Chapter 8

Stormwater Storage-Treatment-Reuse Systems

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Introduction

The overall effectiveness of a variety of stormwater BMP's was evaluated in Chapter 7. Two other aspects of control of stormwater: high-rate treatment and the potential effectiveness of using stormwater for supplemental irrigation are described in this chapter.

Stormwater Treatment

Because of the dynamic nature of stormwater flows and water quality, most control systems are a hybrid of temporary storage and high-rate treatment. For a given level of stormwater control, the engineer can accomplish this objective using various combinations of storage and treatment. Much has been written on this subject and methods for finding the optimal combination of storage and treatment have been developed. Heaney and Wright (1997) provide a summary of these methods. Several unresolved issues remain with regard to evaluating the performance of these treatment systems.

Effect of Initial Concentration

As pointed out in Chapter 7, the effect of initial concentration on the performance of wet-weather controls should not be ignored. A high percent removal for a control will usually occur if the initial concentration is high. Separate and combined stormwater flows exhibit wide variability from storm to storm as well as within a given storm. The effect of initial concentration on performance can be evaluated directly by finding the order of the reaction as well as the rate constant (Heaney and Wright 1997).

Effect of Change of Storage

Another complication in dealing with treatment of wet-weather flows is that the control units are typically filling and emptying during and following the storm. Thus, it is vital to properly measure the change in storage at short time intervals to incorporate this important factor. The effect of changing storage is captured in the calculated detention time for each parcel of water.

Effect of Mixing Regime

Another critical assumption is the type of mixing that takes place in the treatment reactor. Two limiting cases are plug flow wherein the parcels simply queue through the reactor and complete mixing wherein the incoming parcel instantaneously mixes with the water already in the reactor.

Effect of Nature of the Suspended Solids

The nature of the suspended solids changes during the storm and can vary widely. The solids can range over several orders of magnitude from coarse solids to fine colloids. Pisano and Brombach (1996) present a summary of efforts to date to characterize wet-weather solids.

Essential Features of Future Wet-Weather Control Facilities

Given the large variability in the quantity and quality of wet-weather flows and the filling and emptying of treatment reactors, direct monitoring of the wet-weather inflows and the status of the control units is of fundamental importance. Unfortunately, few such systems have been built in the United States. The Europeans are more advanced in trying to evaluate and optimize wet-weather control systems.

High-Rate Operation of Wastewater Treatment Plants

High-rate operation of WWTPs during and following wet-weather events is an important option to evaluate as part of the overall stormwater management program for combined and for separate systems that are affected by I/I. It is possible to model the expected performance of these systems using the GPS-X WWTP software from Hydromantis, Inc., or similar programs, to do continuous simulation of the effect of wet-weather flows on DWF treatment plants. Mangeot (1996) performed a preliminary feasibility study using GPS-X to evaluate the Boulder WWTP during the 1995 high-flow year. High-rate operation of the WWTP during these wet periods and periods with high I/I due to seasonably high groundwater tables appears to be a very attractive option to consider. Not much research has been done on this problem and there are only a few literature citations on results of attempting to model the dynamics of WWTP operation during high flow periods. Some questions remain regarding the ability of GPS-X to properly handle the hydraulics associated with wet-weather flows. However, it is possible to show with direct measurements for the Boulder WWTP, that the plant is capable of operating effectively over a wide range of influent flows and concentrations. Because the influent is already so dilute, caution should be exercised in requiring a specified percent removal under these wet-weather conditions.

Stormwater Reuse Systems

Introduction

At present, there is much interest in local management of stormwater from smaller, more frequent events. The primary on-site option is to encourage infiltration of stormwater from roofs, driveways, parking lots, and streets. This infiltrated water increases the moisture in the unsaturated zone and raises the groundwater table which can provide benefits in terms of increasing base flows in streams and providing storm water to help meet the ET needs of the local vegetation. Higher groundwater levels can have negative effects on basements and on sanitary and combined sewers. This section explores the possibility of the reuse of urban stormwater for irrigation water which is a major component of urban water use.

Previous Studies

As water supplies become more stressed, water conservation and reuse become more attractive options. Wastewater disposal costs also encourage more water reuse. Asano and Levine (1996) provide a historical perspective and explore current issues in wastewater reclamation, recycling, and reuse, and outline requirements of a stormwater and wastewater reuse feasibility study. Lejano et al. (1992) summarize the benefits of water reuse as the following:

1. Water supply related:
   a. Supplements regional water supply, eliminating need to develop additional supplies.
   b. Provides more reliability than the usual supply and is less affected by weather.
   c. Provides a locally controlled supply, reducing dependence on state or regional politics.
   d. Avoids the operating costs of water treatment and delivery.
   e. Eliminates social and environmental impacts of diverting water from natural drainageways.
   f. Eliminates impacts of constructing large-scale water storage and transmission facilities.

2. Wastewater related:
   a. Avoids the capital and operating costs of disposal facilities.
   b. Avoids the costs of advanced treatment facilities needed to meet state and federal discharge requirements.

Urban wet weather flow management needs to be viewed within the context of overall urban water management. Such an integrated framework was proposed in the late 1960s and is regaining favor in the mid-1990s. Changes in urban water use are occurring because of aggressive water conservation practices which will significantly reduce indoor and outdoor water use.

As discussed in Chapter 3, per capita indoor residential water use is very stable at an average of 60 gpcd. Aggressive hardware changes such as low flush toilets should reduce this usage rate to 35-40 gpcd. Only a small proportion of this indoor waste is black water. Most of it is graywater that could be reused on-site for lawn watering and other non-potable purposes. Peak water use in most cities is heavily influenced by urban lawn watering. This outdoor water use does not require potable quality. As the cost of water treatment continues to increase, dual water systems become more of a possibility, particularly with a decentralized infrastructure.

California has been a focal point of reuse activity for some time. Ashcraft and Hoover (1991) found that reclaimed water in southern California is selling at prices ranging from $303/ac-ft to $366/ac-ft, with costs of operation and maintenance of treatment facilities running from $10/ac-ft to $95/ac-ft. The authors argue that “avoided costs,” such as those associated with wastewater disposal should be included in cost calculations.

Mallory and Boland (1970) developed a hydrologic and economic optimization model of a stormwater reuse system in a new town in Maryland. Their system used a network of subdivision level detention ponds. Subpotable reuse required a dual distribution system to deliver it to households. They found that the net capital cost of such a system (scaled up to 1998 dollars) was $560/dwelling unit for a potable reuse system, and $1175/dwelling unit for the subpotable system. This compares favorably with $950/dwelling unit for a conventional system, the differential of 23% premium for subpotable reuse due mainly to the dual distribution system. When pollution control costs are included for stormwater quality, an additional cost of $640/dwelling unit was calculated, making the investment in the subpotable system more attractive.

Requa et al. (1991) developed a wastewater reuse cost model for screening purposes in northern California. More recently, Tselentis and Alexopoulou (1996) describe a feasibility study of effluent reuse in the Athens, Greece metropolitan area. Uses considered were: crop irrigation, irrigation of forested areas, industrial water supply and domestic non-potable use. The most cost-effective scenario was distribution for crop irrigation near the route of the current discharge point.

At the other extreme, Haarhoff and Van der Merwe (1996) describe direct potable reuse of reclaimed wastewater in Windhoek, Namibia. Law (1996) describes the Rouse Hill project in Sydney, Australia, in which a dual non-potable distribution system was installed in a new community in 1994. Oron (1996) developed an integrative economic model, arguing that the optimal cost of a reuse system is a function of treatment method, cost of treatment, transportation and storage costs (pipelines and tanks), environmental costs, and the selling price of reused wastewater. New initiatives for reusing stormwater flows for urban residential and industrial water supply systems in Australia were described by Anderson (1996a, 1996b).

Mitchell, Mein, and McMahon (1996) used a water budget approach to integrate storage and reuse of urban stormwater and treated wastewaters for two neighborhoods in suburban Melbourne, Australia. The authors developed an urban water balance model to determine the impact of stormwater and wastewater reuse; and suggest its application at a number of scales. They determined that water demand from reservoirs in Australia could be halved through the use of this resource.

Nelen, DeRidder, and Hartman (1996) described the planning of a new development for about 10,000 people in Ede, Netherlands that considers a dual water supply system. Storing the treated wastewater on-site during wet weather periods can be more attractive than only using black water for reuse (Pruel, 1996). Herrmann and Hase (1996) described rainwater utilization systems in Bavaria, Germany that save drinking water and reduce roof run-off to the sewerage system. The impact of urbanization on the hydrological cycle of a new development near Tokyo, Japan was performed by Imbe, Ohta, and Takano (1996).

Much of this work has focused upon using treated wastewater from a single effluent plant. The problem then becomes one of finding demand centers for the wastewater that are typically located quite some distance away. This becomes a nonlinear form of the transhipment problem, in which demand and distance are cost drivers in a nonlinear objective function.

