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Effects of Future Precipitation Increases on the Hydrologic Cycle of an Illinois Basin

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ABSTRACT

A key question raised by the increases in precipitation occurring during latter half of the 20th Century over Illinois and the central U.S. concerned the potential effects on the hydrologic cycle. Projections of climate change for the Midwest call for these rain increases to continue into the future, and this study sought to estimate how all components of the hydrologic cycle of a typical Illinois basin would be affected. Most climate change assessments have addressed the impact of the added precipitation on streamflow and flooding of large basins. An existing watershed model that had been developed and calibrated on a well-instrumented small rural basin in central Illinois was used to estimate the distribution of the additional water from three levels of increased summer rainfall simulated to have occurred during actual sequences of recent dry and wet years. Results showed that about half of the added water in all added rain situations percolated into ground water storage, which would have major benefits since most urban and rural water supply systems in central Illinois depend on ground water sources. In dry years, 10% to 15% of the additional water went to transpiration, reflecting crop water use and potential increases in crop yields. In wet years, 35 to 40% of the added water became runoff, whereas runoff in dry years was only 13% to 22% of the added water. The simulated rain increase consisting of a 25% increase on moderate to heavy rain days exhibited the greatest effects on the basin's hydrologic components.

INTRODUCTION

A recent climate study showed that major portions of the United States have experienced temporal increases in precipitation during the past 40 to 80 years (Karl and Knight, 1998). These findings have led to a series of investigations attempting to discern whether the noted precipitation increases, which included heavy rain events, had led to more floods. Flood losses have been steadily increasing over time (Kunkel et al., 1999).

A study of floods and heavy summer rains (>5.1 cm) on major river basins in Illinois during 1921-1980 found a 27% statewide increase in heavy rain days and a 77% average increase in floods (Changnon, 1983). Heavy 7-day rainfall events across the Midwest exhibited upward trends for the 1930-1995 period (Kunkel et al. 1999), and these warm season increases occurred where annual flood events had also increased (Changnon and Kunkel, 1995). Changnon and Demissie (1996) assessed annual streamflow values of four Illinois river basins, and found increases from 1940 to 1990. Increases in precipitation over time accounted for about one-third of the streamflow change, and the remaining change was due to human changes in basin land use.

In summary, these various hydroclimatic studies have defined 1) an increase of warm season rainfall in the Midwest, and 2) increases in streamflow and flooding on large river basins. However, they have not delineated how each of the various components of the hydrologic cycle have been affected by the added rainfall. If the future rainfall increases predicted for the Midwest occur as predicted (National Assessment Synthesis Team 2001), how will the additional water be distributed within the hydrology of a basin?

A watershed model that had been constructed for assessing effects of climate conditions on the hydrologic cycle of a typical Midwestern basin (Durgunoglu et al., 1987) was employed to estimate how three different simulated increases in summer rainfall would alter the various components of the hydrologic cycle.

DATA AND MODEL EVALUATION

A physically-based, quasi-distributed parameter watershed model designed to assess effects of various weather changes on the basin's hydrologic cycle was developed for a central Illinois basin with regionally representative soils and agricultural land use (Durgunoglu at al., 1987). The model could simulate variations in soil moisture, evapotranspiration (ET), infiltration, ground-water flow, and surface flow due to precipitation amounts. Such simulations were calculated using the actual precipitation from several past years, and in turn, those for simulated increases in the actual summer rainfall events. The increases in rainfall assessed were 10% and 25% in the total summer rainfall, and 25% more in the moderate and heavy summer rains. The model operated with variable time steps and hence provided a reliable accounting of water movement over a period of time (Durgunoglu et al., 1987).

The model had been developed and calibrated for a small stream basin (19.8 square kilometers) in central Illinois, the Upper Kaskaskia River Basin. This basin had been chosen for model development because it had long-term records (1949-1989) of precipitation from three raingages, soil moisture measurements of the basin's two different soil types, measurements of ground-water levels from an observation well, and streamgage data. Because of the extensive instrumentation, the model of the basin had been well calibrated. The desirable characteristics of the model included its flexibility, permitting testing against existing hydrologic measurements, and its incorporation of available data on climatic conditions, soils, and crop characteristics. It also had the spatial resolution needed for assessing basins of this size, plus temporal resolutions ranging from annual to hourly increments.

