ELSEVIER

Journal of Hydrology 227 (2000) 21–40

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Regional estimation of base flow and groundwater recharge in the Upper Mississippi river basin

J.G. Arnold[a,*], R.S. Muttiah[b], R. Srinivasan[b], P.M. Allen[c]

[a]USDA-Agricultural Research Service, 808 East Blackland Road, Temple, TX 76502, USA
[b]Blackland Research Center, Texas A&M University, Temple, TX 76502, USA
[c]Baylor University, Department of Geology, Waco, TX 76798, USA

Received 19 August 1998; accepted 9 September 1999

Abstract

Groundwater recharge and discharge (base flow) estimates from two methods were compared in the Upper Mississippi River basin (USGS hydrologic cataloging unit 07). The Upper Mississippi basin drains 491,700 km^2 in Illinois, Iowa, Missouri, Minnesota, and Wisconsin and outlets in the Mississippi River north of Cairo, Illinois. The first method uses the water balance components from the soil and water assessment tool model (SWAT). The model was used to simulate the daily water balance of approximately 16 soil/land use hydrologic response units (HRU) within each of the 131 USGS 8-digit watersheds. The water balance of each HRU is simulated with four storages: snow, soil (up to ten layers), shallow aquifer, and deep aquifer. Groundwater recharge is defined as water that percolates past the bottom soil layer into the shallow aquifer. Recharge is lagged to become base flow and can also be lost to ET. The second method consists of two procedures to estimate base flow and recharge from daily stream flow: (1) a digital recursive filter to separate base flow from daily flow and (2) a modified hydrograph recession curve displacement technique to estimate groundwater recharge. These procedures were applied to 283 USGS stations ranging in area from 50 to 1200 km^2. A smoothed surface was obtained using a thin plate spline technique and estimates were averaged for each 8-digit basin. Simulated flow was calibrated against average annual flow for each 8-digit. Without further calibration, simulated monthly stream flow was compared against measured flow at Alton, Illinois (445,000 km^2) from 1961–1980. To validate the model, measured and simulated monthly stream flow at Alton from 1981–1985 were compared with an R^2 of 0.65. No attempt was made to calibrate base flow and recharge independent of total stream flow. Base flow and recharge from both methods were shown to be in general agreement. The filter and recession methods have the potential to provide realistic estimates of base flow and recharge for input into regional groundwater models and as a check for surface hydrologic models. Published by Elsevier Science B.V.

Keywords: Base flow and groundwater recharge; Soil and water assessment tool; Filter and recession methods

1. Introduction

Shallow aquifer recharge and discharge characteristics are crucial for efficient development and management of groundwater resources, as well as for minimizing pollution risks to the aquifer and connected surface water. Groundwater has been shown to make up greater than 90% of the stream flow in portions of the Atlantic Coastal Plain (Williams and Pinder, 1990), and up to 50% of total flow in Central Texas, (Arnold et al., 1993). Reay et al. (1992) found that neglecting shallow groundwater

* Corresponding author. Tel.: +1-254-770-6502; fax: +1-254-770-6561.
E-mail address: arnold@brc.tamus.edu (J.G. Arnold).

0022-1694/00/$ - see front matter. Published by Elsevier Science B.V.
PII: S0022-1694(99)00139-0

Table 1
Comparison of hydrologic budgets for the Illinois basins (from Arnold and Allen, 1996)

	Goose Creek (1957) measured/predicted (mm)	Hadley Creek (1957) measured/predicted (mm)	Panther Creek (1952) measured/predicted (mm)
Precipitation	944	1009	822
Stream flow	241/254	354/366	249/239
Surface runoff	144/145	306/300	68/86
Groundwater flow	97/121	48/66	182/153
Evapotranspiration	617/603	627/635	608/595
Surface and soil ET	535/521	605/613	557/556
Groundwater ET	81/81	22/22	51/39
Groundwater recharge	264/210	99/89	204/191
Change in ground water storage	+86/+85	+27/+39	−29/−10

aquifer to the stream. Other components include evaporation, pumping withdrawals, and seepage to the deep aquifer. The model offers three options for estimating potential ET–Hargreaves (Hargreaves and Samani, 1985), Priestley–Taylor (Priestley and Taylor, 1972), and Penman–Monteith (Monteith, 1965). The Penman–Monteith method was used in this study and requires solar radiation, air temperature, windspeed and relative humidity as input. Daily values of wind speed, relative humidity, and solar radiations were generated from average monthly values. The model computes evaporation from soils and plants separately (Williams et al., 1984). Potential soil water evaporation is estimated as a function of potential ET and leaf area index (area of plant leaves relative to the soil surface area). Actual soil evaporation is estimated by using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential ET, leaf area index and root depth and can be limited by soil water content. It is assumed that 30% of total plant uptake comes from the upper 10% of the root zone and roots can compensate for water deficits in certain layers by using more water in layers with adequate supplies.

2.2. Stream flow filter and recession methods

2.2.1. Base flow separation

Numerous analytical methods have been developed to separate base flow from total stream flow (McCuen, 1989). Although most procedures are based on physical reasoning, elements of all separation techniques are subjective. The digital filter technique (Nathan and McMahon, 1990) used in this study was originally used in signal analysis and processing (Lyne and Hollick, 1979). Although the technique has no true physical basis, it is objective and reproducible. Arnold et al. (1995) compared the digital filter results with results from manual separation techniques and with the PART model (Rutledge, 1993; Rutledge and Daniel, 1994) for eleven watersheds in Pennsylvania, Maryland, Georgia, and Virginia (White and Slotto, 1990). Annual bases derived from the filter were on average within 11% of base flow estimated by manual techniques and the PART model. A recent study by Mau and Winter (1997) found that this filter method agreed reasonably well with the graphical partitioning method.

2.2.2. Ground water recharge

Several methods have been developed to estimate ground water recharge from stream flow records. One popular method is the recession-curve-displacement method which is commonly referred to as the Rorabaugh method (Rorabaugh, 1964). This method estimates total recharge for each stream flow peak, is theoretically based, and includes ground water variables. The disadvantage is the time required to calculate recharge for each peak. Potential groundwater recharge was shown to equal approximately one-half of the total volume that recharged the system at a "critical time" after the peak (Rorabaugh, 1964). The recession curve displacement method uses this approximation, an estimate of critical time and the principle of superposition to estimate total recharge from daily stream flow hydrographs. Bevans (1986)

Table 2
Monthly statistics of measured vs. filtered base flow (from Arnold and Allen, 1999)

	R^2	Slope	Intercept (mm)	Number of points (months)	Total base flow (mm)	
					Measured	Filtered
Goose, IL 1955–1958	0.87	0.93	2.0	45	200	230
Panther, IL 1951–1952,1956	0.80	0.91	2.0	36	240	270
Hadley, IL April 1956–September 1958	0.91	1.75	−0.16	30	71	120
Brandywine, PA 1928–1931	0.97	1.04	1.2	48	600	660
Brandywine, PA 1952–1953	0.98	1.13	0.06	21	1030	1170
Pomperaug, CT August 1913–December 1916	0.62	1.46	−0.95	41	430	600
Beaverdam, MD	0.97	0.98	1.4	24	580	600

and Rutledge and Daniel (1994) describe and illustrate the method to estimate critical time. The method used in this study is a modification of the recession-curve-displacement method (Arnold and Allen, 1999). It has the advantages of: (1) not requiring analysis of every peak; and (2) having been tested against measured estimates of base flow.

3. Previous validation at selected watersheds

3.1. SWAT application on three Illinois watersheds

A field study was completed in the 1950s to estimate several major hydrologic components including surface runoff, groundwater flow, groundwater ET, ET in the soil profile, groundwater recharge, and groundwater heights from measured data from three watersheds (122–246 km^2) in Illinois (Schicht and Walton, 1961). Table 1 gives measured and SWAT predicted hydrologic budget components for selected years from the three watersheds (Arnold and Allen, 1996). In general, the model results compared well with the measured water budget calculations. Most components are within 5% and nearly all are within 25%. This error is the same order of magnitude as that found by Gerhart (1984), who applied a three-dimensional numerical model to simulate flows in two basins in Pennsylvania and Maryland.

3.2. Stream flow filter and recession methods validation

Six basins were selected for validation that fall within four major groundwater regions (Heath, 1984): the Glaciated Central Region, the Atlantic and Gulf Coastal Plain, the Piedmont Blue Ridge and the Northeast and Superior Uplands. The basins chosen to analyze the automated recharge technique were based on four criteria: (1) recharge was independently analyzed for each basin using manual water balance methods; (2) the basins represented a variety of humid groundwater regions; (3) studies utilized actual groundwater hydrograph response in estimating recharge; and (4) basins were monitored for one year or more. Average conditions at all sites consisted of three years of monitored data, 35 km^2 per rain gage, one recording stream gage, and 19 km^2 per groundwater well. Basin areas ranged from 20 to 750 km^2.