Many researchers have started to focus on less centralized systems, including Tchobanoglous and Angelakis (1996). Decentralized systems can take advantage of the segregation between wet weather flow, graywater, and blackwater, and possibly utilize less contaminated waters closer to their points or origin. Of the three, stormwater runoff is usually the least contaminated prior to central collection. This may avoid construction of additional treatment systems, pipelines, and other infrastructure and present significant cost savings.

From the wet weather flow quality management perspective, there is much interest in local management of wet weather flow from smaller, more frequent events, as these events tend to have more pollutants associated with them. The primary on-site option is to encourage infiltration of this stormwater flow from roofs, driveways, parking lots, and streets.

Herrmann et al. (1996) found that rainwater utilization (using roof runoff water directed into a storage tank) could provide from 30-50% of total water consumption of a residence and reduce heavy metals (in stormwater runoff not reused) by 5-25%. Wanielista (1993) developed design curves in order to determine the storage retention volumes necessary to achieve given proportions of reuse. The design curves are based on a daily water-balance model. The main objectives for this practice in the State of Florida are the costs avoided of using municipal or pumped groundwater for irrigation purposes. From the regulatory viewpoint, the main objective is to discharge some of the stormwater onto the land and thereby get credit for 100% removal of this pollutant source.

Field (1993) did a cost-effectiveness study of the reuse of urban stormwater to meet a variety of differing demands for a hypothetical urban area. The proposed uses varied in their water quality needs, as did the corresponding treatment system designated for that use. Nowakowska-Blaszcyzyk and Zakrzewski (1996) project increases in suspended solids, nitrates, COD, BOD, and lead from rainfall routed through the following sources: roofing, parking areas, streets, storm sewers, infiltration through lawns, and infiltration through sand. The lowest values tended to be from roof runoff. Karpiscak, Foster, and Schmidt (1990) detail the application of stormwater and graywater reuse techniques at a single residence in Tucson, AZ.

Harrison (1993) developed a spreadsheet model to estimate the amount of stormwater captured in a detention pond that could be reused for irrigation in Florida. His work is an application of earlier work by Harper (1991). The Southwest Florida Water

Management District is interested in stormwater reuse as a way of increasing the treatment efficiency of detention systems. Their current design calls for storing the first inch of runoff and draining the pond over a five-day period. They are considering going to an average residence time of 14 days to improve performance from removal rates of 50 to 70 % with a five-day drawdown time. Reusing stormwater would give them a 100% treatment efficiency.

Harrison (1993) uses a daily water budget to estimate the amount of captured urban runoff that could be used for irrigation. The basic storage equation is:

$$\frac{dS}{dt} = R + P + F - RU - D - ET \qquad \text{Equation 8.1}$$

where

$\frac{dS}{dt}$ = the change in storage.

R = runoff volume.
P = direct precipitation onto the pond.
F = water inflow through sides and bottom of the pond which can be negative.
RU =reuse volume.
D = pond outflow.
ET = pond evapotranspiration.

Harrison assumes that there is no net subsurface flow into or out of the pond, i.e., $F = 0$. All values are converted into inches over the equivalent impervious drainage area. A daily time step is used. A minimum precipitation volume of .04 inches is assumed to be needed to produce runoff. This method is identical to the STORM-type calculations with the exception that STORM uses an hourly time step and, in this case, outflows occur either by reuse or direct discharge of the excess water. Harrison does not indicate what he assumed for a pond drawdown rate in addition to the irrigation release. The final results are expressed as a production function showing the percent of the irrigation demand that is satisfied for various combinations of pond size and irrigation reuse rates. The primary purpose of the stormwater reuse study in Florida was to minimize the pond outflow and thereby achieve increased pollutant removal efficiency by infiltrating the water locally. Lawn watering was more of a by-product.

Courtney (1997) explored the potential effectiveness of stormwater runon systems for meeting irrigation needs in Boulder, CO. She used an hourly simulation model that mimicked the operating policy of the University of Colorado’s automatic irrigation system. The overall imperviousness of the campus is about 60% so there is ample opportunity for infiltrating some of this storm water. The results of this study indicate that, while much of the stormwater can be infiltrated, it is unclear how much of this water will ultimately be used to satisfy ET. During and immediately following the storm, the ET needs have already been satisfied. Without detailed concurrent groundwater and soil moisture monitoring data, it is not possible to estimate the longer term fate of this captured stormwater. If this stormwater could be directed to local or regional storage ponds, it could be reused later for irrigation. Some of this reuse already happens on the University of Colorado at Boulder campus because some of the stormwater drains to the local irrigation ponds.

Estimating the Demand for Urban Irrigation Water

Urban Water Budgets

One of the most prevalent themes advanced in the recent literature in stormwater management is to limit the generation of runoff from urban areas through the use of BMPs and on-site control of stormwater particularly in frequent small storm events (Mitchell et al. 1996). This section evaluates residential on-site control.

Butler and Parkinson (1997) suggest that reuse of the stormwater resource provides for a more sustainable urban drainage infrastructure by minimizing available stormwater that could possibly be mixed with wastewater; as well as attempting to minimize the use of expensive drinking water for irrigation purposes. Pitt et al. (1996) suggests that residential stormwater (i.e. roofs and driveways, not streets) generally has the least amount of contamination and advocates infiltration of residential stormwater as a means of disposal with few environmental impacts.

In keeping with this theme, a possible model of a residential on-site control system is shown in Figure 8-1. Precipitation falls on roofs and driveways and is channeled, with some losses, into a storage tank. The storage tank varies in size depending upon the location. Water is taken from the tank for irrigation of landscape surfaces; some is used for evapotranspiration, some is lost to infiltration, and some is lost to runoff. In essence, this model is an irrigation, or water deficit demand, model.

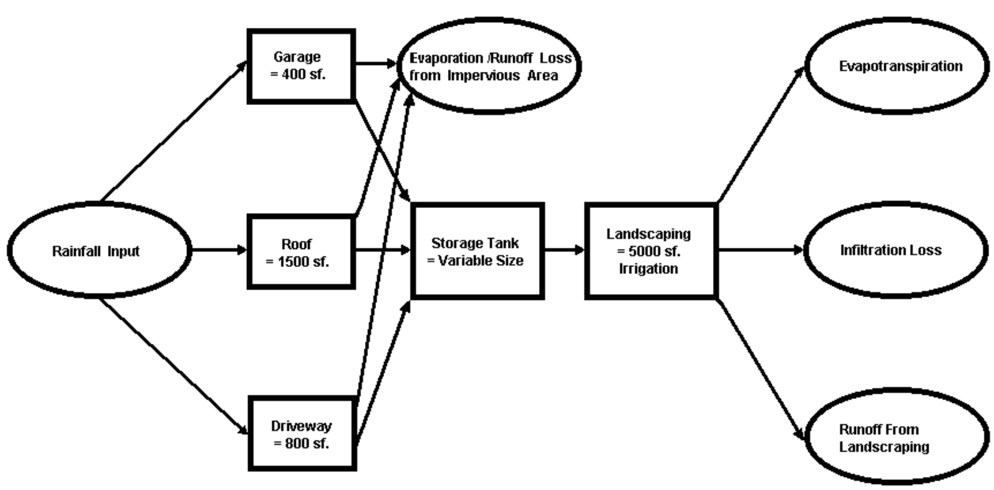

Figure 8-1. Concept of stormwater reuse residential storage system.

Irrigation demand is determined mainly from ET requirements. In order to calculate ET, daily or monthly water budgeting is performed. By examining the water balance of one residential parcel in differing climatic zones, the efficacy of the option of on site reuse of stormwater can be evaluated across the U.S. This section introduces the reader to climatic water balance models, and existing databases for use with these models, develops a parcel level storage/demand analysis using the results from the climatic model and compares results regionally across the U.S.

Water Budget Concepts

The early efforts by Thornthwaite (1948) may have been the first work in climatology in which, by an analytical method, differing characteristics such as rainfall, temperature, and the number of daylight hours in a day were combined to yield regional climatic projections. The number of daylight hours in a day are a function of the latitude of the location, whereas monthly precipitation and temperature are functions of the climate of the location. Average monthly precipitation in the U.S. varies widely with location, as can be seen in Figure 8-2. For example, in comparing the rainfall signature of San Francisco, CA with Memphis, TN, San Francisco has dry summers and wet winters; whereas Memphis appears to have wet springs, with some precipitation falling in every month of the year. Extreme monthly precipitation is also shown in Figure 8-2. San Francisco appears to have much less variability than Memphis.

The Thornthwaite method keeps track of precipitation, calculated potential evapotranspiration (PET), and calculated actual ET on a daily or monthly basis, calculating water deficit, water surplus, soil moisture recharge, and soil moisture utilization by integrating areas under the plotted curves. The graphical representation of this process is a water budget, examples of which are plotted in Figure 8-3, compiled from Mather (1978).