In order to be realistic, the modeling capability also addressed the fact that there is no beginning or ending to the annual hydrologic cycle. In general, evaporated and transpired water condenses in the atmosphere and returns to earth as precipitation. Some of this runs off the surface to water bodies; some infiltrates into the soil and replenishes soil moisture; and excess soil moisture percolates downwards to recharge the groundwater reservoir which in turn feeds lakes and rivers. These processes are typically assessed on a watershed basis. Responses of a watershed to variations in climatic variables can only be meaningfully assessed using a watershed model that adequately describes the temporal movement and distribution of water in the soil-plant-atmosphere interface over sequences of several years, not for just one year.

The modeled basin is in a rural area devoted to the growth of corn and soybean crops, and the two soils of the basin, Drummer (48% of the basin) and Flanagan (52% of the basin), had been well delineated. The surface topography, which was reasonably flat (maximum relief is 33 meters), had also been mapped, and detailed historical crop records existed. The average annual discharge at the basin's outlet is $0.3m^3$/sec. Necessary climatic data input to the model, in addition to the daily precipitation from basin raingages, included air temperatures, wind speeds, relative humidity, and cloud cover, and all were available at a nearby (6 km) weather station. To adjust for rainfall variability, rainfall values used in each part of the basin were those from the nearest of the three gages, and the other weather measures were set the same across the basin. Temperatures, humidities, and winds measured over many years exhibit little spatial variability for areas of this basin size. The entire basin had drainage tiles, a factor that was included in the water distribution model. The model had input defining the drainage pattern including sizes of stream channels throughout the basin. The base of the Wisconsin glacial drift, located 20 to 35 meters below the surface, rested on an impermeable layer, and the ground-water modeling involved assessing the conditions in this thick zone of glacial drift (Durgunoglu et al., 1987).

The watershed model was a hybrid, devised with a modular structure using sub models from several existing models and fusing them together (Durgunoglu et al., 1987). As shown in Figure 1, precipitation, soil moisture, evapotranspiration, infiltration, ground-water flow, and surface flow were all processes treated separately in the model. The model had three major components, one for surface flow, one for soil moisture, and a third for ground water, and each component operated with at least one process to link them to the other components. For example, the surface flow component was linked to the soil moisture component by jointly calculated evapotranspiration and infiltration values. The watershed components were calculated for each of 198 squares, or blocks, as outlined at the base of the diagram in figure 1. Each block in the basin was 400 meters by 400 meters. The model was calibrated for the basin using historical precipitation, streamflow, ground-water, and soil moisture values for 1981-1985 (Durgunoglu et al., 1988).

Verification of the model's performance was conducted using multi-year periods when precipitation was near normal (1981-1985), excessively dry (1951-1954), and much above normal (1972-1975). These calibration tests included comparing the model outputs of soil moisture, ground-water flow, and streamflow values with actual measured values. These tests were performed before assessing the effects of simulated added rainfall. Outputs from the model's soil moisture component, which had 32 soil moisture parameters, were calibrated using the two sets of soil moisture data from within the basin. Figure 2 presents the comparative soil moisture values obtained for three years on one of the basin's two soil types. The model-estimated values for both soil types closely followed the actual in-field soil moisture values from the beginning year throughout the total test time of three years. The average difference between modeled and actual values was only 1.3 cm, less than 2%.

The ground-water component (Fig. 1) was a fully distributed parameter sub-model and its inputs for each soil type included the coefficient of permeability, the storage coefficient, land elevations, thickness of the impermeable layer, and drainage tile information (Durgunoglu et al., 1987). In relatively flat watersheds like the one assessed, streamflow consists mainly of ground-water infiltration and tile drainage (runoff). Therefore, ground-water levels are a good indicator of the streamflows and total soil moisture. The total soil moisture and deep percolation (seepage) values, as calculated for one soil type during 1982-1984, are illustrated in Figure 3. Comparison of the soil moisture and seepage values with the ground-water levels in the basin's well site (bottom diagram) reveals a close relationship.

