Hydrologic Modeling in Arid Areas: Concepts, Theory and Data

Leonard J. Lane and Mary R. Kidwell
United States Department of Agriculture
Agricultural Research Service
2000 East Allen Road, Tucson, Arizona, 85719 U.S.A
e-mail: ljlane@tucson.ars.ag.gov

Abstract

Water resources are strategic national resources and development of knowledge to enable their sustainable management and use must be a high national priority. It is impossible to monitor all of our watersheds, yet we need the ability to predict the consequences of land use and management decisions on watershed resources before use and management is undertaken. Simulation models provide the mechanism for this prediction ability. Water balance modeling is used to illustrate the application of simulation modeling to management of arid watersheds. Arid environments are characterized by extreme hydrologic variability. Simulation models can mimic this variability, but have their conceptual and practical limitations. Major challenges to overcome these limitations and improve our ability to predict water balances in arid environments are identified and discussed.

Introduction

Water resources are of strategic national importance. Development of secure, adequate, and sustainable water resources can only be accomplished in two ways. First is development of additional water resources of such abundance that their wise use is sustainable. Second is conservation of existing water resources coupled with development of new knowledge and technology to utilize existing resources more efficiently. In the very simplest terms, the first way is called the water "supply" approach and the second is called the water "demand" approach. Both approaches require our best science and technology development and transfer. However it should be noted that the first approach often cannot be accomplished because of physical and political constraints limiting sources of new water resources. Even where new water resources are available, they can never be sustainable without coupling water "supply" approaches with water "demand" approaches. For example, Jackson, et al. (2001) conclude that in the next 3 decades the world's accessible runoff is unlikely to increase by more than about 10% while the world's population may increase by about a third. Additional information on water resources at the global scale is available from a number of sources (e.g. see Dickinson, 1991; Gleick, 1998, 2000; and Jackson, et al., 2001).

Increased competition for water and watershed resources is resulting in wider recognition of regional, national, and global water shortages and the need to understand land use impacts on water supply and quality. The wider recognition of water shortages and deterioration of water quality will increase the global impacts of watershed research and the value of new concepts, theory, and data. This wider recognition of global impacts of watershed research, in turn, increases the need for hydrologic modeling in arid areas.

All land is composed of watersheds (also called catchments or drainage basins) and thus understanding and predicting the current status and future trends of our watershed resources are of great practical and broad societal importance. Therefore, watershed management decisions must be based on the best possible science. There is a critical need for simulation model development as a means of integration, or synthesis, of science and decision-making and parallel (concurrent) technology transfer (e.g., NRC, 1999).

We know it is impossible to gage or monitor all of our watersheds, yet we need the ability to predict consequences of land use and management decisions upon watersheds and their resources before the proposed use and management are undertaken. Simulation models offer the potential to provide this prediction capability. Development of improved simulation models with valid prediction capabilities is thus essential to our understanding and management of water resources (e.g. for some recent compendia and general modeling sources and discussion see Singh, 1995; Mays, 1996; Hoggan, 1997; NRC, 1999; Bates and Lane, 2000; and Anderson and Bates, 2001).

Water resources are particularly important in arid and semiarid environments because of their scarcity and because the structure and function of watersheds and their ecosystems in these environments are fragile and subject to dramatic changes (often deleterious to water supply and quality) from unwise utilization and management. Knowledge of the water balance, or budget, is essential to management of water resources. Therefore, modeling the water balance on our watersheds is central to bringing our best science to bear on decision making for joint water supply and water demand approaches.

Scope and limitations

In this paper we:
1) Briefly describe arid climates,
2) Use time series to illustrate hydrologic extremes and their importance in the water balance,
3) Discuss and illustrate selected examples of water balance modeling, and
4) Identify gaps in knowledge, modeling, and data that limit our ability to develop sustainable water resources in arid areas.

This paper is neither a compendium of hydrologic models, nor is it used to develop new models. Rather, it is a call for improved simulation models and their coupling with decision making to provide new concepts, theory, and data for sustainable management of water resources in arid areas of the subtropics.

Arid Climates

The most complete definitions of climate include interactions of weather with topography, soil, vegetation, and land use to produce a physically based method, incorporating aspects of land use, to describe the long-term expectations of precipitation, temperature, etc. for a region. However, for the limited purposes herein, a climate definition scheme based on precipitation, temperature, and their seasonal distributions will suffice. The following description of arid climates is derived in part from Lane and Nichols (1999) and Trewartha and Horn (1980).

Arid (desert) areas generally receive too little precipitation to support dryland agricultural or domestic livestock grazing. In contrast, in semiarid (steppe) areas adequate moisture is usually available at some time during the year to produce forage for livestock, and there are even some years when dryland crop production is successful. It should be noted that both climates are characterized by extreme variability with commonly occurring droughts and infrequent periods of above average rainfall resulting in flooding (see the section below entitled Hydrologic Time Series). Most discussion hereafter will emphasize arid climates, but some of the concepts and examples thought to have direct application in arid areas will be derived from observations and modeling in semiarid areas.

