheds have long been recognized to be the most suitable measurement device for analyzing the water resources of small hydrological systems (Toebes and Ourivaev, 1970; Dubreuil et al., 1972). These are also ideal places for research on mechanisms of the water cycle (Verel and Houi, 1994), and on the interactions between soil use, hydraulic engineering works, and water availability and quality. The difficulty and cost of managing systems of rainwater and water measurement in small watersheds are a serious handicap when attempting to understand the resource constituted by temporary rivers.

Many countries have carried or are now carrying out programmes to build small reservoirs, particularly in semiarid regions, to increase water resources, intensify agriculture in densely populated areas, and to mobilize that vital resource, water. Sri Lanka and southern India are among the world regions in which systems of small water tanks have been installed almost to a point of saturation, and indeed this has been the case for a very long time (since the 3rd or 4th century). The construction of these systems is also becoming intense in the north of the country, and is contributing to the green revolution on that continent (Grewal, Samra et al., 1995). In Brazil's Nordeste region, 70,000 açudes (the Portuguese word for small tanks) have been built (Molle and Cadier, 1992). Minor tanks have existed in the Mediterranean world since Roman times, but it was only recently that ambitious building projects were initiated in Tunisia (Talineau et al., 1994, Albergel and Claude, 1997).

A reservoir fed by a single tributary, or at least by one principal tributary, can provide as much information as a classical hydrometric station. To achieve this, certain conditions must be met, but these are often less difficult and burdensome than those required for the correct functioning of a hydrometric station (Nouvelot, 1993).

In central Tunisia, in the semiarid dorsal region that extends from the Cap Bon to the Algerian border, 30 artificial reservoirs were chosen to constitute a network of hydrological observations (Albergel and Rejeb, 1997). These lakes have highly diverse intake areas ranging from somewhat uninhabited semi-forests to areas that are devoted entirely to agriculture. Their watershed areas vary from a few hectares to several dozen square kilometers. They are also representative of the rainfall gradient of the semiarid region, which is 250 to 500 mm of rainfall annually.

This paper shows that it is possible, from a minimum survey of the reservoir, to assess major hydrological variables and to predict the reservoir behavior, especially concerning water management.

Experimental set-up and methods

Experimental observation set-up of a reservoir and data collection

The small reservoir is equipped with a water level gauge, an evaporation pan, and two stations for automatic data collection. The first of these is connected to a tipping bucket rain gauge (resolution of 0.5 mm rainfall), while the second is connected to a submerged pressure probe that measures the water level, within 1 cm, and temperature.

Figure 1 shows an example of recorded rainfall and water level at the Kamech reservoir in the Cap Bon province of Tunisia, during the hydrological year 1995-1996.

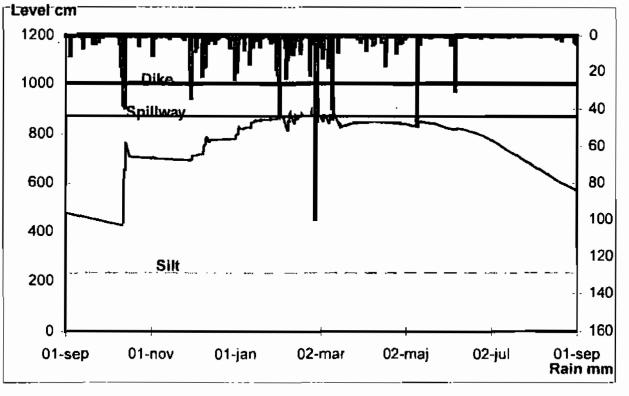


Figure 1. Rainfall and water level at the Kamech dam.

The spillway is arranged in such a way that the discharge can be estimated. At the entrance to each flood channel there is a concrete weir. The slope downstream of the discharge channel is sufficient to prevent this weir from being flooded, except in cases of exceptional flow. The weir lies in the immediate vicinity of the reservoir, making it possible to assume that the initial speed is zero, allowing us to use the flow formula at the weir.

