Developing Index Maps of Water–Harvest Potential in Africa

G. B. Senay, J. P. Verdin

Abstract. *The food security problem in Africa is tied to the small farmer, whose subsistence farming relies heavily on rain–fed agriculture. A dry spell lasting two to three weeks can cause a significant yield reduction. A small–scale irrigation scheme from small–capacity ponds can alleviate this problem. This solution would require a water harvest mechanism at a farm level. In this study, we looked at the feasibility of implementing such a water harvest mechanism in drought prone parts of Africa. A water balance study was conducted at different watershed levels. Runoff (watershed yield) was estimated using the SCS curve number technique and satellite derived rainfall estimates (RFE). Watersheds were delineated from the Africa–wide HYDRO–1K digital elevation model (DEM) data set in a GIS environment. Annual runoff volumes that can potentially be stored in a pond during storm events were estimated as the product of the watershed area and runoff excess estimated from the SCS Curve Number method. Estimates were made for seepage and net evaporation losses. A series of water harvest index maps were developed based on a combination of factors that took into account the availability of runoff, evaporation losses, population density, and the required watershed size needed to fill a small storage reservoir that can be used to alleviate water stress during a crop growing season. This study presents Africa–wide water–harvest index maps that could be used for conducting feasibility studies at a regional scale in assessing the relative differences in runoff potential between regions for the possibility of using ponds as a water management tool.*

Keywords. *Runoff, Curve number, Ponds.*

The primary objective of this article is to present a number of "water harvest index" maps to encourage and guide feasibility studies for the planning, design, and construction of ponds in Africa. These maps range from a simple indicator of rainfall excess (runoff) distribution across Africa to the number of potential ponds per family per ha.

Food security in Sub–Saharan Africa is tied to the small farmer, who relies heavily on rain–fed agriculture. A dry spell lasting two to three weeks can cause a significant yield reduction. The bitter irony is that these regions also face intense rainfall events resulting in loss of topsoil due to severe erosion, likewise reducing productivity. Small–scale supplemental irrigation schemes using small–capacity ponds can help alleviate both of these problems. A small pond (~1000 m^3) filled by runoff can provide about half the water requirements of a half–hectare plot – enough water to help overcome a mid–season dry spell or translate catastrophe into a modest success.

The USAID funded Famine Early Warning System (FEWS) was established in the mid–1980s, triggered by the 1984/1985 famine in Ethiopia. Since then, major advances have been made in detecting the impending danger of drought using satellite–based information and modeling. Although the early warning system has helped in dramatically reducing the response time for relief food assistance, food shortage emergencies have not been eliminated. Actually, unabated population growth and serious land degradation, mainly caused by excessive runoff, has intensified food shortage and overall poverty.

There are two elements that are central to the overall poverty of a large section of the population in Africa: small farm holdings and unreliable water supply. One hundred and forty million Africans were undernourished in 2000, a number that is increasing by 2% to 3% in most Eastern and Southern Africa nations (FAO, 1999). Most agriculture in Africa (92%) is rainfed, and the population in many places is growing at nearly 3% per annum (Jagtap and Chan, 2000). For example, in Ethiopia about 85% of the 67 million people depend on rain–fed agriculture and have land holdings less than a hectare per family. Thus, a long–term solution for chronic food shortage should include appropriate technology that helps the small farmer.

Annual runoff totals suggest that the establishment of a water storage structure for a family can provide enough water to dramatically improve crop production. Generally, too much rain falls in the rainy season and too little to none falls in the dry season. In drought–prone areas, the rainfall pattern is erratic, with short and long dry spells, causing severe crop damage. Studies in arid and semi–arid regions have shown that 1 to 3 applications of supplemental irrigation at critical stages of a crop can make a difference between 1 ton/ha (rainfed) and 4 tons/ha (with supplemental irrigation) for a wheat crop in North Africa and West Asia (ICARDA, 1999).

Water harvesting is a method of collecting surface runoff from a catchment area and storing it in surface reservoirs, or in the root zone of a cultivated area. It can be a source of water

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The authors are **Gabriel B. Senay, ASAE Member Engineer,** Senior Scientist, U.S. Geological Survey, SAIC, and **J. P. Verdin,** Project Chief, U.S. Geological Survey, Earth Resources Observation Systems (EROS) Data Center, Sioux Falls, South Dakota. **Corresponding author:** Gabriel B. Senay, U.S. Geological Survey, Earth Resources Observation Systems (EROS) Data Center, Sioux Falls, SD 57198; phone: 605–594–2758; fax: 605–594–6529; e–mail: senay@usgs.gov.

for a variety of purposes in arid and semi–arid regions when common sources such as streams, springs, or wells fail (Fraiser, 1980). Rockstrom (2000) presented an overview of different water harvesting techniques in smallholder farms in Eastern and Southern Africa. In the review it was highlighted that water storage structures such as ponds are rated as "high" in reducing risk of crop failure from erratic rainfall as compared to other water harvesting techniques. Despite their advantage, ponds are not commonly employed in these regions due to the relatively high cost of construction and the requirement for technical knowledge. In places where ponds were used, they were mainly used for livestock and household uses. The study also pointed out the lack of information on the bio–physical and socio–economic conditions under which water storage structures can be adopted by the smallholder farmer in Africa.

Providing irrigation is a major tool for alleviating poverty by increasing and stabilizing productivity as well as retiring marginal lands. When traditional irrigation systems such as canal and tube–well irrigation are not feasible due to topographical, geological, and hydrological constraints, rainwater harvesting has been found to meet the water requirements of a transplanted rice crop (Srivastava, et al, 2004). From their application in rice fields, Srivastava et al. (2004) pointed out the potential of rainwater harvesting intransforming a subsistence–agriculture into a commercial–agriculture. Tabor (1995) argued that water harvesting encourages farmers to invest in the land for improved productivity.

Runoff behavior is very important for the successful design of the rainwater harvesting system; early water harvesting researchers often reported results as an "annual percentage" which was described as the percentage of the annual rainfall that ran off (Evett and Dutt, 1985). Shanan and Tadmor (1979) warned against the use of annual runoff percentage in the design of micro–catchment systems. Hollick (1982) reported that annual runoff percent suffered from the disadvantage that it gives no indication of the relationship between runoff and rainfall intensity and duration so that extrapolation to new areas or drought years is difficult.