For example, for San Francisco, in January, the precipitation far exceeds the PET (and ET, at this point they are equal). Up until mid February, the soil moisture is being recharged. This occurs until soil moisture capacity is reached, then the rest of the rainfall exceeding PET is surplus (and available for runoff). For San Francisco, the annual surplus is about 4.3 inches. When PET exceeds rainfall (and is greater than ET) in April through October, there are two integrals of importance; the area between PET and ET is the water deficit, or 10.1 inches, and the area between ET and precipitation is what is being drawn from the soil moisture storage. Then, in October, when precipitation exceeds PET, the area between the precipitation curve and PET goes to soil moisture recharge. The annual total PET for San Francisco is 26.6 inches, ET is 16.6 inches, and precipitation is 20.8 inches. Memphis, also shown in Figure 8-3, has an annual total PET of 39.2 inches, ET of 32.5 inches, precipitation of 45.8 inches, a water deficit of 6.7 inches, and a surplus of 13.2 inches. It is readily apparent that the climate, and the subsequent irrigation needs for each location, are significantly different.

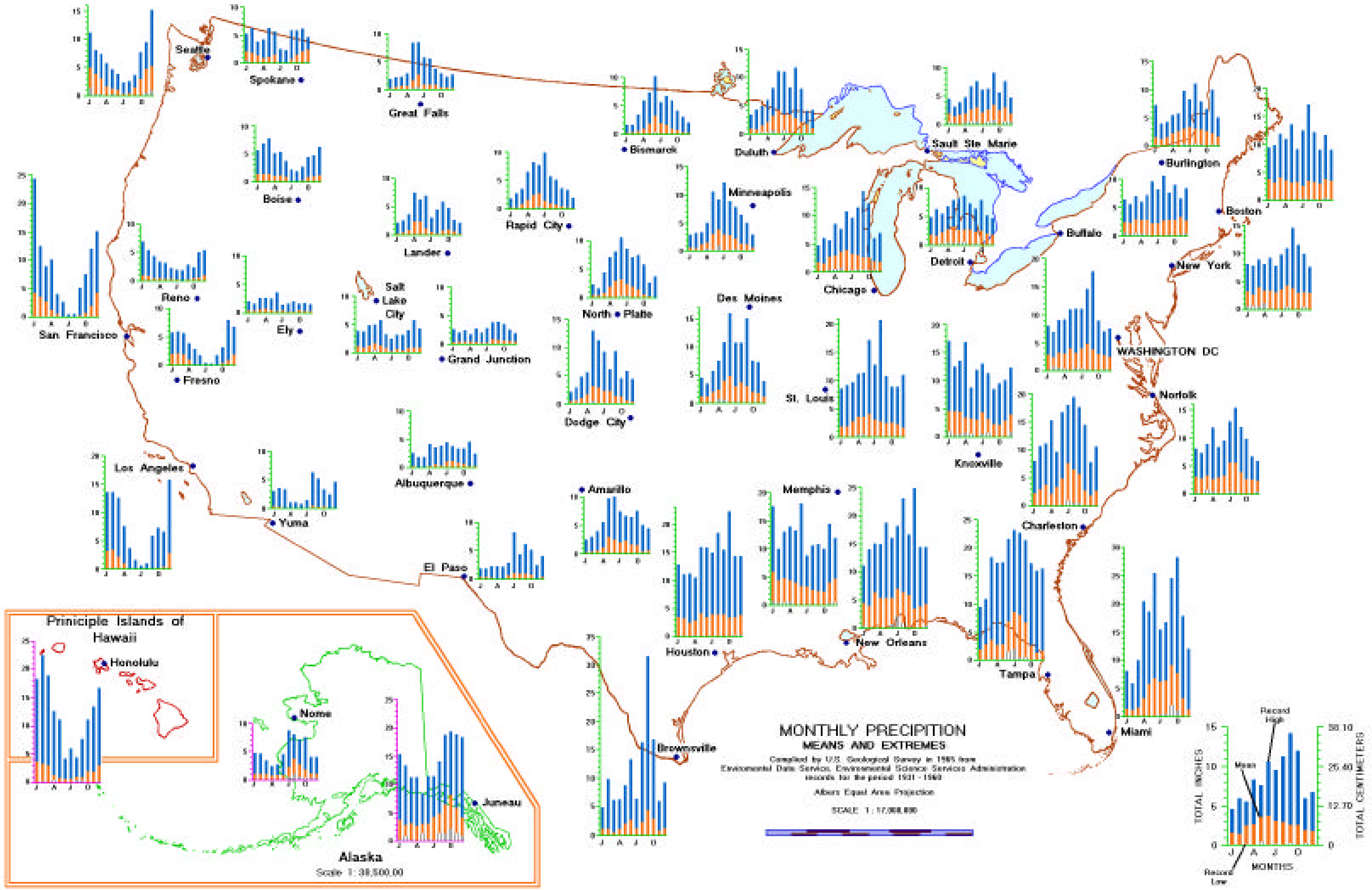

Figure 8-2. Monthly precipitation for selected stations in the U.S., means and extremes (USGS 1970).

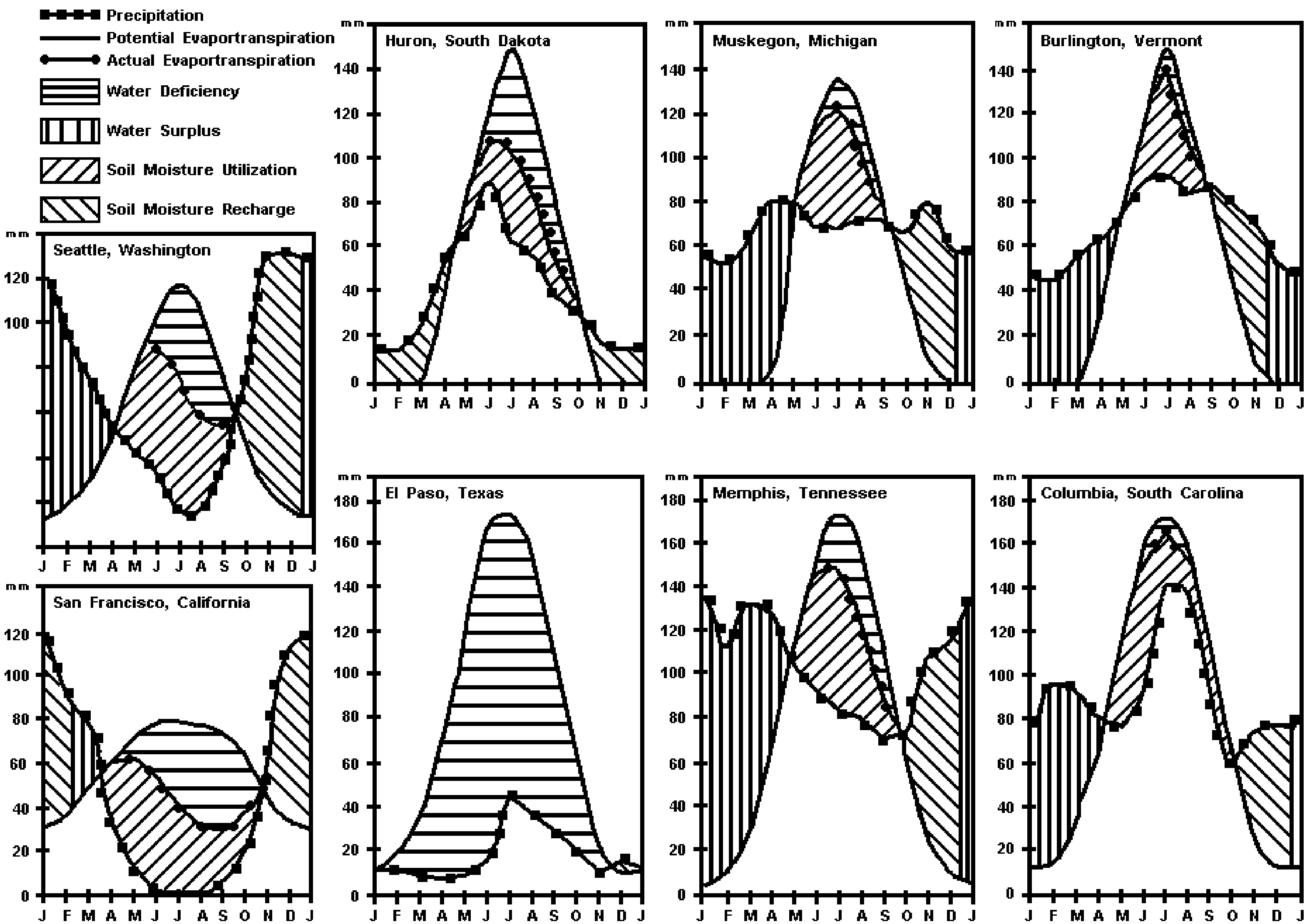

Figure 8-3. Water budgets for selected stations in the U.S. (Mather 1978).