Bazin's formula (Nouvelot, 1993): $Q_S = 0.385\ 2g\ b\ h^{2/3}$ (1)

where Q_S is discharge in m^3/sec, b and h respectively are the width and height, in meters, of the water depth at the weir.

The spillway is designed in the shape of a rectangular channel and the bottom is paved with flat cement blocks. It is thus possible to equip it with a recording gauge and to use the formulas of stationary flow.

Manning-Strickler's formula (Nouvelot, 1993): $Q_S = s\ n\ i\ 1/2\ R_h^{2/3}$ (2)

where Q_S is the discharge in m^3/sec, s is the wet cross section in m^2, n is Strickler's roughness coefficient, i is the slope of the water line in m/m, R_h is the hydraulic radius in m, with $R_h = s/p$ (p being the perimiter of the wet cross section s).

The bathymetry of each reservoir is measured at least once every hydrological year, and is compared with a fine resolution land survey, making it possible to determine the pond's rate of silting, and to establish level-volume and level-surface curves.

Figure 2 shows the change in level-volume curve from the dam construction to present at the Kamech dam.

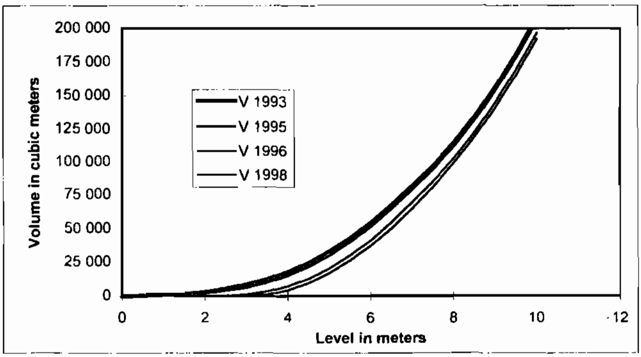


Figure 2. Level-volume relationships at Kamech.

The data characterizing the watershed, the reservoir, and the hydrological measurement station are recorded in a geographically classified data bank which is updated after every modification of the equipment, every new measurement of the bathymetry, and every change noted in land occupancy (Smaoui et al., 1996).

Hydrological balance method

For a specific time step t, the general water balance equation for the reservoir can be found by applying the principle of the conservation of water volume according to:

$$\Delta V = (V_r + V_{ecs} + V_p + V_f) - (V_{ev} + V_d + V_{vi} + V_i + V_u) \qquad (3)$$

where

ΔV: variation of the water volume stored in the lake. This is known very accurately from the gauge recording and from the level-volume curve of the lake (every 5 min for a variation of 1 cm water level);

V_r: water from catchment runoff;

V_{ecs}: contribution from groundwater;

V_p: rainfall directly on the pond. This is known accurately from the rain gauge recordings and from the reservoirs level-surface curve;

V_f: water from melting snow. This is nil for most of the reservoirs studied. There may be some in winter for high-altitude reservoirs, but on an annual level the quantity is generally negligible;

V_{ev}: volume of water evaporated. This is found by multiplying the daily evaporation by the average surface of the reservoir on the same day;

V_d: volume of water discharged from the reservoir. This can be determined with good accuracy when the spillway is gauged. For most reservoirs, it is sufficient to use a spillway formula appropriate to its geometry;

V_{vi}: the volume leaving through the draw-off weir. This is known from the levels noted by observers at the beginning and end of the draw-off, and from the length of time it lasts;

V_i: the losses through seepage (at the level of the dam, or in the bottom of the reservoir);

V_u: the volume of water removed for various purposes. This is estimated from simple observations: a volumetric meter on the arrival pipes, observation of pumping times, etc.

Figure 3 shows the hydrological balance of a reservoir.