The majority of the world's arid areas occur along two wide belts at approximately 30 degrees latitude north and south of the equator. In these subtropical belts the air is usually descending, and dry much of the time. Semiarid areas associated with the arid deserts are mostly north or south of the deserts (Africa, Asia, and Australia) or inland at higher elevations (North America, South America, Middle East, Africa, and Asia). On a more localized scale, a combination of mountains and prevailing wind direction can cause "rain shadow" effects, resulting in arid and semiarid areas downwind of major mountain features.

About a third of the world's land surface is either arid, normally with less than 250 mm of annual precipitation, or semiarid with between 250 mm and 500 mm of annual precipitation. As described below, somewhat more precise definitions of desert and semiarid areas are given by climatic classifications based on precipitation, temperature, and their seasonal distributions. For example, Lane and Nichols (1999) following Trewartha and Horn (1980) and the classifications of Koppen (1931), presented upper and lower mean annual precipitation limits defining arid climates.

The semiarid climates, where annual precipitation is not strongly seasonal, were defined by equations linking mean annual values of precipitation, P (mm), and temperature, T (degrees C). The upper limit for semiarid climates, in terms of mean annual precipitation given a specific value of mean annual temperature, is defined by

$$P = 20T + 140 \qquad (1)$$

The corresponding lower limit that separates arid and semiarid climates (or alternatively desert and steppe climates) was defined as 1/2 the value of the upper limit from Equation 1, or

$$P = 10T + 70 \quad (2)$$

Thus the arid, or desert, areas of the world are those areas where the combination of mean annual precipitation, P, and mean annual temperature, T, fall below the line defined by Eq. 2. For example, long-term mean annual precipitation and temperature at Khartoum, Sudan (15.6^0 N, 32.6^0 E) are 162 mm and 29.1^0 C respectively. For a value of T of 29.1, Eq. 2 requires that P be less than 10 x 29.1 + 70 = 361 mm. Since the mean annual precipitation at Khartoum at 162 mm is less than half of the computed value of 361 mm, Khartoum is classified as an arid climate. The long-term annual precipitation and temperature values at Yuma, AZ, USA (32.7^0 N, 114.6^0 W) are P = 81 mm and T = 22.7^0. While not as hot as Khartoum, the P and T values plot even farther below the line defined by Eq. 2, and therefore Yuma is even more arid than Khartoum. Mean annual precipitation and temperature data for a number of locations around the world, as well as the lines and regions defined by Eqs. 1 and 2, are shown in Fig. 1.

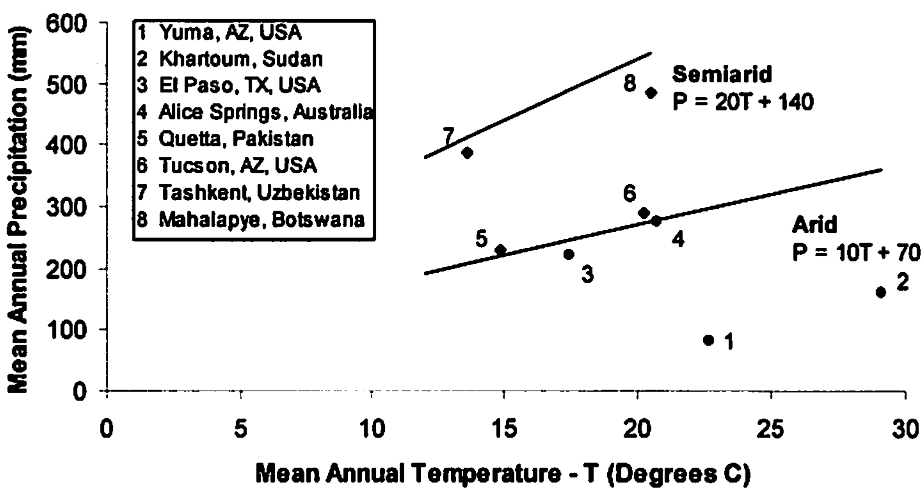

Figure 1. Mean annual precipitation and temperature for arid and semiarid sites around the world. Also shown are the lines (Eqs. 1 & 2) defining semiar id and arid climates.

Evapotranspiration is defined as the sum of water evaporation from soil, litter, etc. and transpiration from living plants. Annual potential evapotranspiration significantly exceeds precipitation in arid and semiarid areas and can be accurately predicted with a number of techniques. In contrast, actual evapotranspiration is nearly equal to precipitation and is difficult to calculate under field conditions.