Observed and estimated daily streamflow values, as determined from the daily percolation values, for the three test years are shown in Table 1. The model-estimated flows were slightly more, by 2 to 9 percent, than the actual observed values in the three test years, indicating that the model's estimates were quite representative.

Model verification was also pursued for conditions more extreme than those in the 1981-1985 period. One period covered very dry conditions during 1952-1954 (driest of the 1949-1989 period), whereas the other period covered the four wettest years, 1972-1975. The observed and estimated daily streamflow values, and the annual precipitation totals, for these eight years appear in Table 2. Comparison reveals that in 6 of the 8 years, the estimated flow differed by less than 9 percent of the observed flow. The average annual difference was 7.7%. Figure 4 illustrates the estimated and observed daily flow distributions for 1953 and 1973. Streamflow estimates for 1953, a dry year, show a close relationship of the estimated with the observed values, and in 1973, a wet year, the relationship is also quite close, particularly in the critical summer months. The correlation coefficient of the two summer sets of values was +0.91, significant at the 1% level. These various comparisons revealed that the model did an excellent job of defining the hydrologic components of the basin in extremely dry and wet years, as well as in years with near normal precipitation.

EFFECTS OF MORE RAINFALL

The effect of added summer rainfall was based on simulating three types of changes to the actual daily rainfall amounts from selected sequences of years during 1950-1990. This approach retained the distribution of the actual rain-producing conditions and did not create additional rain days. Most climatic studies have found small or no temporal increases in the number of rain days, only increases in amounts (Karl and Knight, 1998). The assessment of the effects of added summer rainfall was performed using data from 1951-1954, the 41-year period's driest multi-year period, and for 1972-1975, the wettest multi-year period in the basin.

The rainfall changes were selected to match the reported magnitudes of increases found in most climate records for the Midwest since 1950 and those apt to occur in the future. They included: 1) a 10% rain increase on all rain days, 2) a 25% rain increase on all rain days, and 3) a 25% increase in days when actual amounts were in excess of 63 mm. For each of the levels of rainfall change, model calculations were performed, and a summary was developed describing the distribution of the added rainfall among various hydrologic components over time. The added rainfall associated with these changes could become runoff into the basin's streams, evaporation from the surface or shallow soil layers, infiltration into the soil and later be used by plants to become transpiration, or remain in the soil and percolate down to the ground water table. For each year, the modeled values for each level of changed rainfall were compared with those based on the actual rain that fell.

A detailed summary was then developed for each year showing the disposition of the added water in the various components of the hydrologic cycle. The primary values examined for each year, and each soil type, included the total transpiration (the crop water use), the total evapotranspiration, total surface runoff, and total deep percolation. Selected results for one year on one of the two soil types are shown in Table 3. In this year (1951) the various rainfall increases produced no differences in the evapotranspiration and transpiration amounts, but had differing effects on the amounts of deep percolation and runoff.

The annual values derived for the four dry years (1951-1954) of both soil types were averaged as were the values for the four wet years (1972-1975). The areal extent of each soil type was accounted for in determining these averages. The resulting basin-wide averages, as calculated for each of the three rain increases tested, are shown in Table 4. For example, at the 10-percent level of rain increase, the 4-year evapotranspiration values in the dry years averaged 18 percent of the total water added by the rain increase, and 49 percent of the added water percolated into the ground water. The three sets of rain increase values for the four wet years reveal no difference related to the type of rain increase in the amount of evapotranspiration and amount of transpiration. This is similar to the outcome for 1951 (Table 3). All values were small percentages, ranging from 3 to 5 percent. As the rain increase grew in the wet years, the amount of added water going into percolation decreased from 57 percent (10% more rain) to 52% (25% more on heavy rain days). Conversely, as the rain increase grew, the amount of water going to runoff increased from 35% to 39%. The outcomes for wet years are not surprising but the important findings are identification of the magnitudes of each component.

Comparison of the values for the four dry years also revealed little difference in the amount of water going to transpiration and evapotranspiration, but the highest percentages of both were with the 25% increase in heavy rain days. Evapotranspiration accounted for 15% to 18% of the additional water. Percolation increased as the rain increase went up, from 49% to 54%. As would be expected, the amount of runoff from the added water decreased as the rain increase grew.