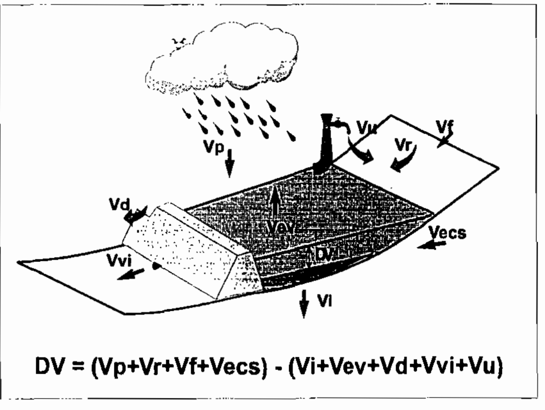


Figure 3. Hydrological balance of a reservoir.

A few models derived from the hydrological balance

Reconstruction of instantaneous water arrival during rainfall

For reconstruction of instantaneous water arrival during rainfall Eq. (3) is used to calculate the quantity $V_r + V_{ecs}$ representing the natural wadi flow entering the reservoir:

$$V_r + V_{ecs} = \Delta V - V_p - V_f + V_{ev} + V_d + V_{vi} + V_i + V_u \qquad (4)$$

The largest inflow to the reservoirs results from direct runoff from the surface slopes. This results in water level rise that is associated with rainfall, and it is well defined in the reservoir level recording. The time span is usually several hours. During runoff, the water balance equation can be simplified in the following way: V_{ecs} is very small in comparison with V_r; V_f is negligible, if not nil; $V_{ev} + V_i + V_u$ is very small during the time of water level rise. Equation (2) then becomes:

$$V_r = \Delta V - V_p + V_d + V_{vi} \qquad (5)$$

Deriving Eq. (5) with respect to time, we obtain:

$$Q_e = d\Delta V/dt - dV_p/dt + Q_s + dV_{vi}/dt \qquad (6)$$

where Q_e = flow entering the reservoir, in liters/sec; $d\Delta V/dt$ = the difference in stored volume during time t (here, 5 min), related to the middle of the time interval; dV_p/dt = the difference in the volume of rainfall during the time related to the middle of the time interval; Q_s = flow leaving through the spillway (Eq. (1) or (2)); dV_{vi}/dt = the difference in volume discharged over the weir during time t related to the middle of the time interval.

Figure 4 shows calculated discharge at the Kamech reservoir during the storm event of 1st February 1996. The figure shows the rainfall in mm/h; the discharge over the weir, and the calculated flow entering in the reservoir. This flood, with a volume of 114,000 cubic meters, and a peak reaching 14.7 m^3s^{-1} occurred when the reservoir was almost full. The overflow over the weir was 109,000 cubic meters and a peak reaching 6.54 m^3s^{-1}. A lot of small floods, from October to January filled the reservoir which capacity is 139,000 cubic meters.

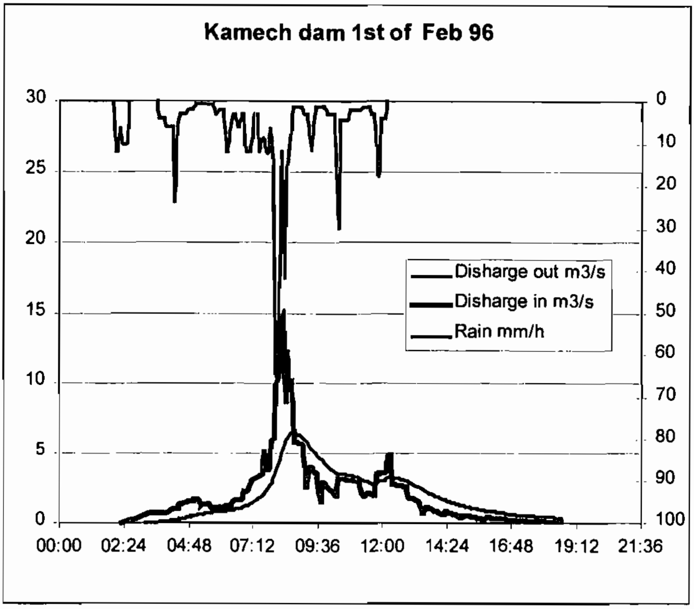


Figure 4. Calculated discharge during the rainfall events of
1st February at the Kamech dam.