Although actual evapotranspiration differs little in magnitude from precipit ation on an annual basis, these small differences are extremely important because they by and large determine soil moisture status, runoff, and groundwater recharge. In brief periods during and then following large precipitation events, precipitation can exceed evapotranspiration and it is in these periods when surface runoff, soil moisture recharge, and even groundwater recharge can occur.

The vegetation growing in arid areas is adapted to lack of moisture, extreme variations in precipitation and tempera ture, soil characteristics, competition, and herbivory. Seasonal distributions of precipitation and temperature also play a dominant role, but it is the absolute amount of seasonal rainfall, particularly the seasonal distribution of rainfall that is most important for the vegetation of arid regions. The flora of these regions is extremely variable and can be rather distinctive as a result of factors such as continental position, rain shadow effect, proximity to cool ocean currents, high pressure air systems, and general air movement over the earth's surface (Brown, 1974). However, a notable feature common to all arid regions is the low density of vegetation that they support.

The soils in arid areas are notable for their variations with topographic featur es. Desert soils are characterized by their non-homogeneity in space and their generally close relationship with the parent geologic material due to their thinness, the lack of moisture, and the slowness of soil forming processes. The better, or more developed, soils are often formed on alluvial deposits or deposits of loess. Vertical differentiation of soil profiles may also be indistinct or lacking due to weak chemical activity resulting from the dryness. A typical exception to this generalization occurs where there has been deposition and leaching of calcium, in the form of calcium carbonate, and other soluble salts which form hard, impermeable subsoil (Lane and Nichols, 1999). Variation in soil properties from undifferentiated profiles to impermeabl e formations have a significant influence on the water balance in desert areas and significantly affect hydrologic processes, erosion and sedimentation, biological productivity, and thus land use and management.

Hydrologic Time Series

Examination of hydrologic time series can add insight to historical trends, illustrate current status of the variables of interest, and suggest possible future trajectories in the trends. The upper portion of Fig. 2 shows some global trends adapted from data presented by Gleick (1998) and Jackson, et al. (2001). During the last century, world population and land area used for irrigated agriculture increased almost exponentially. However, notice that the "demand" time series of world population is out pacing the "supply " time series of irrigated area for agriculture. As stated in the Introduction, a wider recognition of water shortages and deterioration of water quality will increase the global impacts of hydrologic research and the value of new concepts, theory, and data.

As insightful as world or global analyses can be, they do not easily lead to water resources solutions because water resources decision-making is conducted at national, regional, and local scales. Lane, et al. (1994) summarized analyses of hydrologic series from global to regional to point scales. Such analyses are instructive in illustrating the features and variability of hydrologic time series.

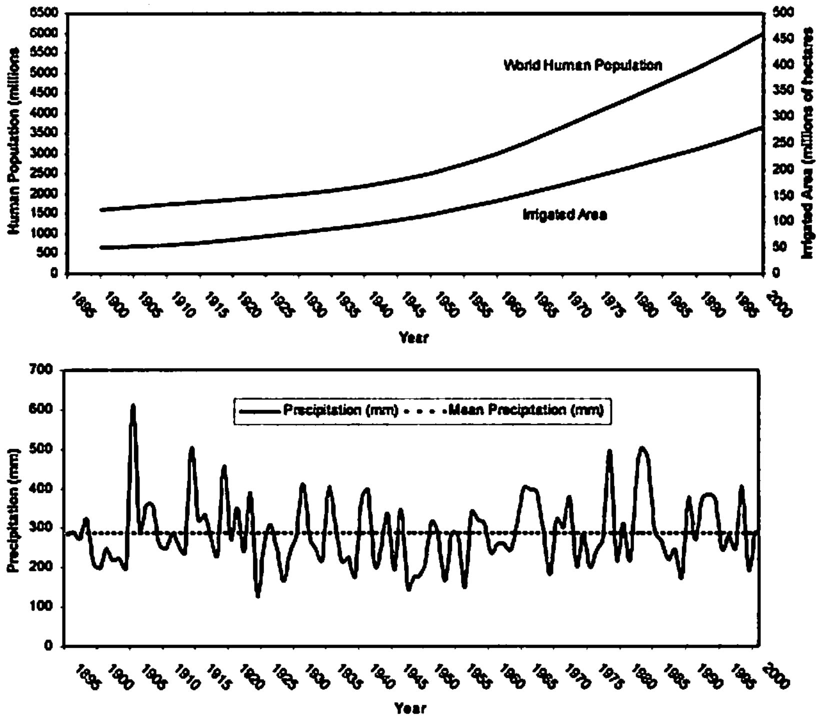

Figure 2. Time series at global and local scales. The upper portion of the figure uses time series to illustrate the "supply" and "demand" features of world water resources and the lower portion illustrates the extreme variability in annual precipitation in a semiarid area.