One of the methods used to estimate runoff is the SCS Curve Number Method (SCS, 1972). The curve number method, also known as the Hydrologic Soil Cover Complex, is a versatile and widely used procedure for runoff estimation. Several researchers use SCS method for runoff estimation because it gives consistently usable results (Rao et al., 1996; Sharma et al., 2001; Sharama and Kumar, 2002). Several hydrological models including AGNPS (Young et al., 1987), EPIC (Williams, 1995), and SWAT (Arnold et al., 1996) use the SCS curve number method for estimating storm runoff. Ponce and Hawkins (1996) presented a review of the conceptual and empirical foundations of the Curve Number Method, stating its wide use in the United States and other countries. They summarized the perceived advantages of the method to be 1) its simplicity; 2) its predictability; 3) its stability; 4) its reliance on only one parameter; and 5) its responsiveness to major runoff–producing watershed properties (soil type, landuse/treatment, surface condition, and antecedent soil moisture condition). On the other hand, the perceived disadvantages are 1) its marked sensitivity to the curve number; 2) the absence of clear guidance on how to vary antecedent soil moisture condition; 3) the methods varying accuracy for different biomes; 4) the absence of an explicit provision for spatial scale effects; 5) the fixing of the initial abstraction ratio at 0.2, preempting a regionalization based on geologic and climatic setting.

In much of Africa, the availability of accurate hydrological and topographical data essential for runoff estimation are limited, and confined to few research institutions. In addition, the available data are organized by countries and not readily available for continent–wide processing and applications. The prominent design practice for sizing water harvesting structures in Sub–Saharan Africa is based on trial and error because of a lack of data in rainfall–runoff relationships (Crithley, 1987). This leads to an under–design and eventual failure of structures or an expensive over–design that is prohibitive and discouraging for implementation. In addition to the technical difficulties in the design and operation of water harvesting structures, the socio–economic factors are important for a successful implementation of the techniques. FAO (1983, 1985) has produced a conceptual planning tool for assessing water harvesting suitability for localized conditions based on land use types that take into account the socio–economic realities of the user.

Some of the techniques used in runoff estimation in Africa were based on rainfall–runoff simulations at a scale of a few square meters. Patrick (1996) cautioned that the up–scaling of these simulation studies to a watershed scale had not been straightforward. He reviewed and reported the use of a database called "Catalogue des etas de surface" for runoff estimation in the Sahel region of Africa. The database provides an equation to calculate runoff for each surface type based on rainfall and antecedent soil moisture. Furthermore, Patrick (1996) reported the work of Puech (1994) where predicting runoff by additive calculation from catalog surfaces types on eight Sahelien catchments of various sizes was found, on average, to yield double the observed runoff.

Other methods have been tried to estimate runoff in African environments including the adaptation of the partial area concept (PAC). The partial area concept (PAC), originally developed for humid climates (Beston, 1964), highlights the differential contribution of different zones within a catchment to the runoff at the outlet. The explanation for the humid regions is the presence of more saturated belts with reduced infiltration capacity within the catchment that contributes more runoff. Tauer and Humborg (1992) attributed the applicability of PAC in arid climates to the short–duration convective rainfall events that would make it impossible for distant parts of the watershed to contribute to the runoff at the outlet due to infiltration and conveyance losses. Ben–Asher and Humborg (1992) reported that not taking PAC into account led to an over estimation of runoff by up to 600% compared to a direct up–scaling from rainfall–runoff simulation studies.

Attempts to up–scale field–based studies have been reported to be successful using remotely sensed data for the estimation of landcover parameters that are essential for runoff generations. Recent advances in remote sensing of land cover and spatial data processing in a Geographic Information Systems (GIS) environment have led to the application of remotely sensed data in hydrological modeling. Because of its reliance on land cover information, most of the work on adapting remotely sensed data to hydrologic modeling has involved the SCS runoff curve number model. Zevenbergen et al. (1988) and Sharma and Singh (1992) have successfully demonstrated the estimation of SCS curve number for semi–arid regions from satellite–derived parameters.

Purwanto and Donker (1991) attributed the difficulty of adapting the SCS curve number outside of the United States to the land cover classification that was based on cover types common to North America. Tauer and Humborg (1992) cautioned the use of curve number (CN) in the Sahel region of Africa since it failed to generate runoff for rainfall amounts less than 40 mm. However, their reference to the 40–mm threshold is unclear since SCS CN Method is recommended for use with rainfall magnitudes above 12.5 mm (0.5 in.) (USDA–SCS, 1985). Simanton et al. (1973) reported a reduction in the runoff curve number (lower runoff) with increasing watershed area in southeastern Arizona, indicating a substantial role of channel transmission losses in semi–arid regions. Furthermore, according to Hawkins (1973), curve number varies with storm sizes where a lower limit curve number (no runoff) can be defined for a given storm. This relationship has the tendency to underestimate runoff, especially on small rainfall amounts where the lower limit CN is high. This appears to be one of the justifications for establishing the minimum storm size of 12.5 mm (0.5 in.) for the SCS CN Method to become more accurate (USDA–SCS, 1985) .

With modifications that assigned appropriate curve numbers to local specific cover types, researchers such as Colombo and Sarfatti (1997) and Artan et al. (2001) have shown the application of the SCS CN Method for runoff estimation in African environments. Gumbo et al. (2001) used a modified SCS CN (Soil Conservation Service South African Manual) by Schulze et al. (1992) to estimate runoff on partly urbanized watersheds in Zimbabwe. It should be noted that the SCS curve number method has parameters that can be modified or calibrated for local conditions. Such parameters include the initial abstraction (Sharma and Kumar, 2002) and the threshold antecedent soil moisture values (Mitchell et al., 1993).

As Satti and Jacobs (2004) showed that regional crop water balances could be estimated using the predominant soil types as opposed to the need to include soil heterogeneity for individual farm water management planning, it is believed that the use of the best available Africa–wide coarse resolution rainfall data (10–km resolution) would suffice for the development of feasibility guidelines for planning water–harvesting as a water management tool at regional scales with the emphasis to encourage further studies for localized applications.

The choice of the SCS CN for this study was purely based on its ease of implementation at a continental scale. Although a number of studies have shown its adequate implementation in Africa, other studies have also pointed out its poor performance in certain parts of Africa. The authors are aware of the problems associated with the implementation of SCS method on larger watersheds as it was initially intended for use in smaller watersheds. In addition, the accuracy of assigning CN for a particular landcover–soil complex at a continental scale was determined by the accuracy of the landcover and soils information used. Despite the shortcomings of the SCS method, it is believed that a uniform application of the method at a continental scale would allow the analyses of the relative differences in runoff potential between regions.