Calculation of filling up of a reservoir with a typical flood occurring for different water or silt levels

Generally, in designing a dam, the designer has defined the hydrograph of a natural characteristic flood, for example, the flood which occurs every 10 or 25 years. With the water balance model it is possible to calculate the overflow depending on the initial volume of the reservoir. For example, Fig. 5 shows a simulation of different overflows created by an observed large flood following different initial water levels between 5 and 9 m in the reservoir of Janet Dam in Central Tunisia.

The knowledge of the overflow allows one to simulate the filling up of the dam. Figure 5b shows that the same flood occurring for a reservoir with a water level exceeding 8 m causes an overflow of the dyke crest. For this situation the dam can be damaged.

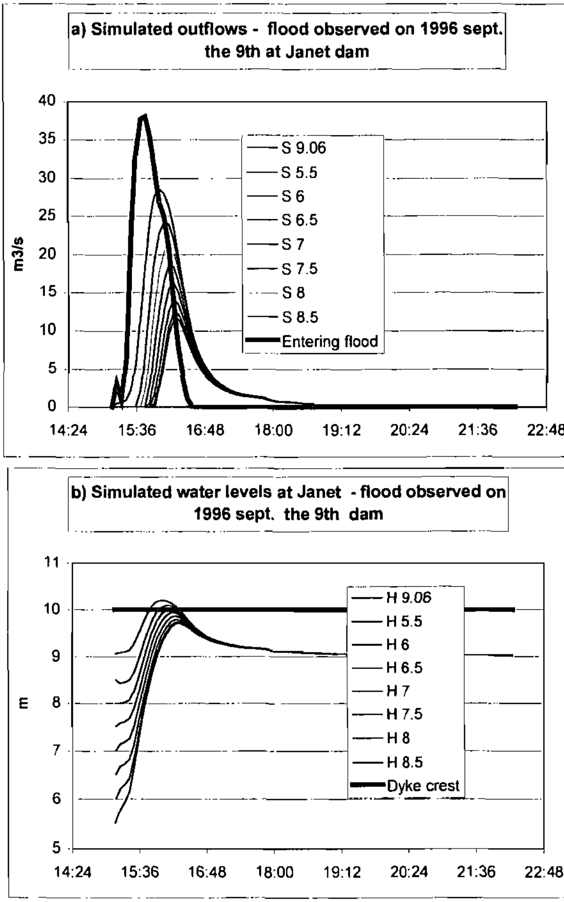


Figure 5a and 5b. Simulation of floods at Janet Dam (94 000 m^3 capacity)

Management plan of a reservoir

Small reservoirs often dry up every year during the summer period. The use of water for irrigation (garden crops, fruit trees, etc) starts in spring and continues until the end of July. The water balance model allows one to estimate an average daily decrease of water excluding pumping. For a reservoir we can calculate the natural decrease from the beginning of spring until fall when the probability of rain starts to increase.

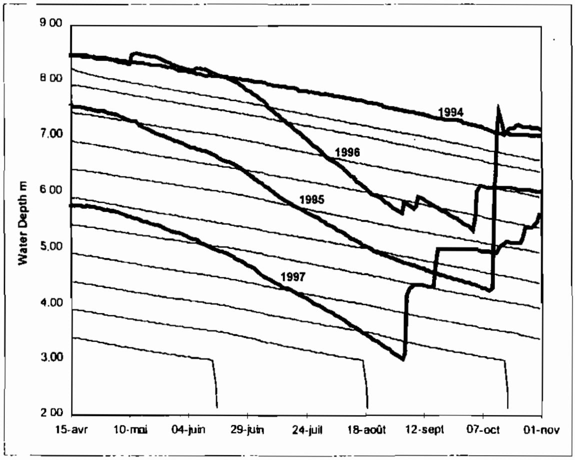
Assuming no rain during the irrigation period, and knowing the water needs of different irrigated crops it is possible to study different scenarios for the coming year, to plan and manage the irrigation.