The lower portion of Fig. 2 shows a time series of precipitation at Tucson, AZ, USA (University of Arizona gage, 32^0 14' N, 110^0 57' W, 734 m MSL, data from 1895 to 2000). Mean annual precipitation at Tucson is 288 mm with a standard deviation of 87 mm resulting in a coefficient of variation (standard deviation divided by the mean) of 0.30 or 30%. The lowest annual precipitation was 129 mm in 1924 and the highest was 614 mm in 1905. This variation of annual precipitation from 129 to 614 mm represents a range of 485 mm, which is 168% of the mean and 557% of the standard deviation of annual precipitation. Finally, the ratio of the maximum daily precipitation to the minimum annual precipitation is 106 mm/129 mm = 0.82 which means that in 106 years of record the maximum daily precipitation was 82%

of the measured annual precipitation in the driest year. The significant variation in precipitation in arid and semiarid areas such as Tucson is obvious.

Time series analyses of the data from Tucson indicated that there were no significant linear trends, serial correlation, or cycles or periods in annual precipitation at Tucson for the period 1895 to 2000. Subsets of the data (i.e. 1905 to 1947 and 1947 to 1984) might show statistically significant decreases or increases, but no trends or patterns are apparent in the entire 106-year record. There is an important point to make in interpreting time series analyses of short periods of record from arid areas – analyses of short periods of record are risky and statistical inferences from them are subject to high levels of uncertainty. In the next section of this paper we present examples of water balance calculations in arid and semiarid areas. The reader should keep in mind the high variability of climate in such areas and the certainty that this high climatic variability induces comparable variability in all components of the water balance.

Examples of Water Balance Modeling

The term hydrologic cycle is the most general of those describing the cycling or movement of water through the lands, oceans and atmosphere. The term water balance as used herein has a similar meaning to the term hydrologic cycle but it connotes a budgeting or balancing of components in the hydrologic cycle. As such, water balance usually connotes a specific spatial scale such as a watershed, field, plot, or point and a specific time period such as annual, seasonal, or daily. Some analyses of the hydrologic cycle/water balance on a global and continental scale suggest that in general we are using too much groundwater relative to surface water resources (see Slutsky and Yen, 1997). In many arid areas groundwater withdrawals far exceed groundwater recharge resulting in the "mining" of historical groundwater resources—a demonstrably unsustainable practice.

To discuss water balances for arid areas at the point to watershed scale, it is necessary to compare and contrast water balances in humid and sub-humid areas with those in semiarid and arid areas. For generalized discussions of water in arid areas see Roberts (1993), Savenije (2000), and DePauw, et al. (2000). Some comparisons and contrasts between humid and arid water balances are summarized in Table 1. The comments are for dominant factors or generalized relationships. There are exceptions, most of which are time, space, or intensity scale dependent and of great scientific interest. However, for the discussions in this paper, we compare and contrast based on generalizations or the usual case.

Water balance models scan a range of complexity and applications dependent upon their intended use, needed precision in predictions, and treatment of temporal, spatial, and process intensity scales. Examples range from a simple, largely data-base model, as presented by Evans and Jakeman (1998), to simplified daily water balance models used in vegetation production modeling at a point or plot scale (Lane, et al. 1984, 1995), to simulation of water balance across vegetation communities (Kremer and Running, 1996), and to complex, process based models (Refsgaard and Storm, 1995).

Table 1. Comparison of water balance components for humi d and arid areas.

Component	Humid	Arid	Comments
Precipitation, P	Abundant	Scarce	See Fig. 1 herein
Potential Evapotranspiration, PET	PET < P	PET > P	
Actual Evapotranspiration, AET	AET < P	AET ~ = P	In arid areas, P does exceed AET during storms and during brief periods of high soil moisture storage
Runoff, Q	Perennial streams and rivers are abundant. Watersheds "store" precipitation and release it as runoff throughout the year	Most streams are ephemeral; perennial streams can rise in wetter regions and flow through arid areas	Runoff often generated only during prolonged wet periods or from intense storms in arid areas
Groundwater, GW	Groundwater-surface water connection direct and obvious, i.e. gaining perennial streams	Groundwater-surface water connection less obvious, i.e. losing ephemeral streams	Groundwater resources in arid areas often "mined" because of low recharge rates
Soil Moisture, SM	Well developed soils with adequate water holding capacity support rainfed agriculture	Poorly developed soils and inadequate soil moisture result in desert landscapes. Cultivated agriculture possible with irrigation	Water erosion, floods, and poor drainage common in humid areas. Droughts, salinity, wind and water erosion common in arid areas.
Quantification of Water Balance	Measurements Possible for P, PET, AET, Q, SM, and GW over relatively short time periods, i.e. years to decades	Longer time periods required to measure P, Q, etc. because of higher natural variability, i.e. infrequent hydrologic events	In arid areas, if some terms of the water balance are obtained by subtracting measured terms that are on the same order of magnitude, then large errors result
Modeling the Water Balance	Space, time, and process intensity scale problems plague modeling efforts	Same comment as for humid climates, but longer time series of measured data required to obtain same relative level of precision for model calibration and validation	

Example water balance calculations using a simple model

Our objective in these example calculations was to compute water balances in three very different climatic regimes and to contrast and compare the results from the three locations. Because of data limitations at the sites, we selected a simple water balance model that could be operated based on limited available climatic, soils, vegetation, and land use data. The CREAMS Model (Knisel, 1980) met the selection criteria and had been previously applied at these and similar sites.