3.2.1. Base flow

The digital filter was run for all six watersheds and total base flow is shown in Table 2 (from Arnold and Allen, 1999). Statistics of monthly comparisons (one pass of the filter) found that R^2 values ranged from 0.62 to 0.98 and slopes ranged from 0.91 to 1.75. Combining all months of all watersheds resulted in an R^2 of 0.86 and slope of 1.07 showing that the digital filter can give reasonable estimates of monthly base flow in comparison to measured estimates.

3.2.2. Recharge

Only Goose, Panther, and Pomperaug basins had estimates for monthly ground water recharge. Recharge of 99 mm was estimated from measured flow at the Hadley Creek Watershed for 1956. Table 3 shows measured and predicted annual recharge for these four basins. The percentage by which the result of the automated recharge technique exceeds that of the manual method is shown. The average difference between the measured recharge and predicted is 28%. The maximum annual difference is 46% for the Goose watershed in 1955, the minimum difference is 11.5% for the Pomperaug watershed in 1915. For the two watersheds with four years of field data, Goose and Pomperaug, the average difference for the four years was 26 and 11%, respectively. For the twelve years of record, including all the basins, the automated model underpredicts the cumulative measured recharge by 10.7%. The automated technique appears to be in the range of other field and water balance techniques for estimating recharge (Winter, 1981; Essery, 1992). In actual field evaluations, Sami and Hughes (1996) compared recharge estimates in a fractured sedimentary aquifer in South Africa from a chloride mass balance to an integrated surface–subsurface model. Their results showed mean annual recharge for the chloride balance to be 4.5 mm compared to 5.8 mm from the model with mean annual rainfall of 460 mm. This is a difference of about 22%.

4. Regional application to Upper Mississippi Basin

The location of the Upper Mississippi Basin is shown in Fig. 2. The USGS has divided the basin into 131 hydrologic unit areas called hydrologic cataloging units (HCU) that average 3750 km^2 in drainage area. These HCU's are generally referred to as "8-digit" watersheds based on the naming convention used by the USGS. A HCU is defined by topographic flow paths and is the basic routing unit for the model. All flows are routed through the main river channel of each 8-digit. Each HCU is further subdivided into hydrologic response units (HRU) by the model. HRU is defined as a practically homogeneous area having a distinct hydrologic response. In this study, the HRU is defined by combinations of unique land use and soil derived from several GIS maps and data bases. Data bases required by the model include topography, land use, soils (USDA, 1992), daily weather data, geology, agricultural land management, pond and reservoir data, and water use. Stream flow contribution from each HRU is defined as the sum of surface runoff, lateral soil flow, and shallow aquifer flow minus abstractions from channels and reservoirs. Stream flow contribution (or total runoff) is then summed to obtain total runoff from each eight-digit HCU. Flow is then routed through reservoirs and channels for each HCU. The model assumes that groundwater flow returns within the HCU and that there is no net groundwater inflow or outflow between 8-digit basins.

The model was run for 21 years (1960–1980) to obtain average annual values of runoff to compare against observed runoff. Observed average annual runoff was obtained by Gebert et al. (1987) from measured stream flow from 5951 gaging stations across the U.S. from 1951–1980.

4.1. Model inputs

The SWAT model requires inputs on weather, topography, soils, shallow aquifer, land use and management, stream channels, and ponds and reservoirs. A GIS interface (Srinivasan and Arnold, 1994) was used to automate the development of model input parameters.

Daily precipitation and maximum and minimum temperatures were obtained from the National Weather Service for over 300 gages and an areal weighting was performed to obtain daily values for each 8-digit HCU. Daily values of solar radiation, wind speed, and relative humidity were generated from 70 stations where monthly generator parameters were developed (Nicks, 1974). The USGS–LUDA (land use/land cover) data (USGS, 1990) were used to develop plant inputs to the model. Agricultural land use was further divided into specific crops (i.e. corn, wheat, soybeans) that were determined from the National Agricultural Census Data. Once plant type is determined, a data base has been developed for over 100 plants with data including maximum leaf area index, maximum rooting depth, maximum canopy height, energy to biomass conversion, and optimum and base temperatures for growth. A heat unit scheduling algorithm was used to find probable planting and harvest dates for annual crops and the beginning and end of the growing season for perennials. If the STATSGO-soil association map (USDA, 1992) data base reported the land use as irrigated agriculture, an automated irrigation algorithm replenished soil water to field capacity when the crop stress reached a specified level. All agricultural crops were fertilized according to an automated routine that attempts to

Table 3
Annual differences in measured and estimated ground water recharge (from Arnold and Allen, 1999)

Basin	Year	Measured (mm)	Predicted (mm)	% Difference
Goose	1955	163	88	−46
	1956	91	57	−37
	1957	241	232	−12
	1958	303	232	−24
Panther	1951	213	297	+40
	1952	204	174	−14
	1956	22	12	−45
Hadley	1956	99	122	+23
Pomperaug	1913	253	150	−41
	1914	233	298	+28
	1915	439	399	−11
	1916	280	237	−15

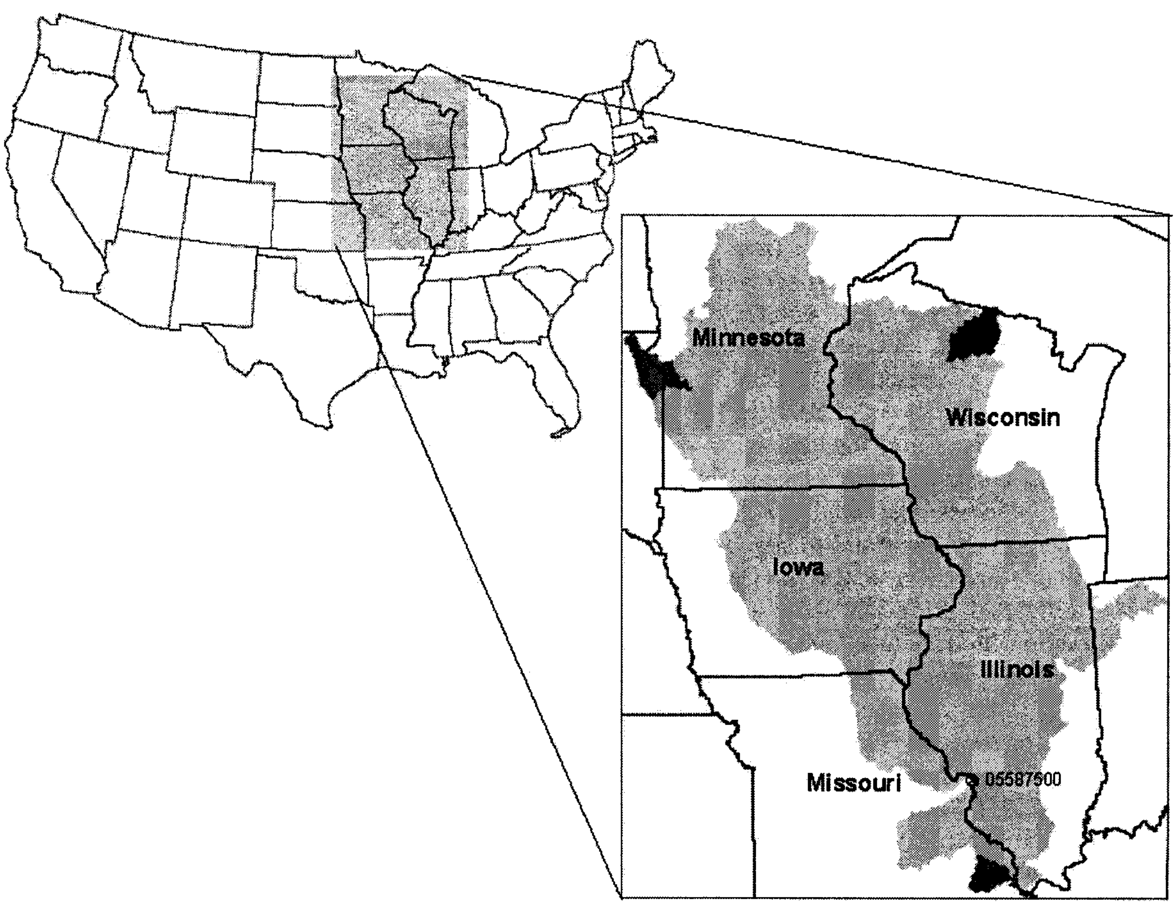

Fig. 2. Location of Upper Mississippi basin.

Table 4
Baseline water balance for three 8-digit basins used in sensitivity analysis (see Fig. 2 for locations)

8-Digit Basin No.	Location	Surface Runoff (mm)	Base Flow (mm)	GW Recharge (mm)	Soil ET (mm)
07020001	NW Minnesota	14.8	7.5	8.2	543.9
07070001	Eastern Wisconsin	53.4	232.7	273.2	465.7
07140107	Missouri	368.0	239.2	294.4	817.3

apply nitrogen and phosphorus to meet crop requirements.