We will develop this model for the case of the Kamech dam. For each period without rain, we calculate the natural daily losses of water (evaporation + infiltration + reservoir leakage). We thus plot the water volume and depth decrease from April to November (average daily evaporation, infiltration, and leaks calculated according to the water depth). The manager reads the reservoir water level gauge before starting field preparation (April the 15th; Fig. 6). He reports this information and the volume decrease (Fig. 6b). By comparing the corresponding curves in Fig. 6a and 6b he will know exactly the available water quantity at the beginning of the irrigation season.

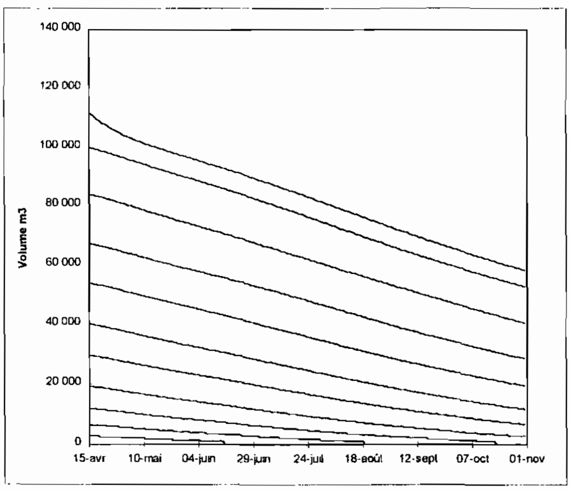
He can thus plan different scenarios for the irrigation schedule, cropping area, and type of crops, and thus reducing the risk by planning for no rain and finishing the water reserve within the cropping period. When a scenario is decided, the manager can survey the progress of the agricultural campaign. At any time it is possible to compare the calculated water consumption with the present situation by reading the water level gauge.

For the calculated natural level curves (Fig. 6), we added the observed water variations in the years 1994-97. The validation of our model was done by the data for 1994, before any use of water, and by the data during periods without irrigation (for example, in September 1997, between the two first rains). In Fig. 6 we can also see the intensive water use for the tomato crops from May to July and after this the decrease of water use in August and September (pepper crops, and few other vegetables).

Ongoing research on water needs for the main cropping systems and for different irrigation systems (traditional, sprinkler, or drop irrigation) will quantify the water needed to abstract from the reservoir. This method allows one to evaluate different scenarios to increase the efficiency between crop water use and water availability.



6a)



6b)

Figure 6a and 6b. Water management plan for the Kamech reservoir.

Conclusion

The above examples of using the water balance equation for a small artificial reservoir show that a relatively simple experimental setup can provide a lot of hydrological information for small watersheds. This information, which in developing countries is easier and cheaper to obtain compared to classical hydrometric stations, can be collected at the outlet of the watershed.

If available the above information is equally well suited for basic research as for water management and agricultural development for small watersheds. However, other applications are equally suited; the optimization of the reservoir size (Ragab and Albergel, 1997).

Since 1994, annual records of all observations made during the hydrological year on a network of 30 small dams in semiarid Tunisia have been published. A computerized bank of hydrological data has been set up. The parameters describing the watersheds have also been recorded in a similar data bank. Maps of the different watersheds have been stored using GIS. The main objective of this work is to find dependent indicators for the hydrological functioning of the watersheds. Modeling and hydrological simulation will provide us with an accurate understanding of this resource, and will make it possible to evaluate the impact of development works and to plan rules for its management.

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