The one-dimensional water balance equation for a unit area, to plant rooting depth, ignoring runon and assuming subsurface lateral flow is zero, can be written as

$$dS/dt = P - Q - AET - L \qquad (3)$$

where dS/dt is the change in soil moisture (mm), P is precipitation (mm), Q is runoff (mm), AET is actual evapotranspiration (mm), L is percolation or leaching below the rooting depth (mm), and t is time (days, months, years, etc.). The CREAMS Model solves Eq. 3 for a daily time step and then sums the results for monthly and annual values.

Renard, et al. (1993) applied the CREAMS Model on the Walnut Gulch Experimental Watershed in Arizona, USA, Lane and Osterkamp (1991) applied the Model in the Mojave Desert of Nevada, USA, and Osterka mp et al. (1995) applied the Model using data from the Al Ain Agromet Station in the UAE. The following summary of water balance calculations is adapted from these three studies.

Results of the CREAMS water balance modeling for three locations are shown in Tables 2 - 4. In each of these tables, Column 1 lists the month or the annual period, Column 2 lists precipitation in mm, Column 3 lists surface runoff in mm, Column 4 lists the actual evapotranspiration in mm, Column 5 lists percolation below the plant rooting depth in mm, and Column 6 list the average plant available soil moisture in mm. Notice that the annual values in Columns 2 - 5 are annual summations whereas the annual value for plant available soil water is an average annual value.

The CREAMS Model was applied to a small semiarid watershed on the Walnut Gulch Experimental Watershed in Arizona, USA (see Renard et al., 1993 and Goodrich et al., 1997 for descriptions of Walnut Gulch). Rainfall and runoff data were available for 17 years (1965 – 1981), and were used to optimize the model parameters for runoff simulation. As P and Q were measured, the model was calibrated to match observed values of runoff, Q, and then AET and L were estimated using a form of Eq. 3. Values of Q, AET and L in Table s 2 – 4 do not exactly sum to P because dS/dt was not zero over the simulation period. However, dS/dt was relatively small, - 1.4 mm for the data shown in Table 2.

The mean monthly precipitation distribution at Walnut Gulch is bi- modal (Table 2) with a strong summer peak from July through September and a small secondary peak from December through March. Soil moisture storage (plant available soil water) follows this trend with recharge occurring July through October and again in December and January. Rapid soil moisture depletion occurs from February through June (Table 2, last column).

Table 2. Average annual water balance for Watershed 63.103 at Walnut Gulch, Arizona, USA as calculated with the CREAMS Model calibrated using 17 years of rainfall and runoff data, 1965 – 1981. All values are in mm.

Month (1)	Precipitation (2)	Runoff (3)	AET (4)	Percolation (5)	Plant Available Soil Water (6)
January	18.0	0.58	18.6	0.03	22.2
February	14.2	0.28	18.0	0.17	20.7
March	15.0	0.18	21.2	0.0	16.1
April	3.8	0.0	11.8	0.0	6.6
May	5.3	0.13	7.4	0.0	2.0
June	8.3	0.28	8.4	0.0	1.3
July	87.9	7.24	62.2	0.0	9.8
August	63.3	4.78	63.7	0.0	14.9
September	39.1	3.45	34.8	0.0	15.7
October	21.0	1.70	16.5	0.0	16.0
November	7.7	0.05	9.7	0.0	16.0
December	19.3	1.02	12.1	0.0	18.8
Annual	302.9	19.7	284.4	0.20	13.3

In contrast with Walnut Gulch, Rock Valley, Nevada (Table 3) is dominated by winter precipitation and soil moisture recharge (November through March) with rapid soil moisture depletion from April through August. Mean annual precipitation at Rock Valley is about half of what it is at Walnut Gulch while mean annual runoff is estimated to be about an order of magnitude less than at Walnut Gulch (Tables 2 and 3).

Mean monthly precipitation at Al Ain is strongly dominated by the winter months. Soil moisture recharge is estimated to occur from January through March with soil moisture depletion and low levels of soil moisture throughout the remainder of the year (Table 4).

Although mean annual precipitation at Al Ain is about 1/3 as much as at Walnut Gulch, mean annual runoff is about 60% as much as at Walnut Gulch (Tables 2 and 4). The relatively high values of runoff estimated by the CREAMS model at Al Ain are due to the combination of large rainfall events, soil p roperties, and the short

Table 3. Average annual water balance for Rock Valley, Nevada, USA as calculated with the CREAMS Model partially calibrated using mean monthly soil moisture data. Simulations for 1965 – 1976. All values are in mm.