Methods

Data

Africa–wide satellite–derived daily rainfall estimates (RFE) from 1998 through 2002 were used in this study. Blended satellite–gauge RFE images for the African continent are prepared by the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA) at 0.1° (~10 km) spatial resolution (Xie and Arkin, 1997). The images are produced using an interpolation method that combines data from Meteosat cold cloud duration (CCD), the Special Sensor Microwave/Imager (SSM/I) of the Defense Meteorological Satellite Program, the Advanced Microwave Sounding Unit (AMSU) on board the NOAA–15 polar orbiter, and rain gauge data from Global Telecommunication System (GTS). Note that the spatial resolution of the rainfall (the best available Africa–wide data) determined the spatial resolution of the runoff output.

Required data sets such as soil texture and annual evaporation were extracted from global data sets assembled by FAO (1994). Africa–wide population density maps were extracted from Landscan 2000 global dataset that is produced and distributed by Oak Ridge National Laboratory (Dobson et al., 2000)

Africa–wide watershed boundaries and stream networks were produced at EDC (USGS, 1998; Verdin and Verdin, 1999). The derivation of SCS runoff curve numbers from land cover and soils data is described by Artan et al. (2001). Although the Africa–wide curve number is available at 1–km resolution, the CN grid was resampled to 10–km resolution to match the resolution of the rainfall grid.

Annual Runoff Calculation

Surface runoff magnitude was determined using the SCS curve number procedure (SCS, 1972). The basic assumption of the SCS curve number method is that, for a single storm, the ratio of actual soil retention after runoff begins to potential maximum retention is equal to the ratio of direct runoff to available rainfall. After algebraic manipulations and simplifying assumptions, this relationship results in equation 1 found in Section 4 of the National Engineering Handbook (NEH–4) (USDA–SCS, 1985), where the curve number is a convenient representation of the potential maximum soil retention, S (Pounce and Hawkins, 1996). In this approach, infiltration losses are combined with surface storage by the relationship shown in equation 1.

$$Q = \frac{(P - Ia)^2}{(P - Ia + S)} \tag{1}$$

where Q is the accumulated runoff from rainfall excess (in.) (Q = 0, when P < Ia); Ia is the initial abstraction in inches that accounts for surface storage, interception, and infiltration prior to runoff. Its value is estimated as a fraction of S (Ia = 0.2S); P is the rainfall depth (in.); and S is a parameter (in.) given by:

$$S = \frac{1000}{CN} - 10 \tag{2}$$

where CN is known as the curve number. Note that 1000 and 10 can be replaced by 25400 and 254, respectively, when the rainfall depth is expressed in mm.

The magnitude of CN depends on soil hydraulic conductivity, land use and antecedent soil moisture (AMC) conditions at the start of the rainfall event. Africa–wide CN for an average antecedent soil moisture (type II AMC) condition, derived by Artan et al. (2001) was used for this work. However, CN and S were adjusted based on the 5–day AMC values during the daily simulations using standard equations as outlined by USDA–SCS (1985). The threshold values to switch from type II AMC were set at less than 3 mm for AMC I and greater than 9 mm for AMC III.

Daily runoff was calculated in ARC/INFO: GRID for each pixel with a spatial resolution of 10 km. Annual total runoff was obtained by simple summation over a given year. In order to avoid unrealistically high and low values, the 5–year total annual runoff was ranked for each pixel. For each pixel, the median runoff of the 5 years was used as the representative runoff for the rest of the analyses.

The smallest sub–watershed (level 6) generated by Artan et al. (2001) was used to calculate a spatially averaged runoff depth for a given watershed. Depending on location, level 6 watersheds can vary in size from less than 1000 to over 10,000 km^2. In some watersheds, pixels with lakes and other depression had little or no runoff. These pixels were excluded before averaging by watershed. Spatially averaged runoff depth per watershed was used to develop the various water harvest index maps such as the recommended watershed area and pond depth for a given pond size.

Pond Capacity

Recommended catchment area is based on the assumption that a net volume of 1000 m^3 is necessary. The 1000 m^3 (0.81 acre–ft) is suggested based on a reasonable amount of water that can be used to grow enough grain and biomass to feed an average farm family in Africa. In many places the average farm size is not more than a 1–ha field. If a farmer can collect a net amount of 1000 m^3 of water (taking into account evaporation losses and seepage) for crop production purposes, he/she should be able to produce enough grain to feed a family. In most places crop evapotranspiration during a crop growing season is between 4 and 5 mm/day. Assuming a seasonal average of 4.5–mm/day crop water demand, a farmer can grow a 90–day cereal crop with a seasonal water demand of 405 mm (~0.4 m). In theory, assuming 100% irrigation efficiency, this would allow a farmer to irrigate a 2500–m^2 field (1000 m^3 / 0.4 m) (0.25 ha) of cereal crop to full production. On the other–hand, this amount will provide 25% of the water required by 1 ha field when used as a source of supplemental irrigation during times of a dry spell.

Irrigated crops generally had much higher yield (two to four times) than rainfed crops (ICARDA, 1999). Maize yield in most African subsistence farms ranges between 1 and 2 tons/ha. With supplemental irrigation it can be expected to rise to 3 tons/ha (an increase of 2 t/ha). Production of 3 tons from a 1–ha plot for a family of seven will exceed the grain ration recommended by WFP (0.5 kg/day–person). In theory, a family of seven will have access to an amount of 1.17 kg/day–person from the 3–ton production. Even with an assumed substantial post–harvest loss of 30%, the family is in a much better situation than without the supplemental irrigation.

Using the foregoing discussion as a backdrop, we decided to create a series of base maps (atlas) that show the approximate watershed area required to collect and store 1000 $m^3$of runoff for beneficial use. In order to obtain a net amount of 1000 m^3 of water, the gross demand was estimated by taking into account evaporation and seepage losses. However, an assumption had to be made on surface area of the pond in order to calculate the volumetric losses due to evaporation and seepage. For this study it is assumed that the pond user will work with a 1–m deep water (net) for beneficial uses after losses. This indirectly limits the surface area of the pond. For example, the 1000–m^3 water can be stored in a 31.6– × 31.6–m^2 pond with a 1–m net depth. Although deeper ponds will reduce seepage and ET losses, a compromise has to be made between pond safety and construction costs on one hand and water losses on the other, since the actual depth of the pond will be greater than this to accommodate evaporation and seepage losses. Although site–specific information should be used for an actual capacity sizing, a 1 m net depth was used to produce these maps as a guideline reference.