The STATSGO-soil association map was used for selection of soil attributes. Relational soil physical properties include texture, bulk density, available water capacity, saturated conductivity, soil albedo, and organic carbon for up to ten soil layers. The condition II curve number was assigned to each HRU based on the hydrologic soil group and land use (USDA, 1972).

Water use data was taken from the USGS Water Use database. Data were collected every five years for each county. In this study, county data from 1985 were aggregated to obtain a value for each 8-digit HCU. The database includes municipal and industrial water use and gives monthly withdrawals from surface and groundwater sources. It was assumed that surface withdrawals were taken from the main channel in the HCU and groundwater withdrawals were pumped from the shallow aquifer. Data on pond and reservoirs was obtained from the DAMS database which is a collection of data from the National Resources Conservation Service, US Army Corp of Engineers, Bureau of Reclamation and local municipalities. Data used by the model included surface areas, volumes and spillway information from small flood control structures to large reservoirs.

Overland slope and slope length for each 8-digit HCU were estimated using the 3-arc second DEM (Digital Elevation Model). Overland slope was estimated using the neighborhood technique (Srinivasan and Engel, 1991) for each cell and calculating an average slope for the entire HRU. Stream channel dimensions were estimated from regression analysis by Allen et al. (1994). Shallow aquifer (ground water) attributes include specific yield, evaporation coefficient and a recession constant. Recession constants were determined for the region using a daily hydrograph analysis technique described in Arnold et al. (1995). The aquifer evaporation coefficient accounts for water that is extracted by deep roots and water that travels down the hill slope from the shallow aquifer to the soil profile and is then lost to soil evaporation or plant root uptake. Snowmelt parameters were not modified. The snow melt rate was set at 4.57 mm/C per day and snow coverage was assumed uniform (the areal depletion curve was not used).

4.2. Sensitivity analysis

The SWAT model is sensitive to hundreds of input variables related to vegetation, land management, soil, weather, aquifer, channels, and reservoirs. Finch (1998) found that the most crucial land surface parameters required by simple water balance models for estimating groundwater recharge are those required by the soil component (particularly available water capacity). A comprehensive sensitivity analysis of SWAT was preformed by Hauck et al. (1999) and was not attempted in this study. However, a sensitivity analysis was performed on the three variables used in the calibration procedure. Three 8-digit basins were used in the sensitivity analysis (Fig. 2). Basin 07070001 is located in the northeast portion of the Upper Mississippi basin in Wisconsin. Basin 07020001 is in Minnesota in the northwest portion of the basin and 07140107 are in Missouri in the far southern portion of the basin. These three basins represent a wide range in climate, base flow and recharge as shown in Table 4.

Hauck et al. (1999) found that the most sensitive parameter in the model is the curve number which is related to both soil and vegetation. Fig. 3 shows sensitivity of surface runoff, base flow, recharge and soil ET to curve number. Surface runoff is extremely sensitive to curve number, however runoff response from basin 07070001 is exaggerated due to low average surface runoff (14.8 mm). Since infiltration

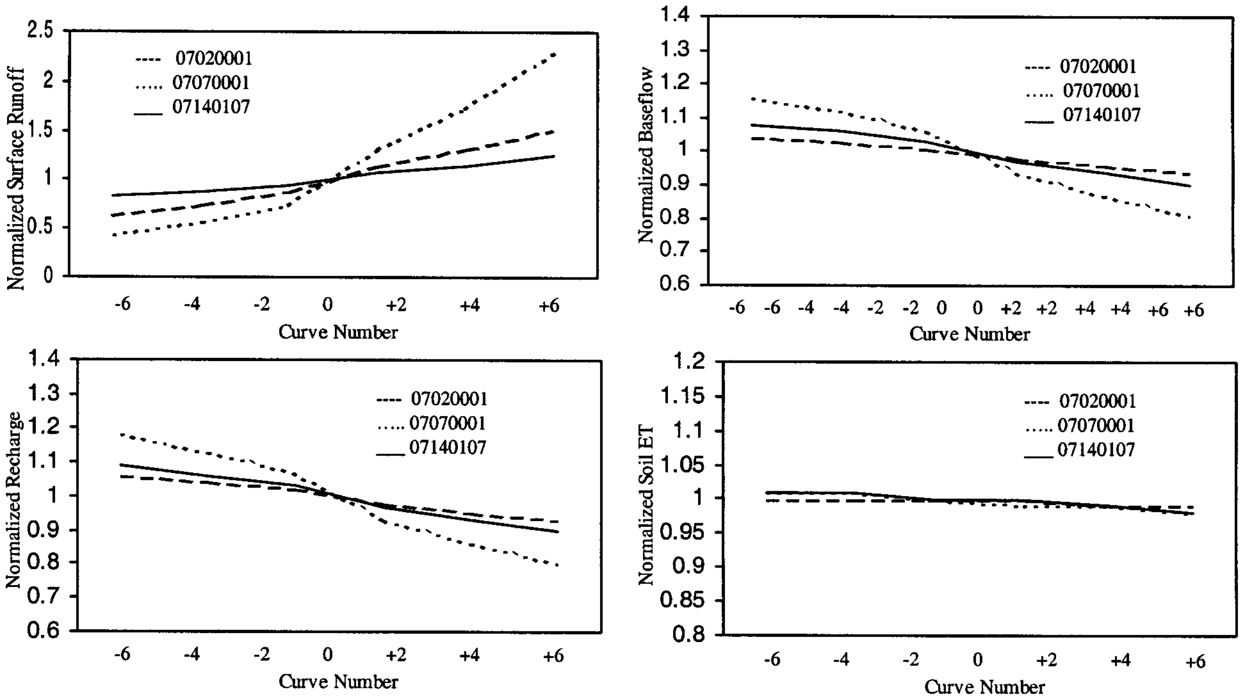

Fig. 3. Sensitivity of surface runoff, base flow, recharge and soil ET to curve number.

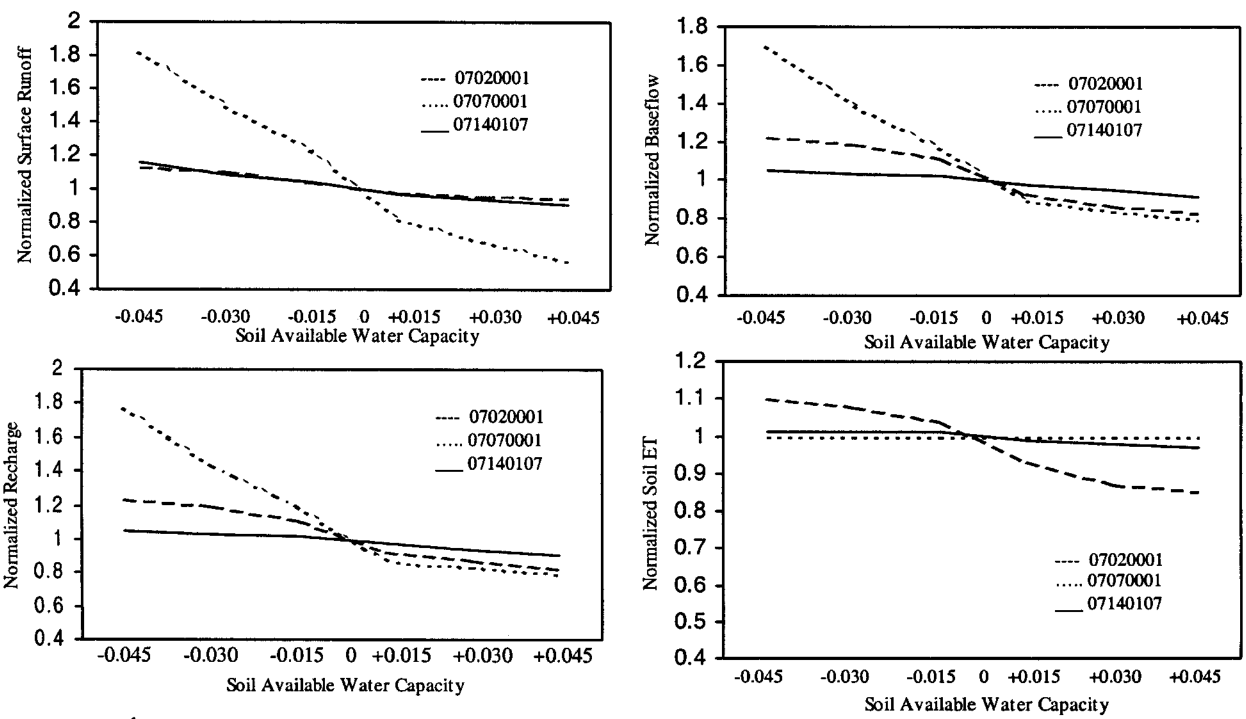

Fig. 4. Sensitivity of surface runoff, base flow, recharge and soil ET to available soil water capacity.