Comparison of the dry year and wet year percentages, as illustrated by the wet-dry differences in Table 4, reveals the percolation to ground water of the added water is the largest value for both extremes, generally ranging from 50 to 60 percent of the additional rain water. Percolation was slightly greater for the wet years. Such ground-water additions would have considerable value in Illinois because most rural and urban water supplies are dependent on ground water.

Water going to runoff is the second largest amount for both wet and dry years. As would be expected, much more of the added water went to runoff in the wet years, 13 to 26% more. This is realized in added streamflow and may reflect an increased potential for flooding.

The amount of added water going into transpiration, which is indicative of crop water use, is very small for the wet years, 3 to 5%. In the drier years, the transpiration amounts shift upward, becoming 11 to 15%, indicative of value to the basin's crop production. The results agree with findings based on use of crop yield-weather models to assess increases in Illinois corn yields from rains increased by cloud seeding. Summer rain increases of 25% were found to be associated with corn yield increases ranging from -3% to 2% (wet summers) and being 11% to 18% in dry summers (Huff and Changnon 1972).

SUMMARY AND CONCLUSIONS

A water balance model developed for a central Illinois watershed that had extensive 41-year measurements of precipitation, soil moisture, ground-water levels, and streamflow, was used to define all basin's hydrologic components and their responses to varying precipitation amounts. Simulated increases in summer rainfall, selected in accordance with climatological findings showing 10 to 25% increases, were used to estimate the distribution of the additional water within the hydrologic cycle. The broader goal was to gain a perspective of how future climatic shifts that are expected to include more rainfall (Working Group One, 2001) would potentially influence the hydrologic cycle of Midwestern stream basins.

The model output verified well with average and extreme summer precipitation conditions. Three levels of rainfall change (+10%, +25%, and +25% on moderate to heavy rain days) were simulated in the model for runs of four dry years and four wet years to measure the distribution of the added water under extreme conditions. Results revealed that for both types of years, between 49% and 57% of the added water percolated into the basin's ground-water system. Runoff was increased between 20% and 40% with much more occurring in the wet years, as expected. Amounts of water transpired, indicative of crop water use, varied considerably between wet and dry years. In the wet years only 3% to 5% of the additional water was transpired, but in dry years, transpiration ranged from 11% (10% rain increase) to 15% (25% increase in heavier rains) of the additional water. These shifts in crop water use match well with findings from earlier studies based on crop yield-weather models for this area (Changnon and Winstanley 2000). The values for evapotranspiration, transpiration, and percolation, as determined for the 25% rain increase on heavier rain days and in dry years, exceeded those for the other two rain increases tested (Table 4). In wet years, the 25% increase in heavier rain days produced the largest runoff value, and collectively these results indicate that this type of change in summer rains would have the largest overall impact on the hydrologic components of a small basin.

If summer season rain increases persist and become a part of future climate conditions, these results indicate the major benefit of the additional water will occur in ground-water supplies. This has substantial importance since much of the region's urban and rural water supplies are derived from ground water. There is also strong evidence that crop yields would be measurably enhanced in drier future summers.

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Table 1. Estimated and observed total streamflow values for Water Years of 1983-1985.

Water Year	Total streamflow, centimeters Estimated	Observed	Difference, as a percent of observed
1983	42.1	39.5	6.5
1984	45.6	44.7	2.0
1985	26.1	23.9	9.2

Table 2. Estimated and observed annual streamflow values and basin-average precipitation amounts for extreme years.

Year	Precipitation, cm	Streamflow, cm Estimated	Observed	Difference Percent of Observed
Dry period				
1951	97.5	37.2	39.3	5.3%
1952	86.0	30.1	27.8	8.2%
1953	66.3	13.6	11.7	16.2%
1954	75.4	4.8	5.0	4.0%
Wet period				
1972	109.1	40.8	36.3	12.3%
1973	125.0	53.8	55.3	2.7%
1974	110.7	51.7	55.8	7.3%
1975	116.6	31.6	30.4	3.9%

Table 3. Model-based calculations of the annual values of the hydrologic components for 1951 and for the Flanagan Soils in the Upper Kaskaskia River Basin. Values are in centimeters.