Month (1)	Precipitation (2)	Runoff (3)	AET (4)	Percolation (5)	Plant Available Soil Water (6)
January	15.0	0.08	13.0	0.0	24.0
February	27.0	2.01	15.0	1.60	31.0
March	17.0	0.05	23.0	0.46	34.0
April	6.0	0.0	19.0	0.0	21.0
May	6.0	0.0	12.0	0.0	11.0
June	5.0	0.0	8.0	0.0	7.0
July	9.0	0.0	10.0	0.0	6.0
August	13.0	0.0	11.0	0.0	6.0
September	11.0	0.10	11.0	0.0	8.0
October	10.0	0.05	9.0	0.0	8.0
November	13.0	0.0	9.0	0.0	10.0
December	19.0	0.28	9.0	0.0	16.0
Annual	151.0	2.57	149.0	2.06	15.0

(20 years) period of simulation. The model estimated 70.7 mm of runoff in 1972 and 51.5 mm in 1990. Together these two years account for about half of the total runoff in 20 years, or half the long term mean. This illustrates the high level of variability of precipitation and thus runoff, AET, percolation, and soil moisture in the data summarized in Table 4. Finally, only precipitation data were available at Al Ain so the model results are predictions only and do not include any calibration or validation. Given this level of uncertainty, the mean annual runoff estimated for Al Ain may be considerably in error.

The modeling results summarized in Tables 2 – 4 illustrate several important features of water balance modeling and water resources management in arid areas. Even in arid climates (not including the hyper-arid deserts devoid of vegetation), one may expect some times during the year when soil moisture may be recharged and thus water is available for plant growth. This is especially true in semiarid areas such as Walnut Gulch (Table 2). Conversely, one may also expect that there will be long dry periods when soil moisture is near zero or exhausted. Although infrequent and small compared with humid regions, some groundwater recharge may occur in upland areas due to percolation of water below the plant rooting depth. However, percolation estimates are infrequent, making statistical inference risky. This is especially true if percolation is obtained by subtracting AET and Q from P. Small differences (percolation estimate s) obtained from subtracting relatively large, nearly equal, numbers are notoriously error prone. Thus, percolation estimates from short periods of record in arid areas should be viewed as qualitative numbers (suggesting percolation), not as quantitative estimates. Similar logic applies to surface runoff estimates in arid areas.

Table 4. Average annual water balance for Al Ain, UAE as calculated with the CREAMS Model without calibration. Simulations are for 1971 – 1990. All values are in mm.

Month (1)	Precipitation (2)	Runoff (3)	AET (4)	Percolation (5)	Plant Available Soil Water (6)
January	6.1	0.20	4.4	0.0	6.5
February	36.2	6.47	11.8	0.33	17.5
March	22.5	4.17	15.8	3.05	23.7
April	11.7	1.04	15.2	0.0	22.4
May	2.1	0.25	8.2	0.0	16.3
June	1.7	0.03	5.5	0.0	10.6
July	1.9	0.0	5.0	0.0	7.4
August	6.0	0.03	5.6	0.0	6.4
September	5.6	0.28	4.9	0.0	7.4
October	0.0	0.0	2.1	0.0	5.7
November	1.3	0.08	1.8	0.0	4.6
December	3.6	0.13	2.6	0.0	4.5
Annual	98.7	12.7	82.9	3.38	11.1

Nonetheless, it is possible to draw some generalizations from data such as presented in Tables 2 – 4. Plant available soil water is seen to vary from zero (monthly averages approach zero but remain positive because of averaging, monthly values in individual years are often zero) to something on the order of a few 10's of mm. This sparse and highly variable soil moisture limits short–term management options. Unless irrigation is used, management schemes should be tailored to long-term objectives involving well-adapted flora and fauna able to withstand climatic extremes. As a corollary of this, management practices may take long periods to positively impact the water balance and thus monitoring and evaluation may require correspondingly long time periods. Again, the converse is true for mismanagement or over utilization of resources. Plant available soil water is so erratic and limited that fragile ecosystems once damaged may take very long periods to recover; or, they may not recover at all.

Discussion

Current research and scientific discussion clearly illustrate that global water demand is increasing faster than water supply. Even where some new water resources are available, they can never be sustainable without coupling water "supply" approaches with water "demand" approaches.

It is also clear that increased competition for water and watershed resources is resulting in wider recognition of regional, national, and global water shortages and the need to understand land use impacts on water supply and quality. The wider recognition of water shortages and deterioration of water quality will increase the global impacts of watershed research and the value of new concepts, theory, and data. This wider recognition of global impacts of watershed research in turn increases the need for hydrologic modeling in arid areas.