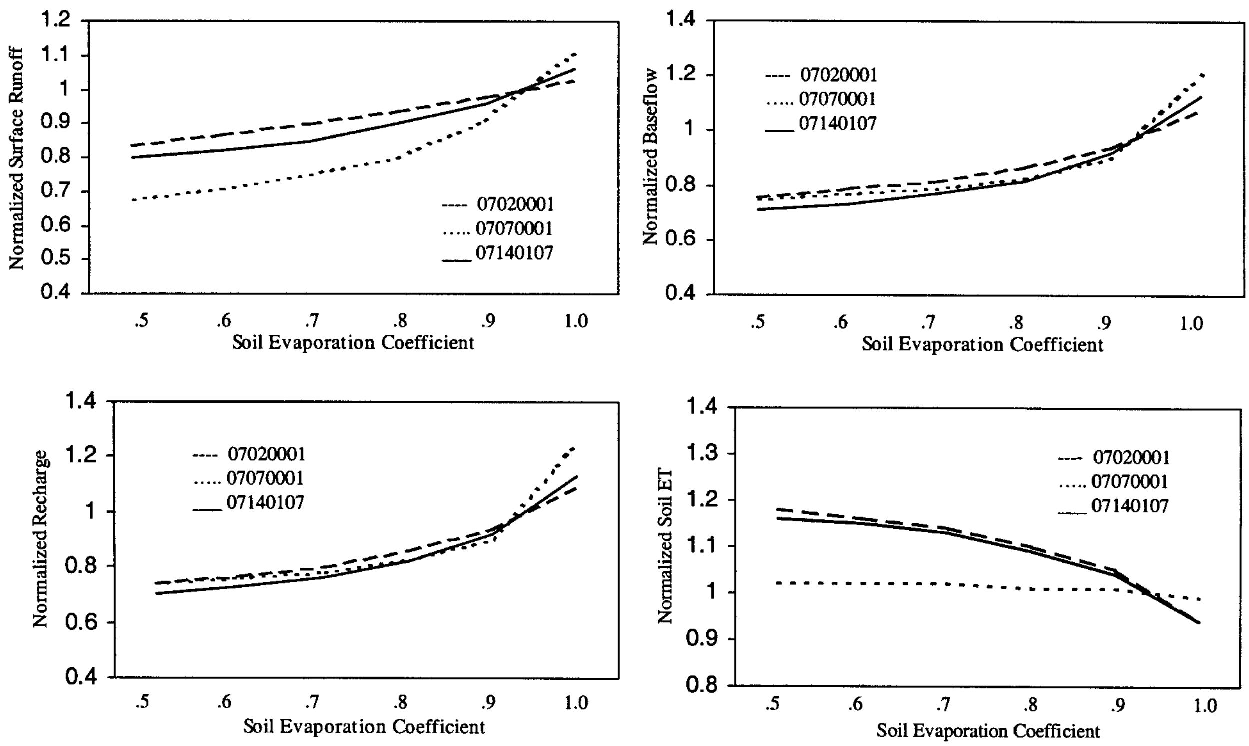

Fig. 5. Sensitivity of surface runoff, base flow, recharge and soil ET to soil evaporation coefficient.

decreases with increased surface runoff, base flow and recharge are both inversely correlated to curve number. The relative impact of curve number on soil ET was relatively small (Fig. 3). Soil available water capacity was also chosen for calibration and sensitivity analysis since it was found to be a critical input to water balance models by Milly (1994), Finch (1998) and Hauck et al. (1999). With decreasing soil water capacity, estimates of surface runoff, base flow and recharge all decreased (Fig. 4), while soil ET increased. With less storage, more water will either runoff or percolate and consequently less water was stored in the soil and available for ET (plant uptake and soil evaporation). The final input used for calibration and sensitivity analysis was the soil evaporation compensation coefficient (ESCO). This factor adjusts the depth distribution for evaporation from the soil (described in Arnold et al., 1998) to account for the effect of capillary action, crusting and cracking. The baseline value of esco is 0.95. Fig. 5 shows the sensitivity of surface runoff, base flow, recharge and soil ET to esco. Decreasing esco allows lower soil layers to compensate for water deficit in upper layers and causes higher soil ET. With soil ET increasing there is less water available for surface runoff, base flow and recharge.

4.3. Calibration procedure

The first step in a traditional watershed model calibration is to break the measured stream flow time series into calibration and validation periods. In the calibration period, model inputs are allowed to vary across the basin until an acceptable fit to measured flow at the basin outlet is obtained. The model is then run using the same input parameters for the validation period and goodness-of-fit is determined. In this study, an attempt was made to "spatially calibrate" the model. We felt it was more important to assure that local water balances within the subbasins were realistic as opposed to "blindly" calibrating model inputs over the entire basin in order to match one stream flow gage near the outlet of the basin. The calibration/validation procedure used in this study is:

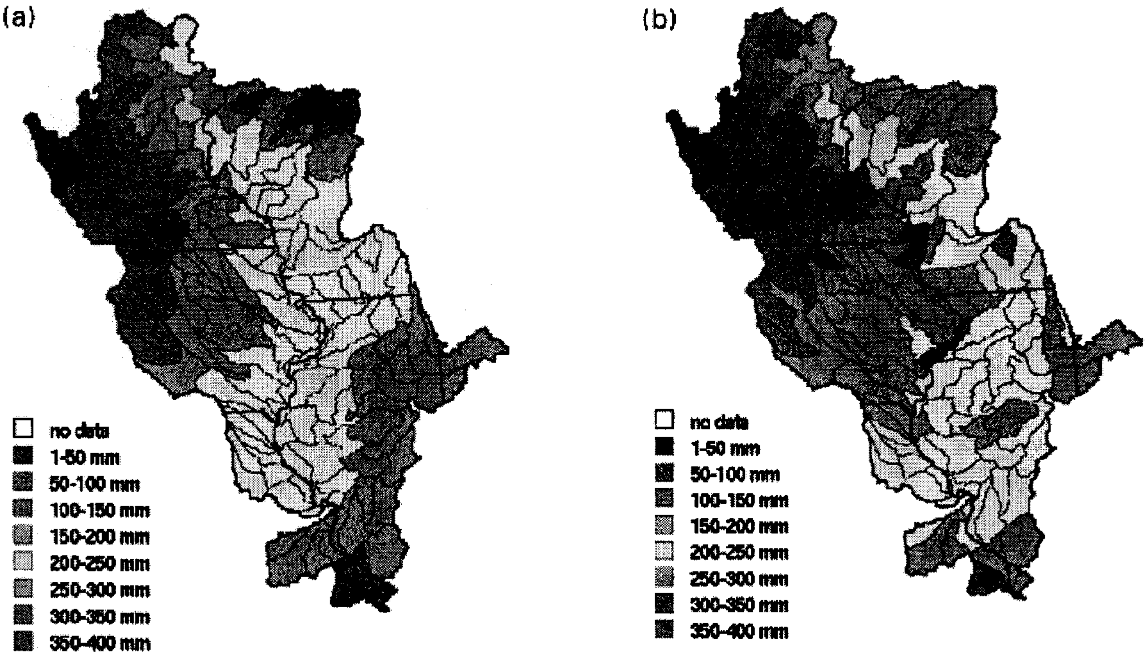

Fig. 6. (a) Total flow for 8-digit basins in the Upper Mississippi from USGS measured flow records. (b) Total flow for 8-digit basins in the Upper Mississippi simulated by SWAT.

(1) calibrate to long term average annual flow for each 8-digit basin; (2) check monthly stream flow during the calibration period to assure proper annual and seasonal variability; and then (3) validate monthly stream flow for a period outside the calibration period.

Average annual simulated flow for a 21 year run (1960–1980) was calibrated against average annual USGS measured flow for each 8-digit basin. Inputs to the model are physically based (i.e. based on readily observed or measured information), however, there is often considerable uncertainty in model inputs due to spatial variability, measurement error, etc. Three variables used in the sensitivity analysis were also selected for calibration: (1) ESCO—a soil evaporation compensation coefficient; (2) AWC—plant available soil water capacity; and (3) CN2—condition II runoff curve number. First, ESCO was allowed to vary between 0.75 and 1.0 with 1.0 signifying no compensation with depth. The model assumes a soil evaporation distribution with depth. The ESCO variable adjusts the depth distribution for evaporation from the soil to account for the effect of capillary action, crusting, and cracking. If simulated and measured flows are within 10% calibration was terminated. If flow differences are greater than 10%, AWC is adjusted within a range given by the soils database (USDA, 1992) which is normally ±0.04. If flow differences continue to exceed 10%, CN2 is allowed to vary ±6 to account for uncertainty in the hydrologic condition of the basin. Calibration was performed on total stream flow only; no attempt was made to calibrate specifically for base flow or recharge.