Net evaporation was used to estimate losses from the pond surface. Annual net evaporation was simply calculated as the difference between climatological evaporation and 5–year annual median precipitation. Since the number of daily–rainfall years was too small (5 years) to develop a statistical distribution for determining below–normal rainfall amounts, the median value was chosen to avoid extreme estimates by the satellite sensors. The limited number of years precludes the development of probability based water requirement estimation and pond–sizing; however, the 5–year median value is capable of demonstrating the relative differences between regions in line with the overall objective of this work. Seepage losses were estimated to be 2.5 mm per day as suggested by USDA (1997).

Thus, recommended pond depth at any location of interest is calculated according to the following equation:

$$D = 1 + \text{EVAPORATION} - \text{RAINFALL} + \text{SEEPAGE} \quad (3)$$

where D is recommended pond depth (m); evaporation, rainfall, and seepage are the annual values (m). Wherever D was negative, D was set to a minimum depth of 1 m.

The required upstream watershed area (drainage basin) to achieve the desired amount of water in the pond is given by equation 4. The recommended pond depth also serves the purpose of adjusting the required catchment area to collect the net 1000 m^3, since it indirectly accounts for the actual catchment area needed to collect the gross runoff amount that will result in a net 1000 m^3.

$$WA = D \times (\frac{1000}{RF}) \times 0.0001 \quad (4)$$

where WA is the required watershed area (ha) per pond; D is the recommended pond depth (m); RF is the average runoff depth (m) in a watershed, 1000 is the net pond volume (m^3), 0.0001 is conversion factor from m^2 to ha.

Once the gross capacity of the pond was estimated, the potential number of ponds in a given watershed was estimated by dividing the runoff volume by the gross pond capacity.

$$NP = \frac{RF \times TWA}{D \times 1000} = \frac{TWA}{WA} \quad (5)$$

where NP is the number of potential ponds in a watershed;*RF* is average runoff (m), TWA is the total watershed area (m^2);

D × 1000 is the gross pond capacity (m^3); WA is required watershed area (m^2).

With population density figures (Dobson et al., 2000), it was possible to estimate the number of ponds per family per km^2. An average family size of seven people was assumed for Africa. First the number of ponds in a given watershed was converted into number of ponds per km^2 (NPKM2) by simply dividing NP by the total watershed area in km^2. Then,

$$NPF = \frac{NPKM2}{PopDen} \times 7 \qquad (6)$$

where NPF is the number of potential 1000 m^3 ponds per family in a given watershed; NPKM2 is the number of ponds per km^2; PopDen is the watershed average population density per km^2; 7 is the number of people per family. Watersheds with an average pop density less than one person have been removed from further analyses in order to eliminate unrealistically large number of ponds per family in areas where there is no significant population centers such as the Sahara Desert.

Generally, sparsely populated areas are those of the arid and semi–arid regions where the runoff magnitude is small and the required catchment area is large. Thus, NPF was normalized by the required watershed area according to equation 7.

$$NPFH = \frac{NPF}{WA} \qquad (7)$$

where NPFH is the number of ponds per family normalized by the required watershed area in a given watershed; NPF is number of potential ponds per family and WA is the required watershed area (ha) per pond from equation 4.

Results

Figure 1 shows the spatial distribution of modeled median annual runoff for the African continent. The runoff values range from a low of less than 5 mm in the desert and arid regions of the Sahara, Namib and the Horn of Africa and a high of more than 200 mm in the Congo Basin. The major crop growing regions fall within the range of 60 to 150 mm of annual runoff. The chronically food insecure regions of Ethiopia demonstrate a runoff potential of 60 to 150 mm. However, some Ethiopian districts that experience a runoff of 200 mm are also listed as food insecure. The modeled runoff–depth as a percentage of the annual rainfall varied from region to region. It ranged from a low of less than 1% in the desert areas to a high of more than 30% percent in few areas (fig. 2). The majority of watersheds fall in the range between 5% and 15%. To fill the ponds with water, the 5% to 15% runoff–percentage is encouraging since field studies in localized areas have reported substantially higher runoff percentages (40% to 50%) in the highlands of Ethiopia (Zeleke, 2000). Ben–Asher and Humborg (1992) reported a 15.4% runoff percentage from a single storm in a watershed in the Northwestern Mali, close to the border between Mauritania and Senegal.

A recommended pond–depth map was produced for the entire continent based on an assumption of 2.5 mm per day for seepage rate and use of climatological evaporation losses (fig. 3). It should be noted that with the use of lining materials such as Polyvinyl Chloride (PVC) geomembranes, seepage rates could be reduced to almost negligible amounts thereby reducing the recommended pond depth by about 1 m, i.e., saving about 912 mm of water loss. In addition, improved