Analyses of trends in global water supply and demand lend insight into generalized water resources problems. However, as insightful as world or global analyses can be, they do not easily lead to water resources solutions because water resources decision-making is done at national, regional, and local scales. Therefore, it is appropriate for scientists and engineers conducting hydrologic modeling to fully recognize, and to report, the high levels of climatic variability present in arid and semiarid areas at all spatial scales, especially point to regional scales. Further, these high temporal and spatial variabilities in arid climates induce comparable levels of variability into hydrologic modeling results. High variability in hydrologic modeling results translate directly into high levels of uncertainty and these too should be recognized and reported in hydrologic modeling activities. Hydrologic models are essential decision-making and management tools, but they can only realize their full potential as such by fully tracking and reporting the levels of uncertainty present in the models and their predictions.

Water balance models are critical in addressing water supply problems and providing basic input to water demand analyses. Water balance modeling in arid areas presents additional challenges. First, the inherent climatic variability is high in arid areas and this requires long periods of hydrologic monitoring to produce baseline data for modeling and analyses. Second, given the infrequent nature of runoff events in arid areas, it may take very long time periods to analyze the impacts of land use and management practices on water supply and water quality. Both the baseline data and the impacts data are essential for developing, calibrating, and validating hydrologic models. Substantial and long-term investments of scientific and monetary resources are required to obtain these data. Third, components of the water balance are not well quantified in arid areas and thus additional knowledge and understanding required for this quantification can only come from additional hydrologic research. This, too, requires substantial long-term investments. Finally, sound social policy must be science-based and this requires integration of biophysical and social science research within our modeling and analyses to bring the best science to bear on decision-making.

Some Gaps in Knowledge, Modeling and Data

The Discussion section presented some needs and gaps in hydrologic modeling especially pertinent to arid areas. However, some specific gaps are listed here based upon the above analyses, current discussions in the literature, and our personal experiences.

- Hydrologic modeling is an essential step in bringing science to bear on decision-making for water resource development and management in arid areas. However, problems of temporal, spatial, and process-intensity scales and the associated high variability limit application of current hydrologic models.

- High variability in climatic inputs (see Fig. 2) results in high variability of model results that in turn produce high levels of uncertainty in model predictions. An important challenge is to incorporate this uncertainty into hydrologic modeling, document and communicate that uncertainty, and quantify the resulting impacts on decision-making.

- Spatial variability of hydrologic model inputs and processes introduce high levels of uncertainty into hydrologic modeling. It is also important to incorporate this uncertainty into hydrologic modeling, document and communicate that uncertainty, and quantify the resulting impacts on decision-making.

- We feel that process-intensity scale effects and their impacts on thresholds and nonlinear responses are under-appreciated by the hydrologic modeling community. For example, there are thresholds and nonlinearities in rainfall-runoff relationships, in flow regime (subcritical vs. supercritical flow), and in suspended solids concentrations (entrainment vs. deposition). Inadequate representation of these process intensity-scale dependent thresholds and nonlinearities limits the ability of hydrologic models to accurately predict responses to a broad range on input values.

- Our hydrologic modeling abilities have outpaced our abilities to conduct field experiments. Simulation models in three spatial dimensions and time can be constructed but we still lack the ability to measure water flow in space and time. Often, hydrologic time series at a point are used to develop, calibrate, and validate distributed models with the result that it is possible to get the "right answer" for all the wrong reasons.

- There is an imbalance in large hydrological experiments with an over emphasis on quantifying components of the water balance (e.g. rainfall-runoff relationships, land surface-atmosphere interactions, groundwater flow) at the expense of systematic research on the entire water balance and the rich interactions and feedback among its components. Component research should continue and be strengthened, but it should be guided and focused by overarching systematic experiments on the water balance.

Acknowledgments

We are pleased to acknowledge the helpful comments of reviewers, H. D. Fox and H. E. Canfield, as well as the anonymous reviewers. We gratefully acknowledge the USDA-Agricultural Research Service for supporting this research and much of the research infrastructure upon which it is based. Finally, we gratefully acknowledge the Conference organizers and sponsors for giving us the opportunity to prepare this manuscript and participate in the Conference.

References Cited

Anderson, M.G., and Bates, P.D. (Eds.) (2001). Model Validation: Perspectives in Hydrological Science, John Wiley and Sons, Ltd., Chichester, UK, 500 pp.

Bates, P.D. and Lane, S.N. (Eds.) (2000). High Resolution Flow Modelling in Hydrology and Geomorphology, John Wiley and Sons, Chichester, UK, 374 pp.

Brown, G.W. (Ed.) (1974). Desert Biology, Volume II, Academic Press, New York, 601 pp.

DePauw, E., Gobel, W., and Adam, H. (20 00). Agrometeorological aspects of agriculture and forestry in the arid zones. *Ag. And Forest Meteorology*, 103: 43-58.