Observed and modeled (calibrated) flow is shown in Fig. 6a and b. Total flow for the entire Upper Mississippi was 207 mm measured by USGS and 192 mm simulated by SWAT. Regression by 8-digit basin yielded an R^2 of 0.89 and a slope of 0.90 (Fig. 7). Calibration beyond the ten percent cut-off was considered inappropriate due to uncertainties in the USGS data and the “smoothing” to obtain complete maps (Gebert et al., 1987).

To further ensure the calibration procedure was successful, model output was compared against monthly stream flow at USGS station 05587500 near Alton, Illinois on the Mississippi River (Fig. 2). The basin drains 445,000 km^2 or approximately 90% of the entire Upper Mississippi Basin. Fig. 8 shows monthly time series of measured and simulated flow from 1961–1980 (1960 was used as a “warm-up”

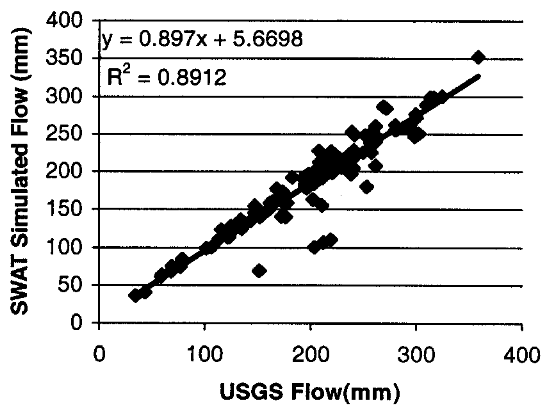

Fig. 7. Regression of SWAT simulated and USGS measured annual total flows by 8-digit basin.

period). Regression analysis yielded an R^2 of 0.63 with mean monthly measured and simulated flows of 3068 and 2648 m^3/s, respectively. General peaks and recessions are preserved by the model. There is a general tendency for the model to underpredict spring peaks and to sometimes overestimate fall stream flow. This may be attributed to snow melt simulation, seasonal variations in ET and soil moisture condition or operation of large reservoirs. The results appear realistic given that no attempt was made to calibrate the model to match seasonal or monthly trends.

4.4. Stream flow validation

Five years of stream flow data outside the calibration period (1981–1985) were readily available at the Alton, Illinois gaging station. Regression analysis yielded an R^2 of 0.65 with mean monthly measured and simulated flows of 4133 and 3509 m^3/s, respectively. Fig. 9 shows the measured and predicted monthly time series from 1981 to 1985 with similar tendencies and error (15%) as the calibration period.

4.5. Results from stream flow filter and recession methods

USGS stream gages in the Upper Mississippi (283 gages) were selected for basins that ranged in size from 50 to 1200 km^2 and had a minimum of ten years of stream flow record. Since the number of years of each gage varied, a base flow ratio was calculated from daily stream flow using the digital filter for each gage. The base flow ratio is the ratio of groundwater flow to total flow. To estimate groundwater flow, the base flow ratio is multiplied by observed runoff from Gebert et al. (1987). Base flow estimates from the digital filter are shown in Fig. 10a.

Recharge estimated from the modified recession curve displacement technique (Arnold and Allen, 1999) is shown in Fig. 11a. Gages used in the base flow analysis were also used for recharge analysis. Recharge for each of the 283 gages was mapped as a point at the outlet of the basin and a surface was obtained using a thin plate spline technique (Muttiah et al. (1998). Recharge for each 8-digit basin was then calculated by averaging the smoothed surface map.

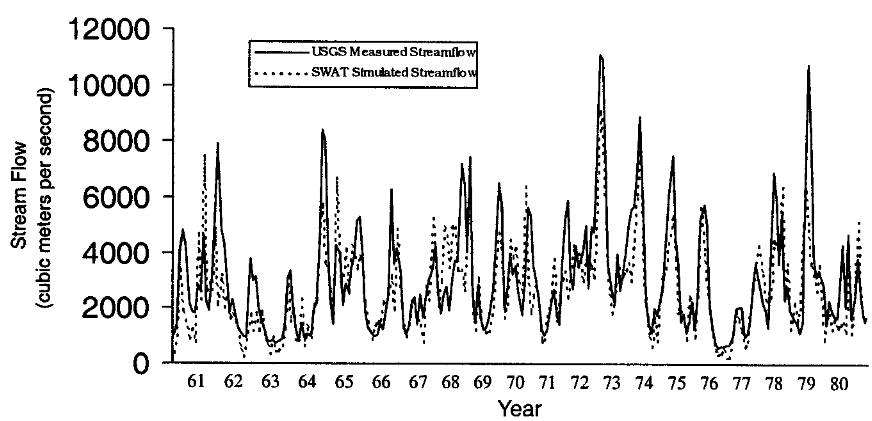

Fig. 8. Monthly time series (1961–1980) of SWAT simulated and USGS measured stream flow at gage 05587500 near Alton, Illinois on the Mississippi River (445,000 km^2) for calibration.

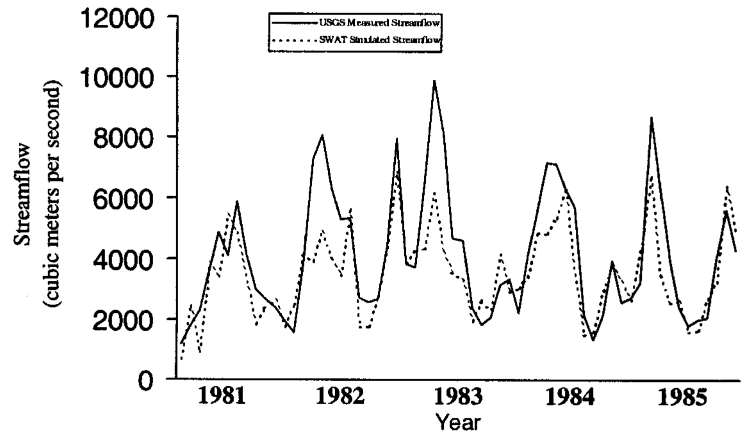

Fig. 9. Monthly time series (1981–1985) of SWAT simulated and USGS measured stream flow at gage 05587500 near Alton, Illinois on the Mississippi River (445,000 km^2) for validation.

5. Discussion

5.1. Base flow discussion

SWAT simulated and filtered base flow for the basin scale model runs was compared to three smaller sub-basins in Illinois with measured base flow estimates by Schicht and Walton (1961). Comparison is difficult since the three basins are much smaller than the 8-digit basins and since only one year of measured data was available for comparison. However, results compare well except for Panther Creek watershed with high measured base flow in 1952 (Table 5). Modeled SWAT output was also compared to another base flow estimation method (a manual separation method that analyzes stream flow duration curves) by Walton (1970) in Illinois and Minnesota. Basins analyzed by Walton in Illinois were compared against SWAT simulated base flow with good agreement. Walton's base flow estimate for basins near Panther Creek in Illinois was 52 mm which is very close to SWAT estimates. Walton (1970) estimated approximately 16 mm for western Minnesota SWAT modeled base flow was in the 0–25 mm range (Table 5).

Filtered and SWAT simulated base flow for the entire Upper Mississippi basin is shown in Fig. 10a and b. Average annual base flow for the entire Upper Mississippi was 83 mm from the filter (hydrograph separation technique) while SWAT simulated 80 mm. Regression of filtered and SWAT simulated base flow is shown in Fig. 12 with an R^2 of 0.62 and slope of 1.14. Fig. 13 shows the difference between filtered and SWAT simulated estimates of base flow. Differences range from +75 to − 70 mm. A positive difference signifies that SWAT base flow is higher than filtered and a negative difference shows that SWAT estimates are lower than filtered. There are two general regions where SWAT base flow is higher than filtered base flow: (1) central and northern Wisconsin; and (2) southern Illinois and Missouri. Surface geology in central and northern Wisconsin consists primarily of thick, permeable glacial outwash with 100 m depth to bedrock (Kammerer, 1995). Southern Illinois and Missouri consist of deeply weathered loess (Olcott, 1992). Both areas have relatively high average annual runoff (250–400 mm). This suggests that SWAT tends to overestimate base flow in high runoff regions with deep soils. This is not surprising since estimating aquifer storage is difficult and it was not a parameter used in model calibration. Also, only total flow was calibrated; no attempt was made to calibrate base flow. It is difficult to analyze regions where the model underestimates base flow since there do not appear to be any glaring spatial tendencies (Fig. 13). There is a slight tendency for the model to underestimate in Minnesota and northern Iowa which is a region with relatively low precipitation and runoff.