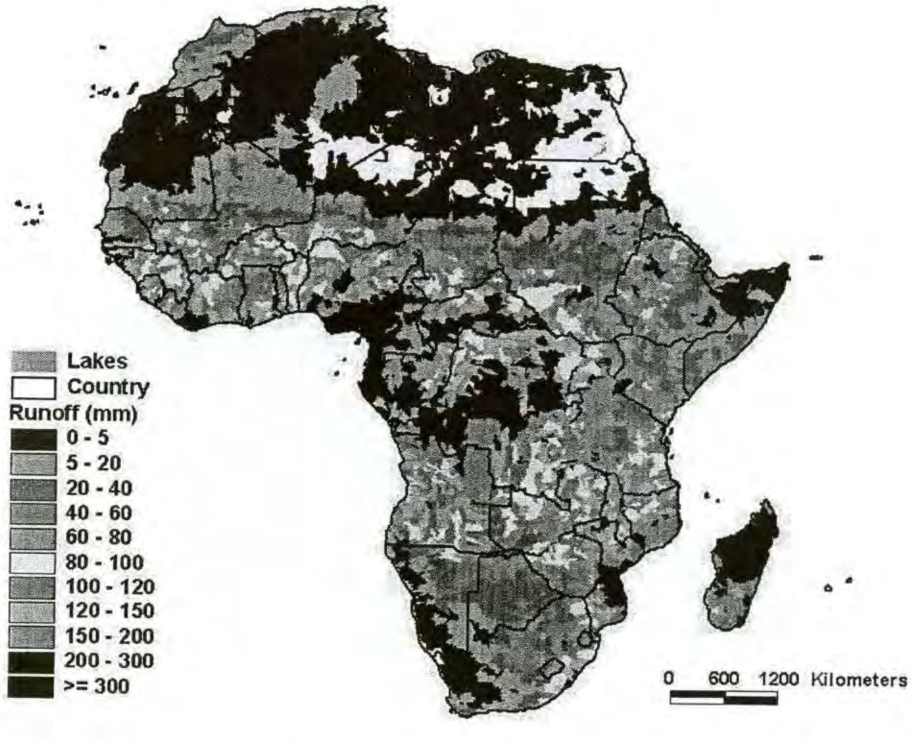

Figure 1. Median annual runoff depth (mm).

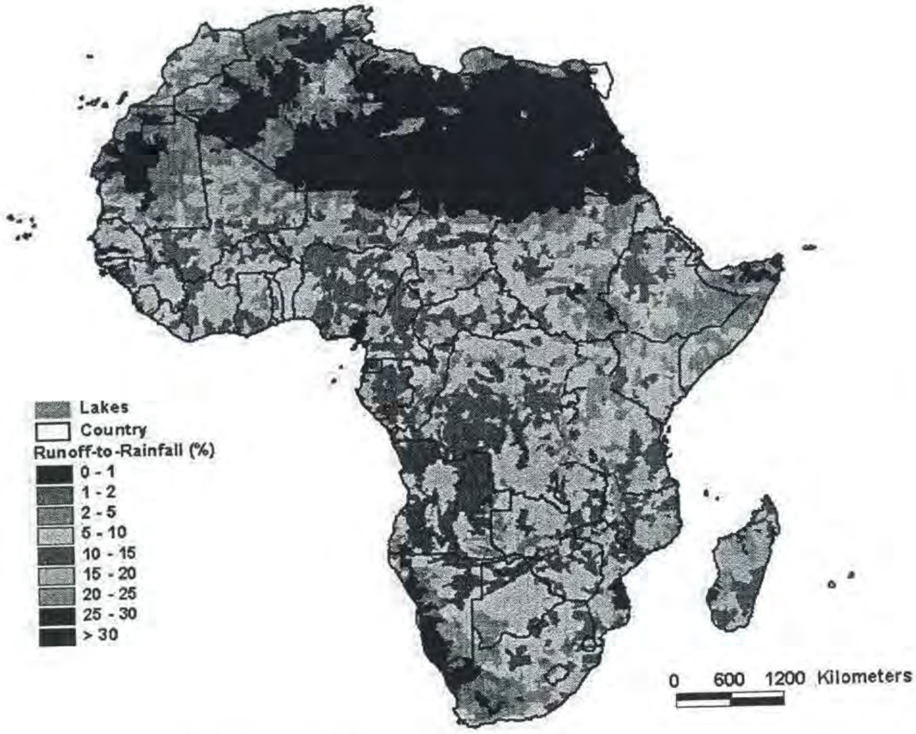

Figure 2. Ratio of annual runoff to annual rainfall (%).

measures, such as shading, that reduce evaporation losses will further reduce the recommended pond depth. The spatial pattern of the recommended pond depth resembles that of the runoff depth where arid and semi–arid regions require deeper ponds while humid and sub–humid areas and cooler highlands require shallower ponds. The minimum pond depth is set at 1 m. Since 1 m is the assumed minimum depth required to achieve the required net volumetric amount, these regions do not need to store more water to account for evaporation and seepage losses since the rainfall is large enough to offset the combined ET and assumed seepage losses. Regions with pond depths of 3 m or higher represent substantial losses

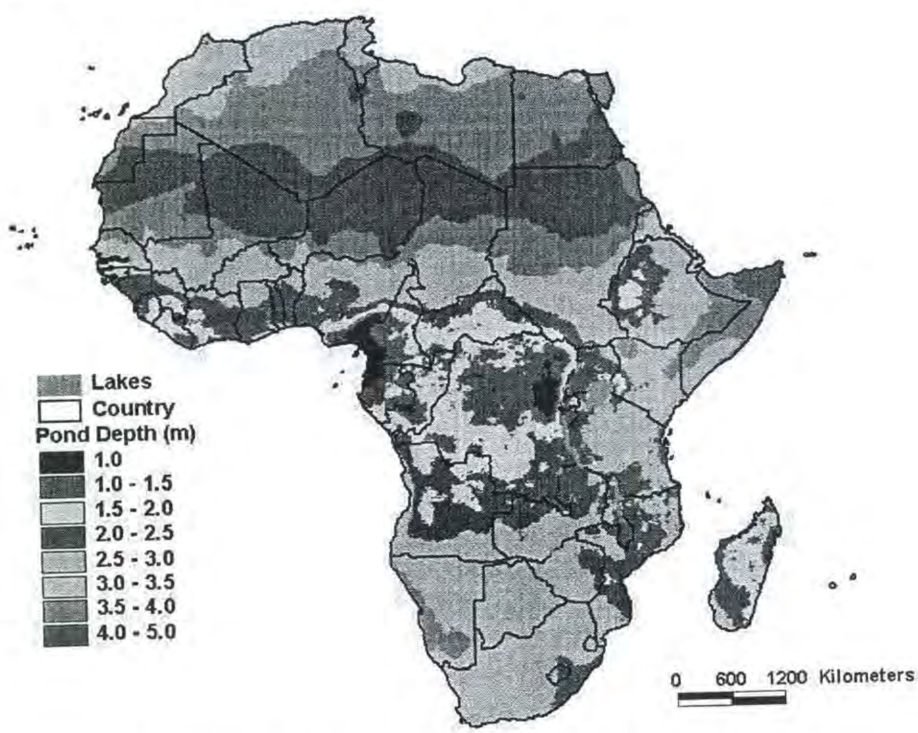

Figure 3. Pond depth required to yield 1–m net supply per year.

where the two–thirds of the stored water is lost to the atmosphere or as deep percolation without meeting the intended objective of plant consumptive use. The recommended pond depth was established only as a guideline with year round use assumption. When ponds are used to offset a dry spell in the rainy season where evaporation losses are much lower, the recommended depth could be adjusted down to reflect the lower evaporative demand and shorter time period for seepage effects. In reality, pond depths are determined by the prevailing conditions at the site based on soils, hydrogeology, and topography. These maps are only useful for comparing different regions in terms of water loss due to evaporation.