Methods of Analysis

The Thornthwaite and Mather temperature based method (Thornthwaite 1948, Mather 1957, and Willmott 1977) was used to calculate monthly PET, projected ET, water deficit, water surplus, and runoff (for undeveloped areas). Other methods, developed later, require more information, such as net radiation measurements, wind speed, or humidity. Such methods are usually found to be more accurate in arid areas (Yates 1996). An even better approach to the daily water balance model is suggested by Vorosmarty et al. (1996) and explained in detail in Vorosmarty et al. (1989, 1991). This work is a continuation of the work of Mather and Thornthwaite at the University of Delaware.

In the work in this section, the Thornthwaite (or other temperature or radiation based PET model) is used as above, but the soil moisture term is actually modeled as well as the PET. The result is a series of coupled differential equations that are solved by a Runge Kutta algorithm. The input data then reduced to soil and vegetation type. The Thornthwaite method was chosen for this analysis because of the simplicity of the algorithm, as well as the availability of both monthly and daily precipitation and temperature data. Daily data are available for most locations from the National Climatic Data Center.

The water budget procedure is presented in Table 8-1 and graphically in Figure 8-4 for San Francisco, CA. The reader may use the table to follow along the calculations step by step. The mean precipitation, mean temperature, and mean PET (for comparative purposes) are input parameters, and can be found in rows 10, 11, and 29, respectively.

The first step is the calculation of the Julian Day Number. This was done by starting with the number 15 and adding 30 to each successive month in row 12. Next, the geodesic variables are calculated by the following formula:

$$\boldsymbol{f} = 2\boldsymbol{p}[Latitude]/360 \qquad \text{Equation 8.2}$$

and

$$\boldsymbol{d} = .4093\sin\left[(2\boldsymbol{p}/365)J - 1.405\right] \qquad \text{Equation 8.3}$$

where $\boldsymbol{f}$=latitude in radians in Equation 8.2, $\boldsymbol{d}$ also in radians, is the earth-sun declination angle in Equation 8.3, and J is the Julian day number (e.g., December 31=365). These formulas are used in rows 12 and 13. Next the following term is calculated:

$$\boldsymbol{w}_s = \arccos\left[-\tan \boldsymbol{f} \tan \boldsymbol{d}\right] \qquad \text{Equation 8.4}$$

using the terms calculated above. $\boldsymbol{w}_s$ is the sunset hour angle in radians (Equation 8.4). This is calculated for each month in row 15. Next, the total day length in hours is calculated in Equation 8.5 as follows:

$$N_i = 24\boldsymbol{w}_s / \boldsymbol{p} \qquad \text{Equation 8.5}$$

Table 8-1. Water budget calculations for San Francisco, CA.

	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
8	**Meteorological variable**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum (mm)**	**Sum (inches)**
9	Days in month	31	28	31	30	31	30	31	31	30	31	30	31	365	
10	Mean Precipitation, mm	116	93	74	37	16	4	0	1	6	23	51	108	529	20.8
11	Mean Temperature, mm	10.4	11.7	12.6	13.2	14.1	15.1	14.9	15.2	16.7	16.3	14.1	11.4		
12	Julian Day Number	15	45	75	105	135	165	195	225	255	285	315	345		
13	delta, radians	-0.37	-0.24	-0.05	0.16	0.33	0.41	0.38	0.26	0.06	-0.14	-0.31	-0.40		
15	Omegas, radians	1.26	1.38	1.53	1.70	1.84	1.91	1.89	1.77	1.62	1.46	1.32	1.23		
16	Ni, hours	9.64	10.53	11.72	12.96	14.02	14.60	14.41	13.56	12.38	11.14	10.05	9.43		
17	I	3.03	3.62	4.05	4.35	4.80	5.33	5.22	5.38	6.21	5.98	4.80	3.48	57.50	
18	alpha	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39		
19	**Thornthwaite Model:**														
20	Thornthwaite PET, mm	30	35	48	55	67	75	75	72	73	65	47	34	677	26.6
21	P-PET, mm	86	58	26	-18	-51	-71	-75	-71	-67	-42	4	74	-148	-5.8
22	Storagei, mm	150	150	150	133	94	59	36	22	14	11	15	89	924	36.4
23	Change in storage, mm	60	0	0	-17	-39	-35	-23	-14	-8	-4	4	74	-1	0.0
24	Calculated ET, mm	30	35	48	54	55	39	23	15	14	27	47	34	420	16.6
25	Water Deficit, mm	0	0	0	1	13	35	52	58	59	39	0	0	256	10.1
26	Water Surplus, mm	26	58	26	0	0	0	0	0	0	0	0	0	109	4.3
27	Runoff, mm	26	58	26	0	0	0	0	0	0	0	0	0	109	4.3
28	P-ET, mm	86	58	26	-17	-39	-35	-23	-14	-8	-4	4	74		
29	Measured PET, mm	31	35	49	59	70	78	79	77	75	66	48	35	702	27.6
30	Initial Storage, mm	90													
31	Storage Maximum, mm	150													
32	Error, mm	1	0	1	4	3	3	4	5	2	1	1	1	26	
33	% error													3.68%	

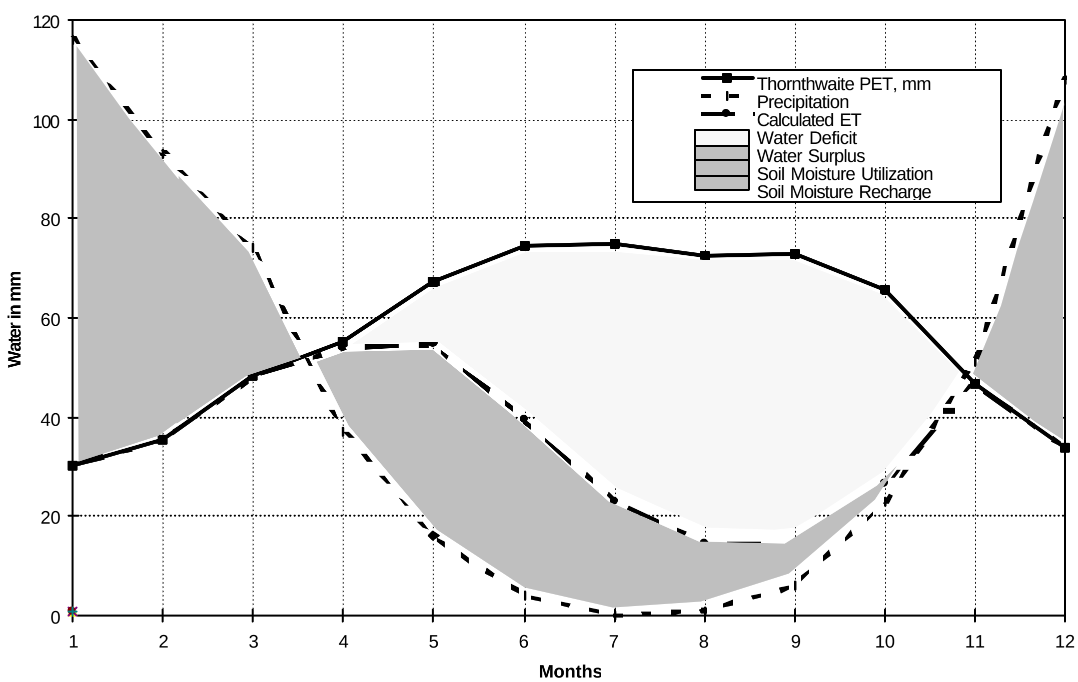

Figure 8-4. Water budget for San Francisco, CA.

and is shown in row 16. Then the following parameters are calculated in Equations 8.6 and 8.7:

$$I = \sum_{i=1}^{n} \left[.2T_i \right]^{1.5} \qquad \text{Equation 8.6}$$

$$a = (6.75*10^{-7})I^3 - (7.71*10^{-5})I^2 + (1.79*10^{-2}) + .49 \qquad \text{Equation 8.7}$$

where n= number of months (or days) in question. These are calculated in rows 17 and 18, the sum of I is calculated by adding all the values of I for the previous 12 months shown in row 17 and is shown in cell P17 . Since T_i (temperature) can be negative, in those cases, I and *PET* are set to zero. I represents an annual heat index for the area in question. Then, actual values for potential evapotranspiration, *PET*, storage, *S*, evapotranspiration, *Et*, and undeveloped runoff, *R* are calculated using the Equation 8.8:

$$PET_i = 16 f_1 f_2 \left[\frac{10T_i}{I} \right]^a \qquad \text{Equation 8.8}$$

where $f_1 =$ the fraction of the number of days in the month *i* divided by the average days in a month, 30; and $f_2 = \frac{N_i}{12}$, the fraction of the number of hours in a day divided by the base of 12 hours in a day. This is calculated in row 20. Next, the soil moisture storage is calculated. This is not to be confused with tank storage, which will be calculated later. The soil moisture storage is modeled as an offline reservoir that leaks when the soil moisture field capacity is reached. Equations 8.9 and 8.10 compute storage in month *i* as follows:

$$S_i = \min\left[((P_i - PET_i) + S_{i-1}), S_{\max} \right] \text{ if } P_i > PET_i \text{(surplus condition)} \qquad \text{Equation 8.9}$$

$$S_i = S_{i-1} \exp\left[\frac{(PET_i - P_i}{S_{\max}} \right] \text{ if } P_i \le PET_i \text{ (deficit condition)} \qquad \text{Equation 8.10}$$

in which S_i is the soil moisture storage term for month *i*, P_i is precipitation term for month *i*, and S_{max} is the maximum storage availability found in cell D31. The initial storage term for month 0 is found in cell D30. The calculated S_i for each month is found in row 22. The change in storage, or $\Delta S = S_i - S_{i-1}$ is calculated in row 23. Next, actual evapotranspiration is calculated by Equations 8.11 and 8.12:

$$Et_i = PET_i \text{ if } P_i > PET_i \qquad \text{Equation 8.11}$$

$$Et_i = P_i + S_{i-1} - S_i \text{ if } P_i \le PET_i \qquad \text{Equation 8.12}$$

and can be found in row 24. Finally, runoff is computed by Equation 8.13,

$$R = P_i - Et_i - \Delta S \qquad \text{Equation 8.13}$$

and is shown in row 27. In cases in which *R<0*, runoff is then set to zero.