The differences illustrated in Fig. 13 appear to be in the range of other field and water balance techniques for estimating base flow and recharge. Rushton and Ward (1979) concluded that uncertainties of ±15%

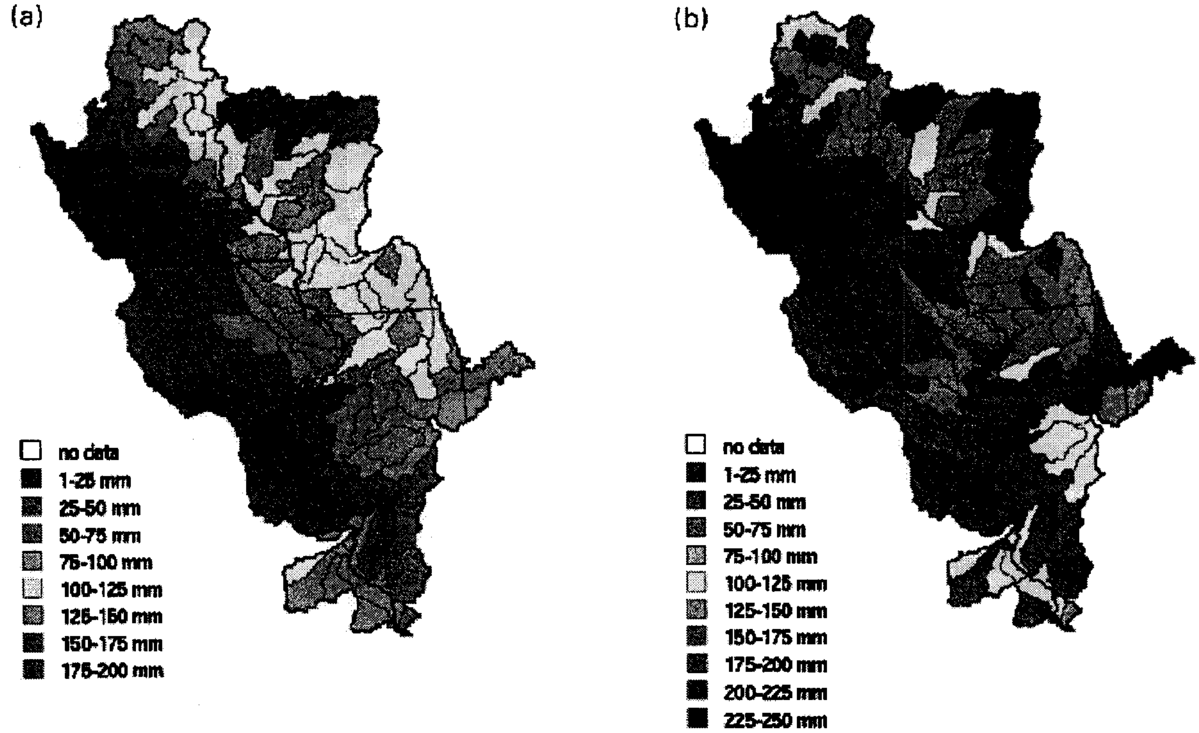

Fig. 10. (a) Base flow for 8-digit basins in the Upper Mississippi from USGS measured flow records. (b) Base flow for 8-digit basins in the Upper Mississippi simulated by SWAT.

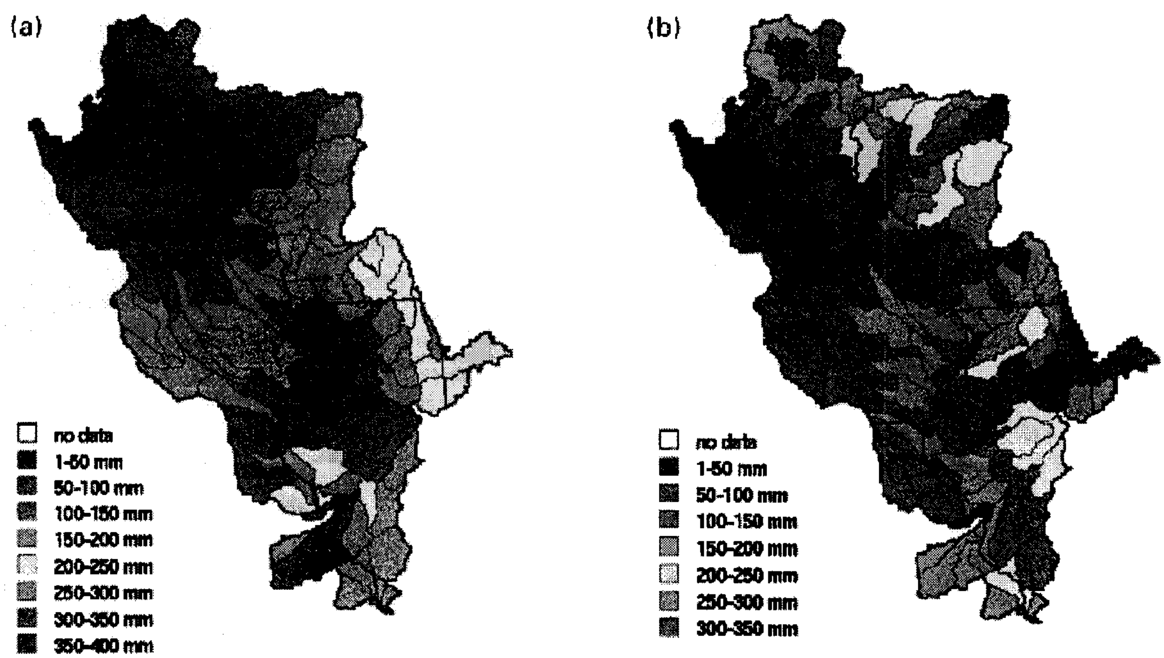

Fig. 11. (a) Recharge for 8-digit basins in the Upper Mississippi from USGS measured flow records. (b) Recharge for 8-digit basins in the Upper Mississippi simulated by SWAT.

Table 5
Comparison of SWAT simulated base flow, measured estimates and another separation technique at selected basins

Selected basin	SWAT (Average annual)	Schicht and Walton (1961) measured estimates	Walton (1970) (average precipitation) flow duration curves
1	07130009, 100–125 mm	Goose Creek (1957), 96 mm	Basins 78-79, 120 mm
2	07130011, 50–75 mm	Hadley Creek (1957), 48 mm	Basins 64-68, 83 mm
3	07120001, 50–75 mm	Panther Creek (1952), 181 mm	Basin 36, 52 mm
4	07020001-09, 0–25 mm		Basins 2940, 3045, 3135, 16 mm

should be expected with the soil water balance approach to estimating recharge. Winter (1981) also discussed various errors inherent in measurement and computation of the various components of the water balance, indicating that long term averages had less error than short term values. Winter (1981) suggests errors in annual estimates of precipitation, stream flow, and evaporation ranged from 2–15% whereas monthly rates could range from 2–30%. This premise was subsequently questioned by more recent work by Essery (1992) who suggested that even long term measurements could be subject to recurring errors of a similar magnitude.

5.2. Recharge discussion

Fig. 11a and b show groundwater recharge calculated by the hydrograph recession displacement method (recession method) and by the SWAT model. Total recharge for the entire Upper Mississippi basin was 156 mm/y from the recession method and 148 mm/y simulated by SWAT. Recharge ranges from under 25 to over 350 mm. Fig. 14 shows the difference between filtered and SWAT simulated estimates of base flow. Differences range from +70 to −105 mm. A positive difference signifies that SWAT recharge is higher than the displacement method and a negative difference shows that SWAT estimates are lower than the displacement method. The general trends are similar to base flow, with SWAT estimates tending to be higher in central and northern Wisconsin and southern Illinois and Missouri. This is reasonable since both recharge and base flow are based on the same stream flow records. In all other regions, SWAT is consistently lower than the recession method. In central Illinois we have some confidence in SWAT due to previous validation efforts. Table 6 shows recharge, ET, and revap (shallow aquifer evaporation) for the three Illinois watersheds and comparable SWAT results. Again, comparison is difficult due to differences in drainage area and period of analysis. It is encouraging that soil ET is relatively close and revap from the shallow aquifer is of the same general magnitude. Since runoff is close to measured and soil ET and revap are reasonable, added confidence is given to the recharge estimates. In western Minnesota and Iowa, SWAT underestimates base flow and may also be underestimating recharge. At the same time the recession method may be overestimating recharge in western Minnesota and Iowa when comparing recharge to other estimates of runoff and base flow (Walton, 1970). We must remember that this is only a comparison of two methods. Both have inherent errors and uncertainties and in some cases the water balance model may give more reliable estimates than the recession method (Arnold and Allen, 1999).