Figure 4 shows the recommended catchment area for collecting a net amount 1000 m^3 of water. The net 1000 m^3 is best understood by looking at the recommended pond depth. For example when the recommended pond depth is 2 m for a volume of 2000 m^3, the nominal catchment area was multiplied by a factor of 2 to obtain what is shown in figure 4 in accordance with equation 4. This means one needs to store twice the net amount (2000 m^3) to account for the losses, hence the catchment area needs to be expanded as well. Again, desert and semi–arid areas require substantially larger catchment areas than humid and sub–humid regions. This atlas is useful for pond planners and developers to study the feasibility of establishing a pond in a given region. As the size of the required catchment area increases, the number of potential ponds in a given watershed decreases. Furthermore, larger catchment area increases unaccounted losses during conveyance from the site of runoff generation to the collection pond, thereby increasing further the required catchment area. In addition, larger catchment areas will incur more costs in the construction of a network of collection ditches for directing the runoff to the pond. Regions with recommended catchment area more than 4 ha stand out as areas that belong to arid and semi–arid regions of Africa. However, a large part of the agricultural regions fall under 4 ha. The Congo Basin requiring the least amount of catchment area.

Figure 5 shows the number of potential 1000–m^3 ponds per km^2. Although figure 5 shows the abundance or scarcity of runoff in a given area in absolute terms, figure 6 adjusts the availability of the ponds per family by accounting for uneven distribution of population in the region. In figure 6, family size of seven people has been assumed. Watersheds with number of ponds per family less than 0.5 generally coincide with major urban centers and irrigation schemes along riverbanks such as the case along the Nile River. However, in rare instances, a less than 0.5 pond per family in a given watershed can be seen in high population density rural centers in Rwanda, Burundi, and parts of southern Ethiopia.

Although watersheds with population densities less than 1 person per km^2 were masked out of analysis (shown in white), there are still sparsely populated regions in figure 6 that suggest an abundant number of ponds per family; for example parts of Eastern Ethiopia and Somalia watersheds. Therefore, figure 7 was produced to factor in the required watershed size in obtaining the number of ponds per family as normalized by the required watershed area. Thus, according to figure 7, Eastern Ethiopia and a large part of Somalia show watersheds with relatively high water limitation compared to what figure 6 suggests. Basically, while figure 6 shows the potential number of ponds per family, figure 7 takes into consideration the size of the required catchment area to gather the runoff, thereby providing information on the extra water loss during conveyance and the increase in cost of construction and maintenance of channel networks for collecting and directing the runoff.

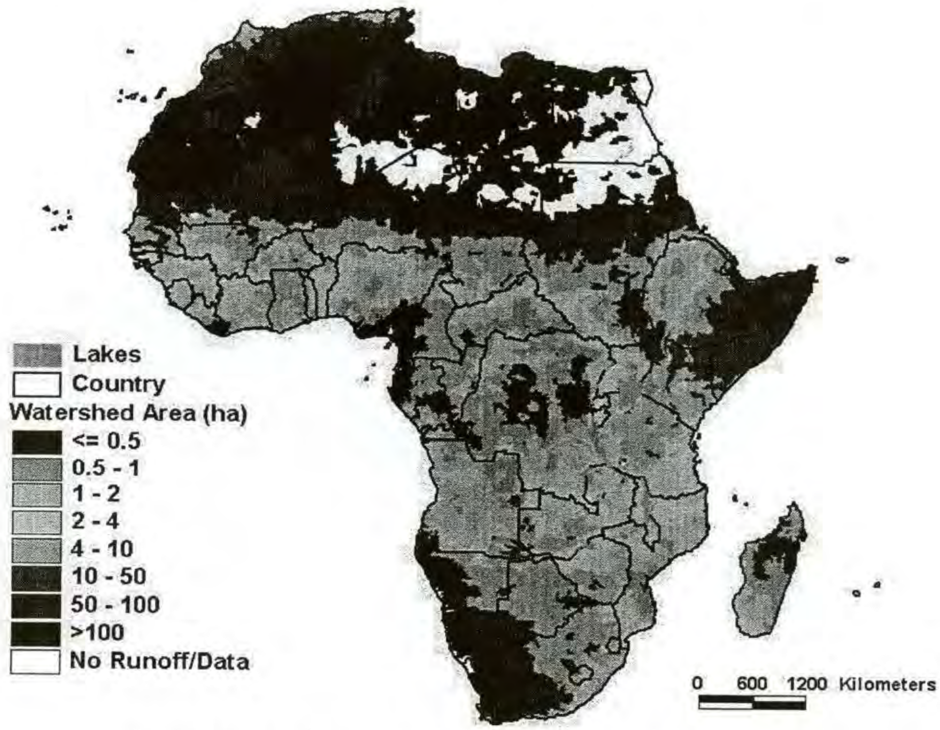

Figure 4. Required watershed area for collecting 1000–m³ net runoff.