The parameters for which the least amount of information is usually available are the initial storage term (when *i*=1) and the maximum soil moisture storage. In this case, an equal S_{max} of 150 mm was used and the initial storage term was determined by using the calculated S_i for December (and iterating if necessary). Water deficit was calculated by subtracting the estimated ET from the calculated PET in months in which PET exceeds rainfall (otherwise there is no deficit). This is shown in row 25. Water surplus was calculated by Equation 8.14:

$$SU_i = P_i - PET_i - \Delta S_i \text{ if } P_i > PET_i \qquad \text{Equation 8.14}$$

and is shown in row 26. The percent error is calculated by taking the absolute value of the difference between the calculated PET and measured PET, summing for the 12 months, and dividing by the sum of the measured PET for 12 months, and is shown in cell P33. For San Francisco, the error is 3.68%, indicating that there is a reasonably good fit with the Thornthwaite model.

The tank calculations for San Francisco are shown in Table 8-2. Using a parcel size of 10,000 sq. ft. (cell D36), and a 1500 sq. ft. house (cell D37), 400 sq. ft. garage(cell D38), an 800 sq. ft. driveway (cell D39), and an irrigated area of 5000 sq. ft. (cell D40), an irrigation demand model was developed in which 80% of the runoff from the house, garage, and driveway was recovered into a storage tank (unless spilled), converting mm of runoff into gallons by multiplying by the impervious areas and conversion factors. This is shown for each month in row 42. These criteria are approximately equal to the dimensions used in the “Casa Del Agua” house in Tucson, AZ (Foster, et al.,1988 and Karpiscak et al., 1990). For purposes of this exercise, runoff from the roof, garage, and driveway are assumed to be channeled into the proposed cistern, which is assumed to be 80% efficient at capturing rainfall (which is consistent with the “Casa Del Agua” case). An initial guess of 100 gallons was given for the storage tank to initiate the calculations.

Water requirements of the landscaped vegetation were assumed to be similar to that predicted by the deficit calculations using the Thornthwaite procedure and losses due to runoff and infiltration were considered negligible. The cumulative volume was then calculated, assuming that the tank initially is empty and that cumulative volume cannot exceed the size of the storage tank, subtracting actual use in the previous month from the storage volume. This is shown in row 43. Next, the potential use or demand for the water was calculated by multiplying the deficit by the irrigated area and converting the number into gallons. This is shown in row 44. The actual use from the storage tank, shown in row 45, is equal to the potential use if it does not exceed the cumulative volume. This procedure is followed in the Table 8-2 for San Francisco.

Table 8-2. Water storage tank calculations for San Francisco, CA.

	C	D	E	F	G	H	I	J	K	L	M	N	O	P
35	**Stormwater calculations:**													
36	size of lot, square footage	10000												
37	square footage of house	1500												
38	square footage of garage	400												
39	square footage of drive and sidewalk	800												
40	square footage of landscaping	5000												
41	Size of tank, gallons	14311												
42	Urban Runoff into tank, gallons	6149	4930	3923	1961	848	212	0	53	318	1219	2703	5725	
43	Cumulative volume, gallons	6149	11079	14311	14311	14184	12741	9995	7978	7222	7089	9528	14311	
44	Potential Use from tank, gallons	0	0	0	127	1570	4316	6333	7089	7222	4783	0	0	31439
45	Actual Use from tank, gallons	0	0	0	127	1570	4316	6333	7089	7222	4783	0	0	31439
46	Difference													0
47	% used													100%

Next, the potential use and actual use are summed for the 12 month period and the difference taken (cell P46). The percentage of the resource used is in cell P47. Because the objective is to maximize the use of the stored stormwater volume, this difference is minimized by successfully selecting larger volumes until the difference is zero or remains constant. In cases in which the difference is zero, the EXCEL function GoalSeek may be used to simplify iterations. If the difference remains constant and not zero, it indicates that it is not possible to meet 100% of the irrigation demand with the available storage, regardless of the tank's volume.

The volume calculated is based upon historically averaged rainfall in a month; a perhaps more accurate method would be to use daily temperature and rainfall data to develop a daily PET model, using several years of data, after developing an autocorrelation model for the precipitation input, and do a Monte Carlo analysis. This would enable the user to capture droughts and probably increase the size of the tank to achieve a greater degree of reliability.

Results

The methodology outlined in the previous section was applied to the cities shown in Figure 8-5. The user can easily create a new worksheet for any city not shown, and copy the database information into it. Then the user may copy the bottom part of any of the existing worksheets containing the model, adjust the initial storage and the latitude to the desired location, and iterate the solution on the tank size, following the procedure in the previous section. By plotting PET, precipitation, and projected ET over the year, and then comparing these numbers to the water deficit, water surplus, and soil moisture storage data, an illustrative plot of the average climatology of a location can be done. Such a plot is given for the city of San Francisco, CA in Figure 8-5.

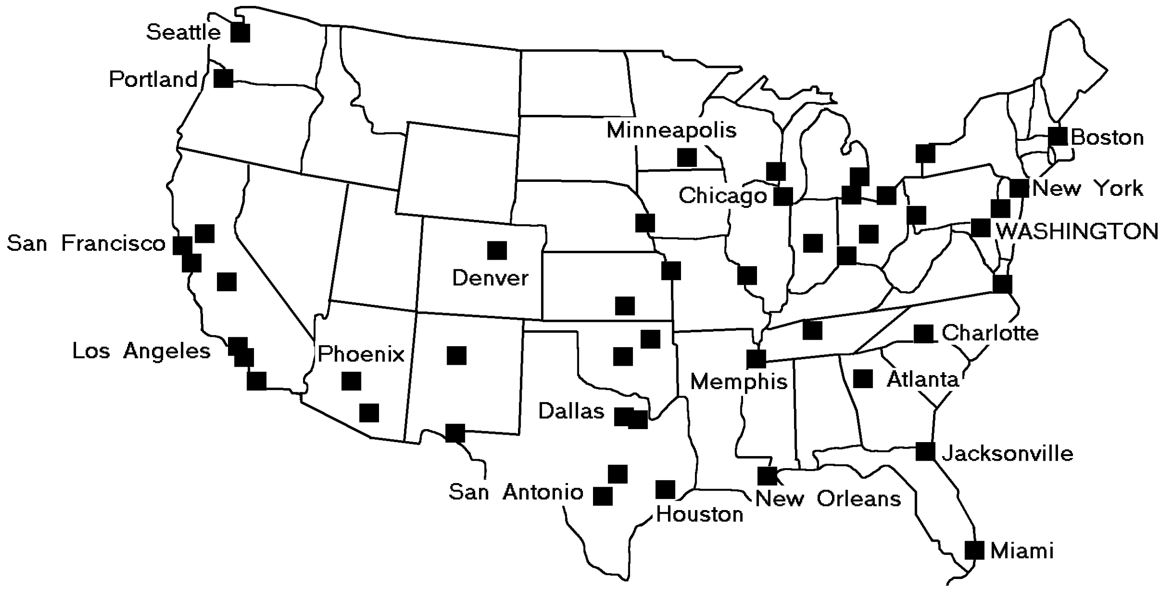

Figure 8-5. Cities used in water balance analysis.

Notice that the winter rain period in which soil moisture is being recharged by the high precipitation which is much greater than ET at that time of the year. The water surplus occurs when the soil cannot store any more water and results in runoff (in natural, undeveloped areas), and coincides with the early spring flood/landslide season in San Francisco. During the late spring and summer, as precipitation becomes almost negligible, available soil moisture is utilized by vegetation for ET purposes. Because the ET is less than PET, there is a deficit that is also shown in Figure 8-4. The deficit is the integral of the PET less the calculated actual ET. This area is calculated month by month in Table 8.2. By comparing Figure 8-4 with the chart for San Francisco in Figure 8-2, it is apparent that the calculations of Mather (1978) and Thornthwaite (1948) have been reproduced.