Differences in the two methods also compare well with other regional studies. Holtschlag (1997)

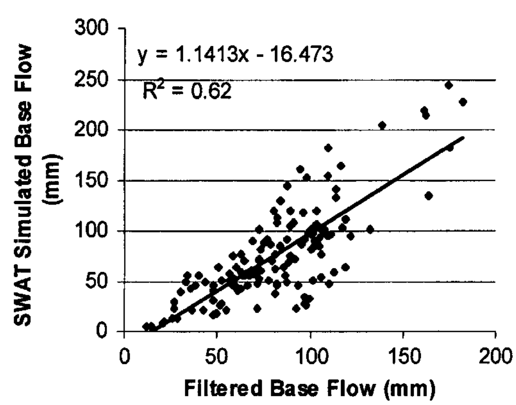

Fig. 12. Regression of SWAT simulated and USGS measured annual base flows by 8-digit basin.

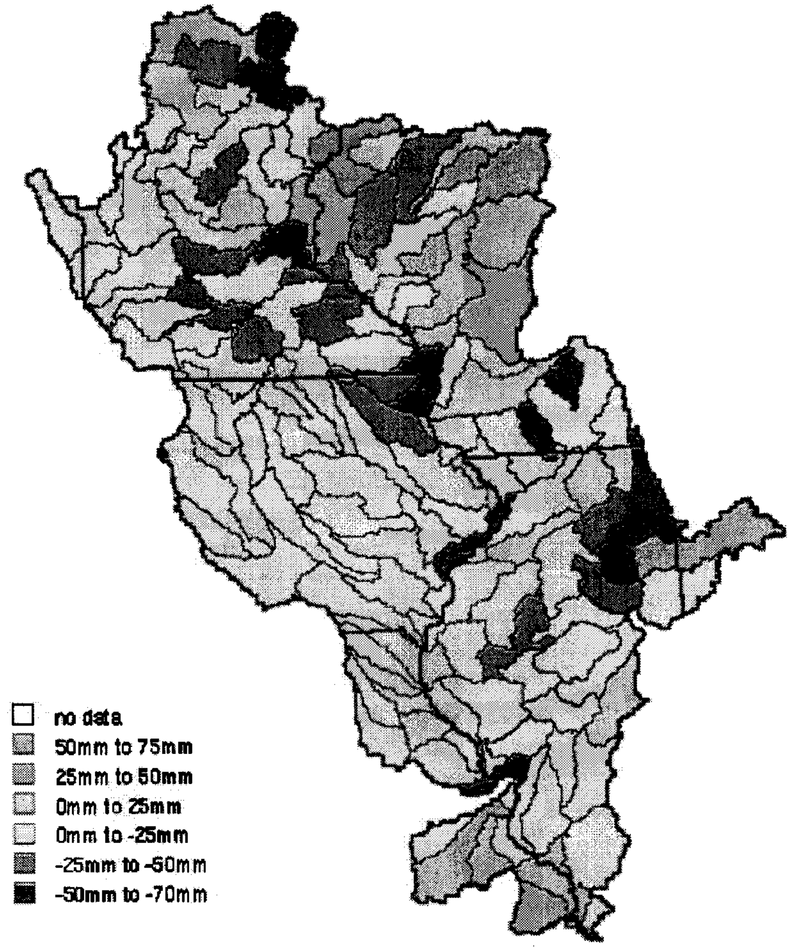

Fig. 13. Difference in SWAT simulated and filtered average annual base flow.

prepared generalized estimates of groundwater recharge rates in the lower peninsula of Michigan. Multiple regression was used to estimate spatial variation in recharge over the Lower Peninsula. Variables found to be important were latitude and longitude, surficial geologic materials, deciduous forest and coniferous forest. Basin specific estimates and the generalized regression estimates were within ±100 mm/y.

6. Summary and conclusions

Regional base flow and recharge estimates from two methods were compared in the Upper Mississippi River basin. The first method is a continuous water balance model and the second is an automated technique to separate base flow and recharge from daily stream flow. The model was calibrated to average annual flow from each 8-digit ($R^2 = 0.89$). Monthly flows (1961–1980) were then compared (without further calibration) at Alton, Illinois on the Mississippi River (445,000 km^2) showing a tendency to over predict spring flows but overall timing and magnitude of peaks and recessions matched reasonably well. Monthly steam flow validation (1981–1985) was performed at Alton with an R^2 of 0.65. Comparison of base flow showed that both methods followed the same regional trends. Both methods were comparable to measured base flow for three watersheds in Illinois and to another separation technique. Recharge was the most difficult to validate

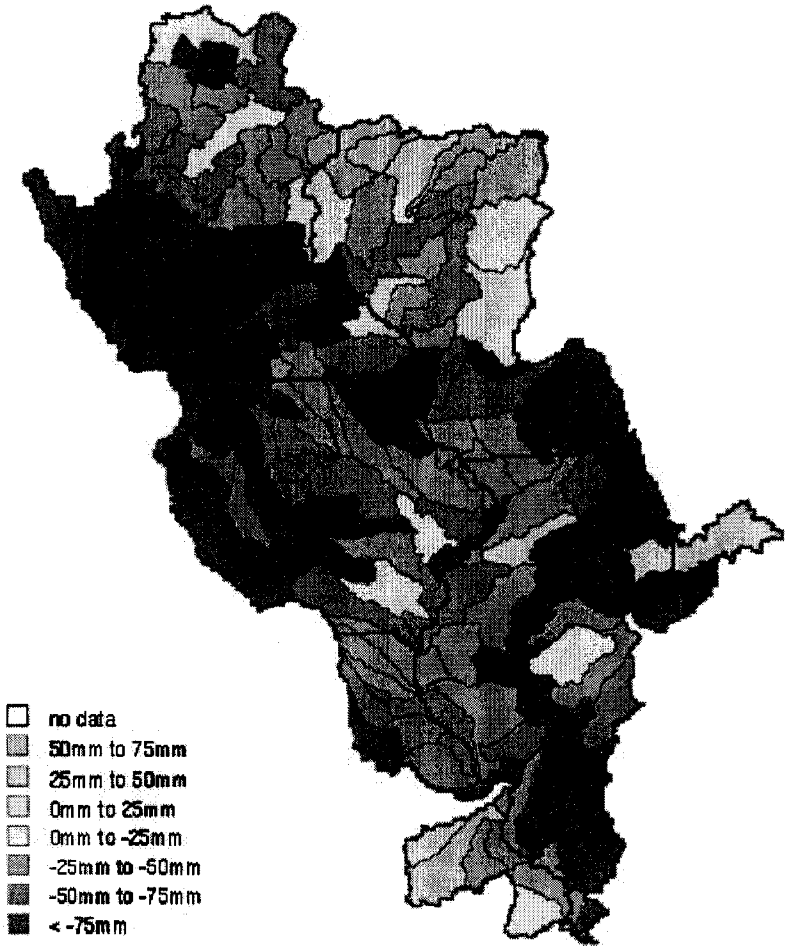

Fig. 14. Difference in SWAT simulated and filtered average annual recharge.

and showed the largest discrepancies between methods. However, general trends were evident and results compared favorably when examining the comprehensive water balance on the three Illinois watersheds.

The advantage of the filter/recession techniques is that they require only daily stream flow and are easy to apply. Models require input data for weather, soils, land use, management, geology, and topography. The advantage of models is in their ability to simulate management and climate scenarios. Climate scenarios include changes in precipitation, temperature, radiation, humidity, and CO_2. Management scenarios include cropping systems, tillage, irrigation, fertilization and reservoir management. Models also consider nutrient and pesticide simulations which may be particularly important in developing strategies for the Gulf of Mexico hypoxia issue.

It is important to simulate the major components of the hydrologic budget to determine the impacts of proposed land management, vegetative changes, groundwater withdrawals, and reservoir management on water supply and water quality. To simulate such management scenarios realistically, a model should be able to simulate the individual components of the hydrologic budget. Unfortunately, most field studies at the watershed scale only attempt to measure one component (i.e. total stream flow, ET, etc.). In this study, the filter/recession techniques were used to assess the components of the water budget model. For large watersheds under short time periods (months to years), this methodology appears to provide

Table 6
Water balance comparison of SWAT 8-digit results and measured data from the three Illinois watersheds

	SWAT 07130009 (average annual)	Measured Goose Creek (1957)	SWAT 07130011 (average annual)	Measured Hadley Creek (1957)	SWAT 07130001 (average annual)	Measured Panther Creek (1952)
Recharge (mm)	217	264	151	99	120	204
ET (mm)	552	536	632	604	561	557
Revap (mm)	48	81	52	22	42	51

additional verification of model parameters and thus aids in model calibration and validation. The inherent problems of such large scale modeling efforts will always be a balancing act between the spatial and temporal variability of the data and the sophistication of the model itself. This research indicates a methodology which should assist in validating such regional scale modeling efforts.

References

Allen, P.M., Arnold, J.G., Byars, B., 1994. Downstream channel geometry for use in planning-level models. Water Resour. Bull. 30 (4), 663 671.

Arnold, J.G., Allen, P.M., 1996. Simulating hydrologic budgets for three Illinois watersheds. J. Hydrol. 176, 57–77.