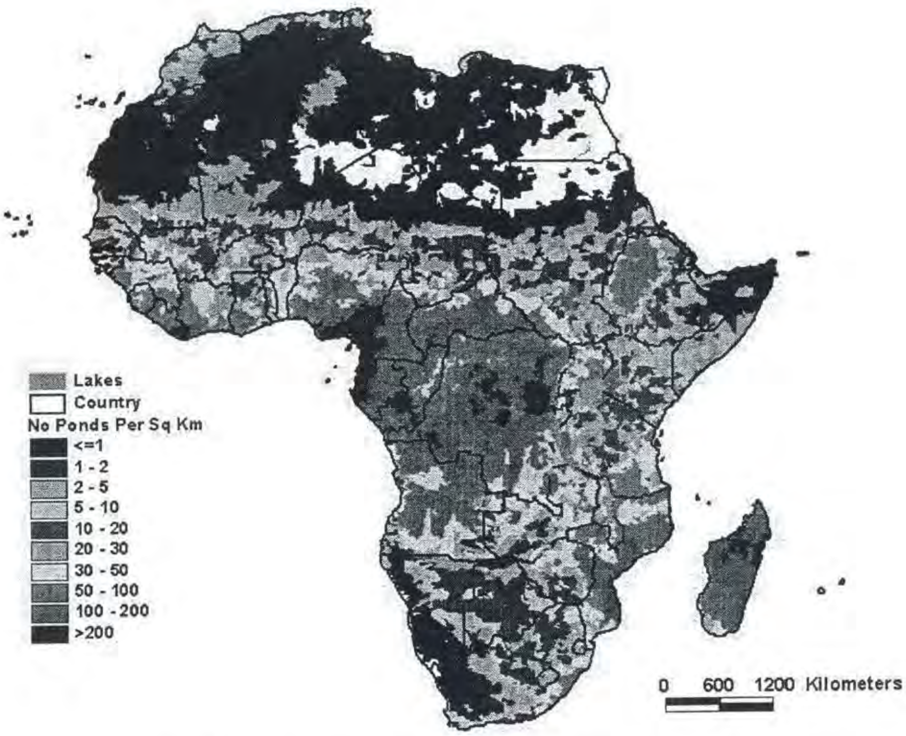

Figure 5. Number of potential 1000–m^3 capacity ponds per km^2.

Therefore, a value of 1 in figure 7 indicates the theoretical potential for each family in the watershed to establish a 1000–m^{3}pond. Values less than 1 suggest that the required watershed area per pond is so large (low runoff potential), for the given population density, that every family in a given watershed can only establish a less than 1000–m^3 capacity pond. On the other hand, values greater than 1 suggest that the required watershed area to fill the pond is low enough (high runoff potential), for the given population density, to allow every family in the watershed to build more than one pond. Again, these are only indicative figures for regional comparison only. For example, not every family will need to have

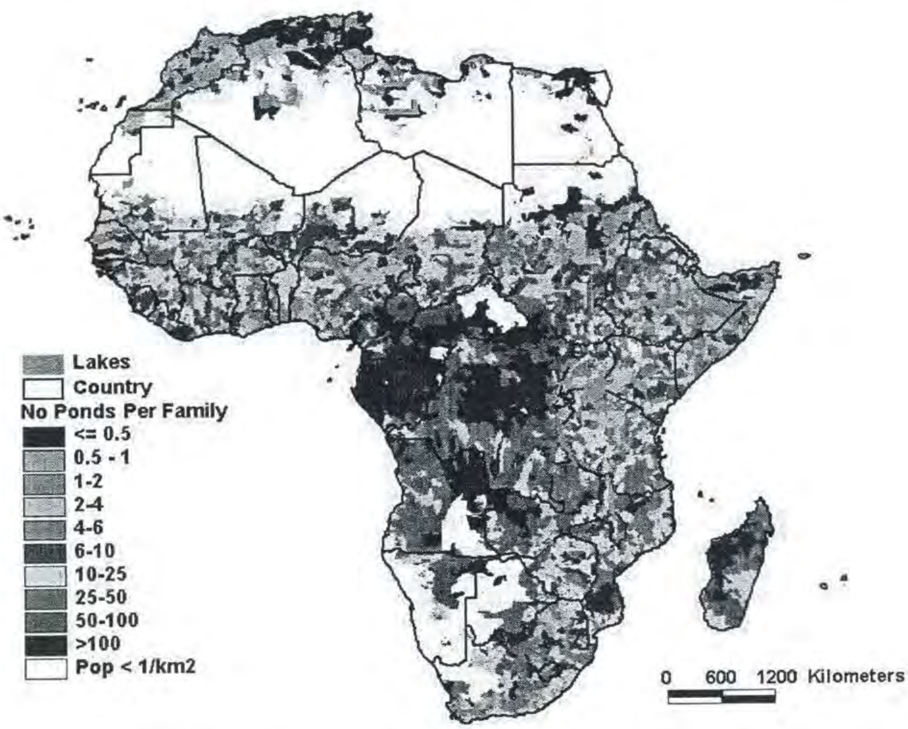

Figure 6. Number of potential 1000–m^3 capacity ponds per family.

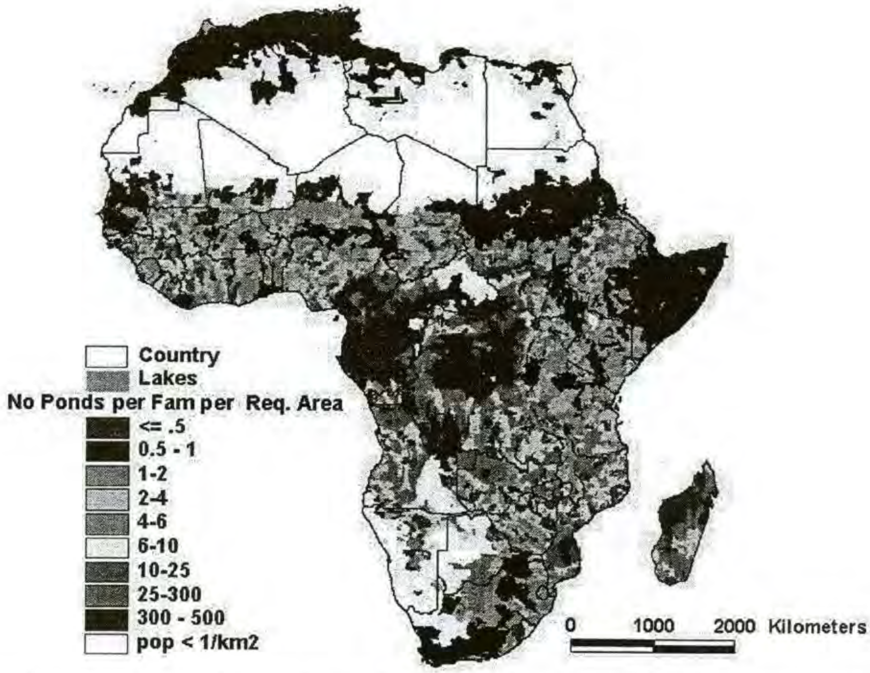

Figure 7. Number of potential 1000–m³ capacity ponds per family normalized by the required watershed area.

ponds, in which case, even in areas where figure 7 shows less than 1, it is still possible to plan on the use of ponds as a water management tool.