The amount of the stormwater resource able to be used in each region was plotted in the bar graph shown in Figure 8-6. Most eastern (and western coastal) cities were able to use nearly 100% of the resource. Of course, in using a monthly time step, flooding events are not part of the model. The Rocky Mountains and semi-arid southwest were able to achieve over 90% and the desert southwest (Phoenix) was only able to achieve 24%. Supplemental water would need to be provided in these locations, if reused water is desired to meet irrigation demand, graywater would have to supplement the reused stormwater.

The projected average water deficit for each region are plotted in Figure 8-7. The highest deficit was the desert southwest, with a low rainfall and high PET, followed by the semiarid southwest, then by the Rocky Mountain west, then the northwest,

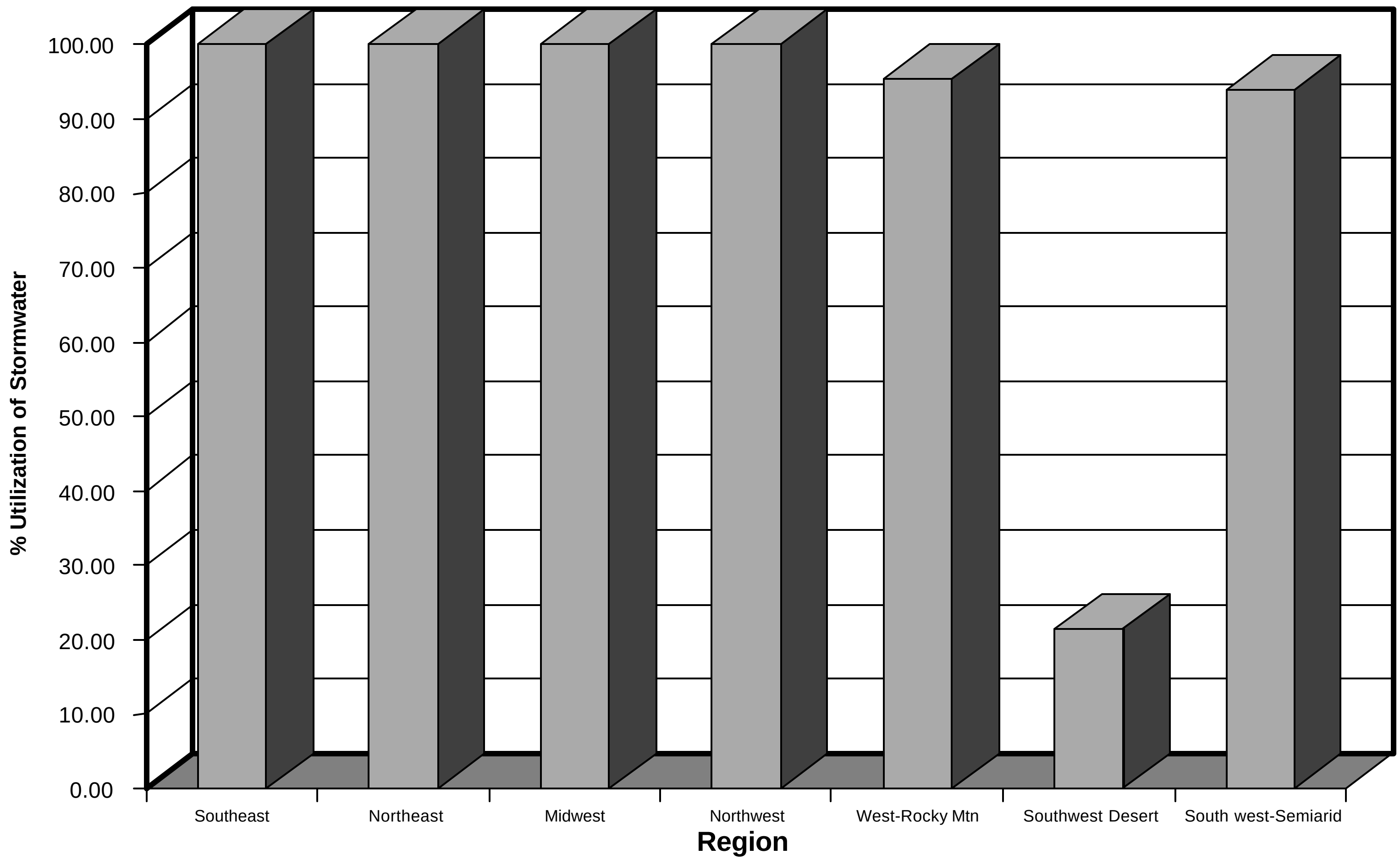

Figure 8-6. Utilization of stormwater by region.

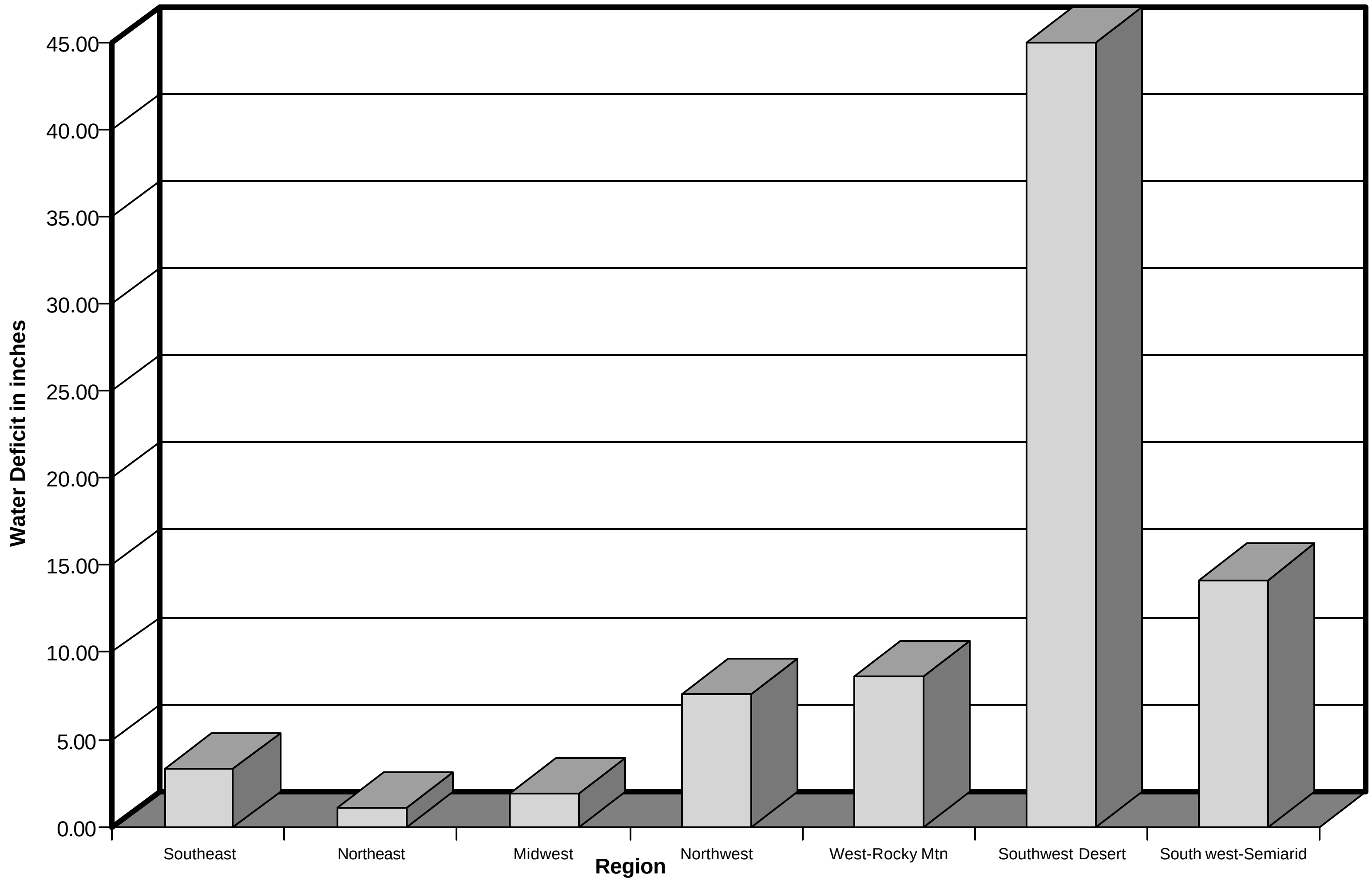

Figure 8-7. Water deficit by region.

southeast, midwest, and northeast.