Arnold, J.G., Allen, P.M., 1999. Validation of automated methods for estimating base flow and groundwater recharge from stream flow records. J. Am. Water Resour. Assoc. 35 (2), 411–424.

Arnold, J.G., Allen, P.M., Bernhardt, G., 1993. A comprehensive surface-groundwater flow model. J. Hydrol. 142, 47–69.

Arnold, J.G., Allen, P.M., Muttiah, R., Bernhardt, G., 1995. Automated baseflow separation and recession analysis techniques. Groundwater 33, 1010–1018.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment. Part I. Model development. J. Am. Water Resour. Assoc. 34, 73–89.

Bauer, H.H., Vaccaro, J.J., 1987. Documentation of a deep percolation model for estimating groundwater recharge. US Geological Survey Open File Report. 86-536.

Berger, D.L., 1992. Groundwater recharge through active sand dunes in Northwestern Nevada. Water Resour. Bull. 28 (5), 959–965.

Bevans, H.E., 1986. Estimating stream-aquifer interactions in coal areas in eastern Kansas by using streamflow records. In: Seymour (Ed.). Selected Papers in the Hydrologic Sciences, US Geologic Survey Water Supply Paper. 2290, pp. 51–64.

Essery, C.I., 1992. Influence of season and balance period on the construction of catchment water balances. J. Hydrol. 130, 171–187.

Finch, J.W., 1998. Estimating direct groundwater recharge using a simple water balance model—sensitivity to land surface parameters. J Hydrol. 211, 112–125.

Gebert, W.A., Graczyk, D.J., Krug, W.R. 1987. Average annual runoff in the United States 1951–1980. US Geological Survey Hydrologic Investigations Atlas HA-710.

Gerhart, J.M., 1984. A model of regional ground water flow in secondary permeability terrain. Groundwater 22 (2), 168–175.

Gerhart, J.M., 1986. Groundwater recharge and its effects on nitrate concentration beneath a manured field site in Pennsylvania. Groundwater 24 (4), 483–489.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture 1, 96–99.

Hauck, L.M., Arnold, J.G., Kruzic, A.P. 1999. Sensitivity analysis of hydrologic and water quality response of a watershed using SWAT, submitted for publication.

Heath, R.C., 1984. Groundwater regions of the United States. US Geological Survey Water Supply Paper. 2242, p. 78.

Holtschlag, D.J., 1997. A generalized estimate of groundwater recharge rates in the lower peninsula of Michigan USGS Water Supply Paper. 2437, pp. 1–37.

Hoos, A.B., 1990. Recharge rates and aquifer characteristics for selected drainage basins in middle and east Tennessee. US Geological Survey Water Resources Investigations Report. 90-4015, p. 34.

Kammerer, P.A. 1995. Groundwater flow and quality in Wisconsin's shallow aquifer system USGS Water Resources Investigations Report 90-4171. Madison, WI, pp. 1–42.

King, K.W., Arnold, J.G., 1999. A comparison of two excess rainfall/runoff modeling procedures on a large basin. Trans. ASAE 42 (4), 919–925.

Knisel Jr., W.G., 1963. Base flow recession analysis for comparison of drainage basins and geology. J. Geophys. Res. 68 (12), 3649–3653.

Krulikas, R.K., Giese, G.L., 1995. Recharge to the surficial aquifer system in Lee and Hendry Counties, Florida. US Geological Survey Water Resources Investigations Report. 95-4003, pp. 1–21.

Lyne, V., Hollick, M., 1979. Stochastic time variable rainfall runoff modeling. Hydrology and Water Resources Symposium Berth, 1979, Proceedings, National Committee on Hydrology and Water Resources of the Institution of Engineers, Australia, pp. 89–92.

Mau, D.P., Winter, T.C., 1997. Estimating groundwater recharge from streamflow hydrographs for a small mountain watershed in temperature humid climate, New Hampshire, USA. Groundwater 35 (2), 291–304.

McCuen, R.H., 1989. Hydrologic analysis and design, Prentice Hall, Englewood Cliffs, NJ, pp. 355–360.

McMahon, T.A., Mein, R.G., 1986. River and Reservoir Yield, Water Resources Publication, Littleton, CO, p. 368.

Memon, B.A., 1995. Quantitative analysis of springs. Environ. Geol. 26, 111–120.

Meyboom, P., 1961. Estimating groundwater recharge from stream hydrograph. J. Geophys. Res. 66 (4), 1203–1214.

Milly, P.C.D., 1994. Climatic soil water storage and the average annual water balance. Water Resour. Res. 30 (7), 2143–2156.

Monteith, J.L., 1965. Evaporation and environment. Symposia of the Society for Experimental Biology 19, 205–234.

Muttiah, R.S., Arnold, J.G., Allen, P.M. 1998. Groundwater recharge mapping using Anuspline thin plate splines. ASAE International Meeting, Orlando, FL. Paper No. 98-3138.

Nathan, R.J., McMahon, A.T., 1990. Evaluation of automated techniques for baseflow and recession analysis. Water Resour. Res. 26 (7), 1465–1473.

Nicks, A.D., 1974. Stochastic generation of the occurrence, pattern, and location of maximum amount of daily rainfall, Proceedings of the Symposium of Statistical Hydrology, Tucson, Arizona, US Department of Agriculture, Miscellaneous Publication No. 1275, pp. 154–171.

Olcott, P.G. 1992. Groundwater atlas of the United States, Segment 9. USGS Hydrologic Investigations Atlas 730-J. Reston, VA, pp. J1–J31.

Olmsted, F.H., Hely, A.G. 1962. Relation between groundwater and surface water in Brandywine Creek Basin, Pennsylvania. US Geological Survey Professional Paper 417-A, p. 21.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Rev. 100, 81–92.

Reay, W.G., Gallagher, D.L., Simmons Jr., G.M., 1992. Groundwater discharge and its impact on surface water quality in a Chesapeake Bay inlet. Groundwater 28 (6), 1121–1133.

Rorabaugh, M.I., 1964. Estimating changes in bank storage and groundwater contribution to streamflow. Int. Assoc. Sci. Hydrol. 63, 432–441.

Rushton, K.R., Ward, C., 1979. The estimation of groundwater recharge. J. Hydrol. 41, 345–361.

Rutledge, A.T., 1993. Computer programs for describing the recession of groundwater discharge and for estimating mean groundwater recharge and discharge from streamflow records. Water Resources Investigations Report 93-4121, p. 45.

Rutledge, A.T., Daniel, C.C., 1994. Testing an automated method to estimate groundwater recharge from streamflow records. Groundwater 32 (2), 180–189.

Sami, K., Hughes, D.A., 1996. A comparison of recharge estimates to a fractured sedimentary aquifer in South Africa from a chloride mass balance and an integrated surface-subsurface model. J. Hydrol. 179, 111–136.

Schicht, R.J., Walton, W.C., 1961. Hydrologic budgets for three small watersheds in Illinois, State Water Surv. Rep. Invest., 40, p. 40.

Sharma, M.L., 1989. Groundwater Recharge, Balkema, Brookfield, VT, p. 323.

Srinivasan, R., Arnold, J.G., 1994. Integration of a basin scale water quality model with GIS. Water Resour. Bull. 30 (3), 453–462.

Srinivasan, R., Engel, B.A., 1991. A knowledge based approach to extract input data from GIS. ASAE Paper No. 91-7045. ASAE Summer Meeting, Albuquerque, New Mexico.

USDA Soil Conservation Service, 1972. National Engineering Handbook. US Government Printing Office, Washington, DC, Hydrology Section 4, chaps 4–10.

USDA Soil Conservation Service, 1992. States Soil Geographic Database (STATSGO) Data User's Guide. Publ. No. 1492, US Government Printing Office, Washington, DC.

USGS. 1990. Land use and cover digital data from 1:250 000 and 1:100 000 scale maps—data user guide 4, Reston, Virginia, p. 33.

Walton, W.C., 1970. Groundwater resource evaluation, McGraw-Hill, New York, p. 494.

White, K., Slotto R.A., 1990. Base flow frequency characteristics of selected Pennsylvania streams. US Geological Survey Water Resources Investigation Report 90-4160, p. 66.

Williams, J.B., Pinder III, J.E., 1990. Groundwater flow and runoff in a coastal plain stream. Water Resour. Bull. 726 (2), 343–352.

Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27, 129–144.

Winter, T.C., 1981. Uncertainities in the estimating of water balances of lakes. Water Resour. Res. 17, 82–115.

Wood, W.W., Sanford, W.E., 1997. Chemical and Isotopic methods for quantifying groundwater recharge in a regional semiarid environment. Groundwater 33, 458–468.

Wu, Jinquan, Zhang, Renduo, Wang, Jinzhong, 1996. Analysis of rainfall-recharge relationships. J. Hydrol. 177, 143–160.