Discussion

To put the significance of 1000–m^3 ponds in perspective, a comparison was made with the volumetric capacity of Lake Mead that was created by the famous Hoover Dam, along the border of Nevada and Arizona in the United States. The reported capacity of Lake Mead is about 37 billion m^3. This is equivalent to having 37 million 1000–m^3 ponds. If we take the country of Ethiopia as an example, where there are about 10 million farming families, one pond per family is equivalent to storing 10 billion m^3 of water which is still less than a third the capacity of Lake Mead. However, small ponds distributed throughout the country will form the basis to tackle major food insecurity issues by providing water to the subsistence farmer without displacement. In addition, small ponds will contribute toward the betterment of the environment through the reduction of soil erosion that will result from the various detentions structures associated with the ponds.

It is important to note that allowance was not made for sedimentation during the calculation of the pond volume. Unless measures are taken to reduce the flow of sediments into the pond, the capacity of the pond will decrease substantially with time. Since sedimentation rates vary depending on the size of the watershed area, its land cover treatment and rainfall–runoff characteristics in general, it is recommended that ponds be protected from sedimentation through proper catchment treatment and use of detention basins upstream of the pond. Although ponds are beneficial in providing and regulating water supply for various purposes, the effect of the concentration of several ponds on the regional water balance and quality should be studied and regulated according to local conditions.

The strength of this study lies on the use and application of a spatially distributed unique rainfall and topographic data sets. Uncertainties, though not quantified, in these products could be caused by the accuracy of the satellite rainfall estimate and the assignment of Curve Numbers for each 10–km pixel. Although the 100 km^2 represented by each pixel is less than the 250 km^2 upper–limit recommended by Pounce and Hawkins (1996) for the application of the SCS Curve Number method, the results should only be used to estimate runoff yield within the pixel as opposed to aggregating the results to estimate watershed yield at the outlet. Based on the work of Simanton et al. (1973), watershed–wide aggregation of runoff from the individual pixels without runoff routing between pixels and connecting channels in large watersheds could overestimate the watershed yield.

In addition, modeling assumptions in the use of the antecedent soil moisture (AMC) threshold for Type I (3 mm) and Type III AMC (9 mm) could contribute to the uncertainties. For example, Mitchell et al. (1993) recommended the use of 12 and 41 mm for the lower and the upper limit for switching from AMC Type II to AMC I and AMC III, respectively, during a validation study of the AGNPS model on small mild topography watersheds in the United States. The original threshold values for the corresponding lower and upper limit are 36 and 41 mm, respectively (USDA–SCS, 1985).

Although we were unable, because of lack of data, to validate the accuracy of the runoff estimates at the watershed level used for this study, we believe the overall runoff estimate is lower than what might be generated in reality. This assessment is based on several factors, which point to the general runoff underestimation of the SCS CN Method. These include the lower–limit CN (no runoff) by Hawkins (1973); the low antecedent soil moisture (AMC) conditions that are generally exhibited in semi–arid regions; and the tendency of the satellite rainfall estimate (RFE) to underestimate rainfall amounts (work in progress by the authors) in the continent. On the other hand, according to Simanton et al. (1973), the application of the SCS CN Method at larger watershed areas may result in an overestimation of the runoff when the substantial transmission losses are not considered. However, this study does not involve runoff routing to estimate runoff–yield at the watered outlet and thus it is unclear how the large size of the modeling unit affects the runoff estimation. In addition, simple comparison between modeled median yearly watershed volumes (knowing the tendency to overestimate) to widely–published long–term average yearly river discharges in several basins in Africa suggests a lower runoff estimate. But this is not a scientific estimation as the contribution of the base–flow, included in the river discharge volumes was not known. Comparable observation was made by Tauer and Humborg (1992) where they reported the underestimation of the SCS CN Method in the Sahel region of West Africa. The tendency to underestimate runoff was acceptable for this study as it gives a conservative runoff volume for water harvesting. This, however, points out the need to test and adapt the SCS CN Method for localized applications using formal model calibration techniques.

The alternative to the daily simulation of runoff using the CN Method in data–scare African continent was the use of an assumed annual rainfall fraction. While Shanan and Tadmor (1979) warned against the use of annual runoff percentage in the design of micro–catchment systems, Hollick (1982) reported that annual runoff percent suffered from the disadvantage that it gives no indication of the relationship between runoff and rainfall intensity and duration so that extrapolation to new areas or drought years is difficult. On the other hand, using the daily rainfall–runoff simulations, it was possible to show the spatial distribution of the annual runoff as fraction of the annual rainfall (fig. 2) where the majority of watersheds fall in the range between 5% and 15%. Localized studies reported a substantially higher runoff percentages (40% to 50%) in the highlands of Ethiopia (Zeleke, 2000). Thus, this study probably shows a conservative low–end estimate of the available runoff for pond storage. It should be pointed out this study has focused mainly on the surface water component of the regional water balance. Areas that show low runoff amounts may have high groundwater resource potential for development due to higher infiltration characteristics of the soil–landcover complex.

To sum up, the most important use of these atlases is to show the relative difference in runoff generation potential between regions, largely dependent on the rainfall characteristics and topographic factors. The coarse resolution data of 10 km prevents the application of these products for individual farm–pond planning and design. Local specific rainfall–runoff relationships should be used during the actual design process whenever possible. However, these products will give a generalized view of the relative differences between regions for conducting feasibility studies in the assessment and planning of farm ponds as a tool for water management

Conclusion

The objective of this study was to develop water harvest index maps for Africa for use by regional planners to study the feasibility of using ponds as a water management tool. The SCS Curve Number Method was applied uniformly to continental Africa to estimate daily runoff over a five–year period using satellite–based daily rainfall estimates. Due to the uncertainties in the application of the Method at this scale, the results have more merit in terms of showing regional differences rather than the absolute values for a given location.

Various water harvest index maps were developed. These maps are believed to be the first of their kind for continental Africa. Comparable maps have been produced for the conterminous United States by NRCS (USDA, 1997). The maps in this article show a number of quantitative parameters that can be used for quick reference in pond feasibility studies. The maps include: average runoff depth by catchment area, recommended watershed area for a small pond, and recommended pond depth. In addition, with the use of population density, various maps that show the relationships between pond number and family size have been produced.

This study shows that a large part of food insecure regions in Africa have sufficient amount of runoff that can be stored in small ponds for smoothing out the erratic rainfall patterns. It is hoped that these maps will encourage regional planners to conduct further feasibility studies to pursue economically feasible pond–based small–scale supplemental irrigation schemes.

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