The annual precipitation, calculated PET, water deficit, and an estimate of the percent error of the Thornthwaite model for each studied city is found in Table 8-3. There may be some variation between these values and other published data depending upon the location of the measurement, as well as the length of the data record. This may affect the error calculation as well. The Thornthwaite model, as stated previously, tends to give better results in non arid areas. The station chosen for Seattle, WA is probably at a higher elevation than published data for the city of Seattle, as the value for precipitation in Table 8-3 is much higher than expected.

The projected storage tank size for each location is plotted in Figure 8-8. San Antonio, TX had the largest tank size, at 25,000 gallons, followed by Dallas, TX at about 17,500 gallons, then Denver, CO at 15,500 gallons. Areas with very dry summers and wet winters such as San Francisco, CA and Los Angeles, CA tended to be next, at around 14,500 gallons. Most areas in the humid east were under 5,000 gallons, except in locations where ET needs outstripped available precipitation, such as in Tampa, FL at 9,000 gallons. The reason very high water deficit areas such as Phoenix, AZ did not result in the largest tanks is that no available storage would have any benefit, that is, the ET needs far exceed available rainfall.

This data compares favorably with Pazwash and Boswell (1997) who found the same nationwide trends when their results are scaled up to the same lot size. They found that the arid southwest tended to require smaller tanks than the rest of the country, due to the lack of available rainfall. Average tank size for other areas ranged from 4320 gallons in the northeast to 6750 in the southeast.

Table 8-3. Summary of annual data for selected stations.

City	State	Annual Precipitation (in)	Annual PET (in)	Annual ET (in)	Annual Water Deficit (in)	Annual Water Surplus (in)	% Error of Model (%)
Atlanta	GA	47.1	37.5	33.4	4.0	13.7	8.10
Boston	MA	47.5	22.3	21.8	0.5	25.6	15.17
Charlotte	NC	43.4	36.8	33.4	3.3	10.0	8.43
Chicago	IL	33.2	26.7	24.1	2.5	9.1	3.73
Dallas	TX	34.6	39.0	30.8	8.2	4.0	25.60
Denver	CO	15.0	23.5	14.9	8.6	0.0	6.76
Houston	TX	45.3	50.0	43.0	7.0	2.3	16.24
Jacksonville	FL	53.3	48.8	48.4	0.5	5.2	19.35
Los Angeles	CA	14.7	39.1	14.8	24.3	0.0	18.16
Memphis	TN	45.7	39.2	32.5	6.7	13.2	7.84
Miami	FL	59.8	57.1	54.3	2.8	6.0	14.21
Minneapolis	MN	24.8	22.3	20.9	1.4	4.3	12.13
New Orleans	LA	63.5	50.4	50.2	0.2	13.3	16.04
New York	NY	42.4	29.1	27.4	1.7	14.9	3.27
Phoenix	AZ	7.2	52.6	7.6	44.9	0.0	15.88
Portland	OR	41.9	25.4	18.9	6.5	23.0	9.71
Salt Lake City	UT	13.9	25.5	13.3	12.2	0.6	8.15
San Antonio	TX	27.9	48.0	27.9	20.1	0.0	13.84
San Francisco	CA	20.8	26.6	16.6	10.1	4.3	3.68
Seattle	WA	64.1	24.1	17.8	6.3	46.3	10.48
Tampa	FL	50.6	52.7	48.8	3.9	1.8	15.21
Washington	DC	40.8	32.2	30.4	1.8	10.4	3.27

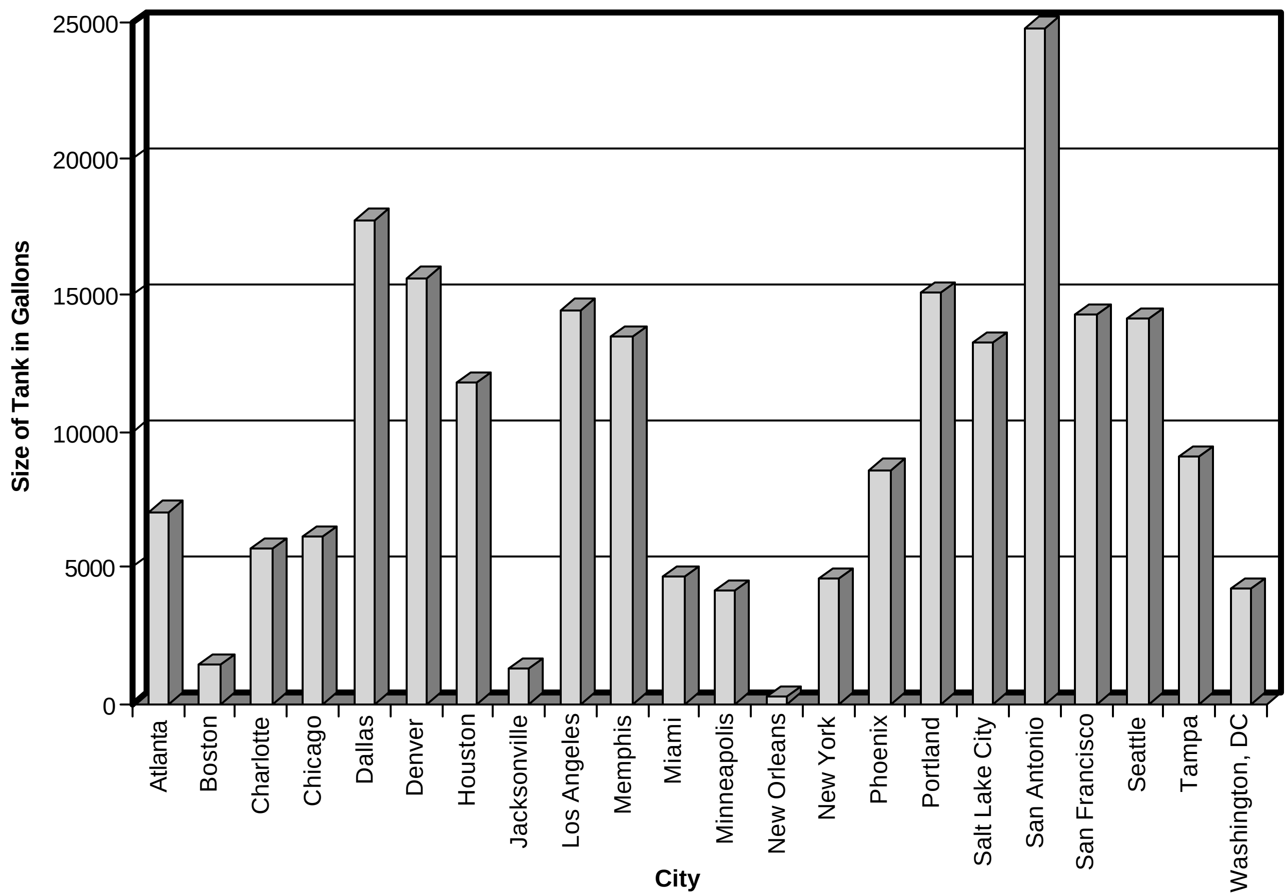

Figure 8-8. Projected residential stormwater storage tank size for studied locations.

Conclusions

In summary, in many areas of the country, particularly in humid areas, enough stormwater can be collected to satisfy average irrigation demands. If driveway areas are eliminated due to possible problems with water quality and ease of collection, the result will be a larger tank size, however, irrigation demand may still be satisfied in a majority of cases. In arid areas, particularly those with high ET requirement, stormwater reuse may not be justified by itself. In these cases, the option of combining storage with treated graywater may be worth considering.

A possible enhancement in the technique could be to apply the model to a daily time series and developing an autoregessive time series model of the PET, ET, and precipitation for each city. Next, a Monte Carlo analysis can be performed to determine that, given the historical data series, a tank sized by this procedure will serve, say, 90% of the ET needs of the parcel. Such an analysis and computer model was developed for rural regions of India by Vyas (1996). An extrapolation of this work to urban/suburban areas of the U.S. needs to be done. In addition, consideration of a daily time step model may be more realistic in this effort. The effect of using several years of data will be to enlarge the tank, as the tank size will increase in order to serve ET needs during more extreme events, such as droughts.

References

Anderson, J.M. (1996a). Current water recycling initiatives in Australia: scenarios for the 21st century. Water Science Technology. (G.B.), 33: 10-11, 37-43.

Anderson, J.M. (1996b). The potential for water recycling in Australia: expanding our horizons. Desalination, 106: 1-3, 151-156.

Asano, T., and A. D. Levine (1996). Wastewater reclamation, recycling and reuse: past, present, and future. Water Science Technology. (G.B.), 33: 10-11, 1-13.

Ashcraft, J. G., and M. G. Hoover (1991). Water reuse--implementation and costs in southern California. In Water Supply and Water Reuse: 1991 and Beyond. Proceedings of the AWRA Conference. Denver, CO.

Butler, D. and J. Parkinson (1997). Towards sustainable urban drainage. Water Science and Technology. 35 (9), 53-63.