Dikinson, R.E. (1991). Global change and terrestrial hydrology – a review. *Tellus*, 43 AB: 176-181.

Evans, J.P. and Jakeman, A.J. (19 98). Development of a simple, catchment-scale, rainfall-evapotranspiration-runoff model. J. *Environmental Modeling & Software*, 13: 385-393.

Gleick, P.H. (1998). Water in crisis: Paths to sustainable water use. *Ecological Applications*, 8(3): 571-579.

Gleick, P.H. (2000). The World's Water 2000 – 2001. The Biennial Report on Freshwater Resources, Island Press, Washington, D.C., 315 pp.

Goodrich, D.C., Lane, L.J., Shillito, R.A., Miller, S.N., Syed, K.A., and Woolhiser, D.A. (1997). Linearity of Basin Response as a Function of Scale in a Semi-Arid Ephemeral *Watershed. Water Res. Res.*, 33(12): 2951-2965.

Hoggan, D. H. (1997). Computer – Assisted Floodplain Hydrology and Hydraulics, McGraw-Hill, 676 pp.

Jackson, R.B., Carpenter, S.R., Dahm, C.N., McNight, D.M., Naiman, R.J., Postel, S.L., and Running, S.W. (2001). Water in a changing world. Issues in Ecology, Technical Report. Ecological Applications, 11(4):1027-1045.

Knisel, W.G. (1980). *CREAMS*: A field-scale model for chemicals, runoff and erosion from agricultural management systems: USDA Conserv. Res. Report 26.

Koppen, W. (1931). Grundriss der Klimakunde. Berlin: De Gruyter.

Kremer, R.G. and Running, S.W. (1996). Simulating seasonal soil water balance in contrasting semi-arid vegetation communities. *Ecological Modelling.* 84:151-162.

Lane, L.J. and Osterkamp, W.R. (1991). Estimating Upland Recharge in the Yucca Mountain Area. Proc. ASCE Irrig. and Drain. Conf., Honolulu, HI, pp. 170-176.

Lane, L.J. and Nichols, M.H. (1999). Semi-Arid Climates and Terrain. *In:* Encyclopedia of Environmental Science (Ed. D. E. Alexander and R.W. Fairbridge), Encyclopedia of Earth Sciences Series, Kluwer Academic Publications, The Netherlands, pp. 556-558.

Lane, L.J., Romney, E.M. and Hakonson, T.E. (1984). Water balance calculations and net production of perennial vegetation in the northern Mojave Desert. *J. Range Mgt.* 37(1):12-18.

Lane, L.J., Nichols, M.H. and Osborn, H.B. (1994). Time Series Analyses of Global Change Data. *J. Environmental Pollution*, 83:63-68, Huntington, UK.

Lane, L.J., Hakonson, T.E., and Bostick, K.V. (1995). Applications and limitations of the water balance approach for estimating plant productivity in arid areas. *In:* Proc. Symposium on Wildland Shrub and Arid Land Restoration, Las Vegas, NV, USA, Oct 19-21m 1993 (Roundy, B. A., McArthur, E. D., Haley, J. S., and Mann, D. K., Eds.), pp. 335-338.

Mays, L.W. (Ed.) (1996). Water Resources Handbook. McGraw -Hill, New York, USA.

NRC (National Research Council). (1999). New Strategies for America's Watersheds. National Academy Press, Washington, D.C., 311 pp.

Osterkamp. W.R., Lane, L.J. and Menges, C.M. Techniques of Ground -water Recharge Estimates in Arid/semiarid Areas, with Examples from Abu Dhabi. *J. Arid Environments*, 31:349-369. 1995.

Refsgaard, J.C. and Storm. B, (1995). MIKE SHE. *In*: Singh, V.P., (Ed.), Computer Models of Watershed Hydrology. Water Resources Pubs., CO, USA, pp. 806-846.

Renard, K.G., Lane, L.J., Simanton, J.R., Emmerich, W.E. , Stone, J.J., Weltz, M.A., Goodrich, D.C., and Yakowitz, D.S. (1993). Agricultural impacts in an arid environment: Walnut Gulch studies. *Hydrol. Sci. & Tech*, 9: 145-190.

Roberts, B.R. (1993). Water Management in Desert Environments, A comparative Analysis. Springer-Verlag, Berlin, 337 pp.

Savenije, H.H.G. (2000). Water scarcity indicators; the deception of the numbers. *Phys. Chem. Earth (B)*, 25:199-204.

Singh, V.P. (Ed.). (1995). Computer Models of Watershed Hydrology. Water Resources Pubs., CO, USA, 1130 pp.

Slutsky, A.H. and Yen, B.C. (1997). A macro-scale natural hydrologic cycle water availability model. *Journal of Hydrology*, 201:329-347.

Trewartha, G.T. and Horn, L.H. (1980) An introduction to climate. 5[th] ed. New York: McGraw-Hill Book Company, 415 pp.