Courtney, B.A. (1997). An Integrated Approach to Urban Irrigation: The Role of Shading, Scheduling, and Directly Connected Imperviousness. MS Thesis. Department of Civil, Environmental, and Architectural Engineering. University of Colorado. Boulder, CO.

Field, R. (1993). Reclamation of Urban Stormwater. Integrated Stormwater Management. Field, R., M.L. O'Shea, and K.K. Chin (Ed.), p.307.

Foster, K. E., M. M. Karpiscak, and, R. G. Brittain (1988). Casa Del Agua: a residential water conservation and reuse demonstration project in Tucson, AZ. Water Resources Bulletin. 24(6):1201-1206.

Grimmond, C. S. B. and T. R. Oke (1986). Urban water balance 2: Results from a suburb of Vancouver, British Columbia. Water Resources Research. 22(10):1404-1412.

Grimmond, C. S. B., T. R Oke, and D. G. Steyn (1986a). Urban water balance 1: a model for daily totals. Water Resources Research. 22(10):1397-1403.

Haarhoff, J., and B. Van der Merwe (1996). Twenty-five years of wastewater reclamation in Windhoek, Namibia. Water Science Technology. (G.B.), 33: 10-11, 25-35.

Harper, G. (1991). Reuse of Stormwater: Design Curves for Florida. MS Thesis. University of Central Florida. Orlando, FL.

Harrison, T.J. (1993). Stormwater Reuse Design Curves for Southwest Florida Water Management District. In SWFMD. Proceedings of 3rd Biennial Stormwater Research Conference. Brooksville, FL.

Heaney, J.P. and L.T. Wright (1997). On Integrating Continuous Simulation and Statistical Methods for Evaluating Urban Stormwater Systems. Chapter 3 in James, W. (Editor). Advances in Modeling the Management of Stormwater Impacts. Vol. 5. CHI. Guelph, ON, Canada. P. 44-76.

Heaney, J.P., L.T. Wright, D. Sample, B. Urbonas, B. Mack, M. Schmidt, M. Solberg, J. Jones, J. Clary, and T. Brown (1998). Development of Methodologies for the Design of Integrated Wet-Weather Flow Collection/Control/Treatment Systems for Newly Urbanizing Areas. Draft Rep. to U.S. EPA. Natl. Risk Manage. Res. Lab. Cincinnati, OH.

Herrmann, T., and K. Hase (1996). Way to get water rainwater utilization or long-distance water supply? A holistic assessment. In Proc. of the 7th Int. Conf. Urban Storm Drainage. Hannover, Germany. IAHR/IAWQ Joint Committee Urban Storm Drainage.

Herrmann, T., U. Schmida, U. Klaus, and V. Huhn (1996). Rainwater utilization as component of urban drainage schemes: hydraulic aspects and pollutant retention. In Proc. 7th Int. Conf. Urban Storm Drainage. Hannover, Germany. IAHR/IAWQ Joint Committee Urban Storm Drainage.

Imbe, M., T. Ohta, and N. Takano (1996). Quantitative assessment of improvement in hydrological water cycle in urbanized river basin. In Proc. of the 7th Int. Conf. Urban Storm Drainage. Hannover, Germany. IAHR/IAWQ Joint Committee Urban Storm Drainage.

Karpiscak, M. M., K. E. Foster, and N. Schmidt (1990). Residential water conservation: Casa Del Agua. Water Resources Research. 26: 6, 939-948.

Law, I. B. (1996). Rouse Hill—Australia's first full scale domestic non-potable reuse application. Water Science Technology. (G.B.), 33: 10-11, 71-78.

Leemans, R. (1988). Dataset developed during the YSSP summary program 1988, at IIASA. Laxenburg, Austria for the BIOSPHERE.

Lejano, R. P., F. A. Grant, T. G. Richardson, B. M. Smith, and F. Farhang (1992). Assessing the benefits of water reuse: applying a cost-benefit allocation procedure. Water Environment & Technology. 4 (8), 44-50.

Mallory, C. W., and J. J. Boland (1970). A system study of storm runoff problems in a new town. Water Resources Bulletin. 6 (6), 980-989.

Mangeot, E.F. (1996). City of Boulder Wastewater Treatment Plant Model Stormwater Surge Analysis Using GPX-X. Independent Study for Professor Silverstein. Department of Civil, Environmental, and Architectural Engineering. University of Colorado. Boulder, CO.

Mather, J. R.(1978). The Climatic Water Budget in Environmental Analysis. D. C. Heath and Company. ISBN: 0-669-02087-7.

Mitchell, V.G., R.G. Mein, and T.A. McMahon (1996). Evaluating the resource potential of stormwater and wastewater: an Australian perspective. In Proc. of the 7th Int. Conf. Urban Storm Drainage. Hannover, Germany. IAHR/IAWQ Joint Committee Urban Storm Drainage.

Nelen, A.J.M., A.C. de Ridder, and E.C. Hartman (1996). Planning of a new urban area in a municipality of Ede using a new approach to environmental protection. In Proc. of the 7th Int. Conf. Urban Storm Drainage. Hannover, Germany. IAHR/IAWQ Joint Committee Urban Storm Drainage.

Nowakowska-Blaszczyk, A., and J. Zakrzewski (1996). The sources and phases of increase of pollution in runoff waters in route to receiving waters. In Proc. 7th Int. Conf. Urban Storm Drainage. Hannover, Germany. IAHR/IAWQ Joint Committee Urban Storm Drainage.

Oron, G. (1996). Management modeling of integrative wastewater treatment and reuse systems, wastewater reclamation and reuse 1995. Water Science Technology. (G.B.), 33: 10-11, 95-105.

Pazwash, H., and S. Boswell (1997). Management of roof runoff conservation and reuse. Proc. 24th ASCE Water Resources Planning and Management Annual Conf., Aesthetics on the Constructed Environment. Houston, TX. 784.

Pisano, W.C. and H. Brombach (1997). Solids Settling Curves. Water Environment Technology. Vol. 8, No.4, P 27-33.

Pitt, R., R. Field, M. Lalor, and M. Brown (1996). Groundwater Contamination from Stormwater Infiltration. Chelsea, MI. Ann Arbor Press.

Pruel, H.C. (1996). Combined sewage prevention system (CSPS) for domestic wastewater source control. In Proc. of the 7th Int. Conf. Urban Storm Drainage. Hannover, Germany. IAHR/IAWQ Joint Committee Urban Storm Drainage.

Requa, A., J. M. Kelly, J. A. Burgh, and M. Manzione (1991). Successful implementation of an urban landscaping recycled water program. In Water Supply and Water Reuse: 1991 and Beyond. Proceedings of the Conference of the AWRA. Denver, CO.

Tchobanoglous, G., and A. Angelakis (1996). Technologies for wastewater treatment appropriate for reuse potential for application in Greece. Water Science Technology. (G.B.), 33: 10-11, 15-24.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. Geographical Review. volume 38 pp. 55-94.

Tselentis, Y., and S. Alexopoulou (1996). Effluent reuse options in Athens metropolitan area: a case study. Water Science Technology. (G.B.), 33: 10-11, 127-137.

U.S. Geological Survey (1970). The National Atlas of the United States of America. Reston, VA.

Veldkamp. R. G., T. Hermann, V. Colandini, L. Terwel, and G. D. Geldof (1997). A decision network for urban water management. Water Science Technology. (G.B.) 36: 8-9, 111-115.

Vorosmarty, C. J. and B. Moore (1991). Modeling basin-scale hydrology in support of physical climate and global biogeochemical studies: an example using the Zambezi River. Surveys in Geophysics. volume 12, pp. 271-311.

Vorosmarty, C. J., C. J. Willmott, B. J. Choudhury, A. L. Schloss, T. K. Stearns, S. M. Robeson, and T. J. Dorman (1996). Analyzing the discharge regime of a large tropical river through remote sensing, ground-based climatic data and modeling. Water Resources Research. 32(10):3137-3150.

Vorsomarty, C. J., B. Moore, A. L. Grace, M. P. Gildea, J. M. Melillo, B. J. Peterson, E. B. Rastetter, and P. A. Steudler (1989). Continental scale models of water balance and fluvial transport: an application to South America. Global Biogeochemical Cycles. 3(3):241-265.

Vyas, V. (1996). Monte-Carlo simulation of rainwater harvesting systems. Raindrop. December, 1996 and web page http://www.geocities.com/RainForest/Canopy/4805/FAQ.html.

Wanielista, M. (1993). Stormwater Reuse: An Alternative Method of Infiltration. In Proc. National Conf. on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels. U.S. EPA. Cincinnati, OH.

Willmott, C. J. (1977). WATBUG: A FORTRAN IV Algorithm for Calculating Climatic Water Budget. Water Resources Center. Delaware University; Contribution Number 23, Report Number 1. Publications in Climatology Vol. XXX, No. 2.

Yates, D. N. (1996). WatBal: an integrated water balance model for climate impact assessment of river basin runoff. Water Resources Development. 12(2):121-139.