Process	Rain increases[1] No increase	10% increase	25% increase	25% increase heavy rains
Precipitation	97.5	99.7	102.98	101.4
Evapotranspiration	62.8	63.0	63.0	63.0
Transpiration	35.5	35.6	35.6	35.6
Deep percolation	25.5	26.7	28.3	29.2
Surface runoff	4.8	5.7	7.3	5.1

[1]Increases shown were to summer (J-A) rainfall which was 22.1 cm in 1951.

Table 4. Comparison of 4-year average values of water dispositions for wet and dry years, expressed as a percent of the total water, for the three levels of summer rainfall increases.

	10-percent increase			25 percent increase			25 percent increase In heavy rain days		
	Dry years	Wet years	Difference W-D	Dry years	Wet years	Difference W-D	Dry years	Wet years	Difference W-D
Evapotranspiration	18	5	-13	15	4	-11	18	4	-14
Transpiration	11	3	-8	12	4	-8	15	5	-10
Percolation	49	57	8	50	54	4	54	52	-2
Runoff	22	35	13	23	38	15	13	39	26

Figure 1. Components of the watershed model showing the inputs, outputs, and interactive processes (from Durgunoglu et al., 1987).

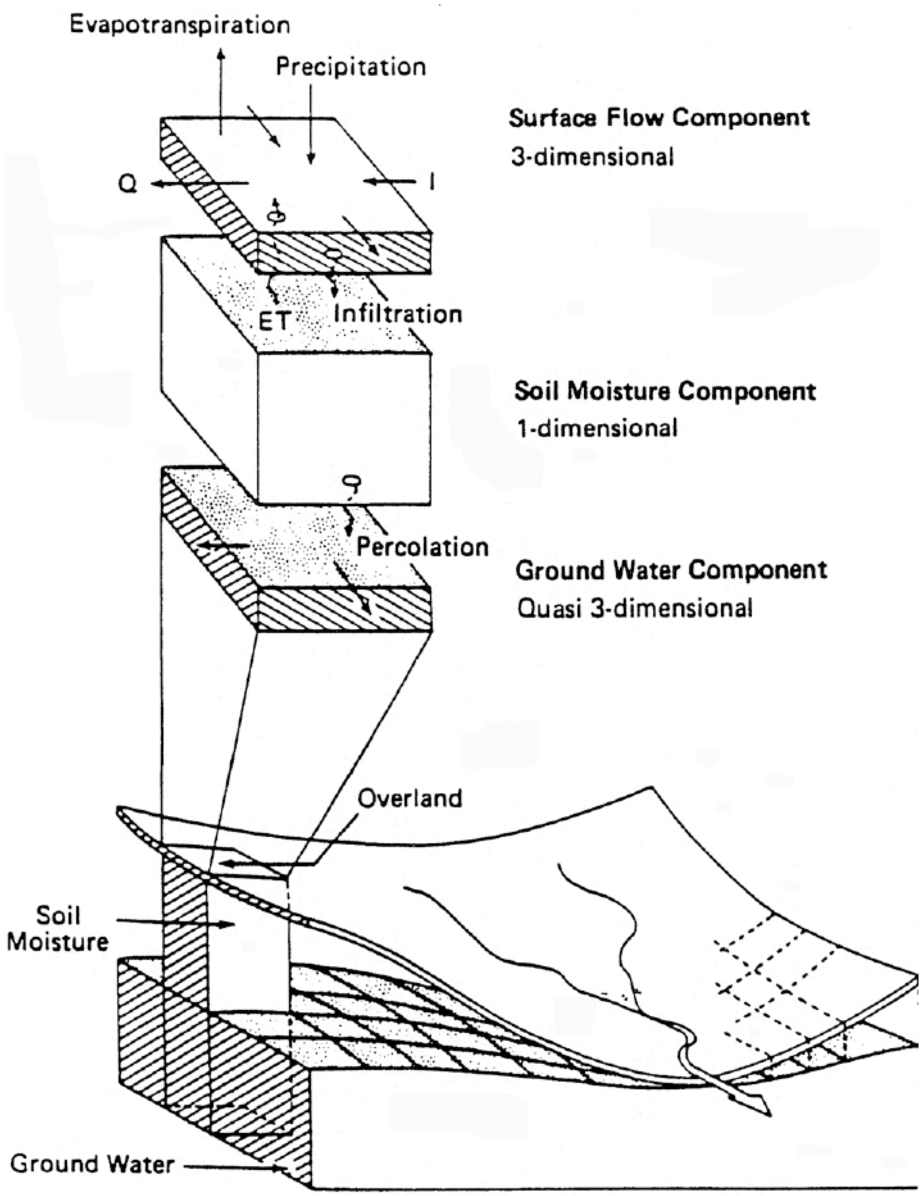

Figure 2. Estimated and observed total soil moisture values for Drummer soils in the Upper Kaskaskia River Basin for three test years.

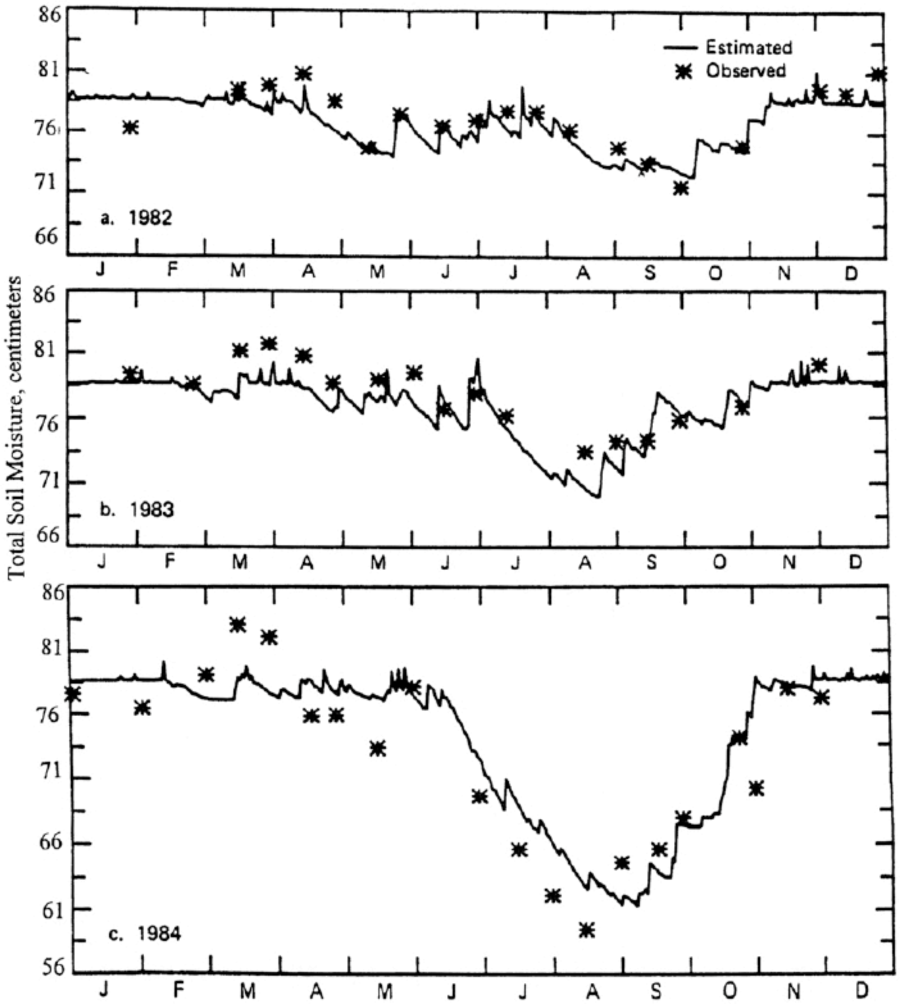

Figure 3. Estimated total soil moisture, estimated seepage (percolation) for the Flanagan soils and the ground-water elevations for the Upper Kaskaskia River Basin.

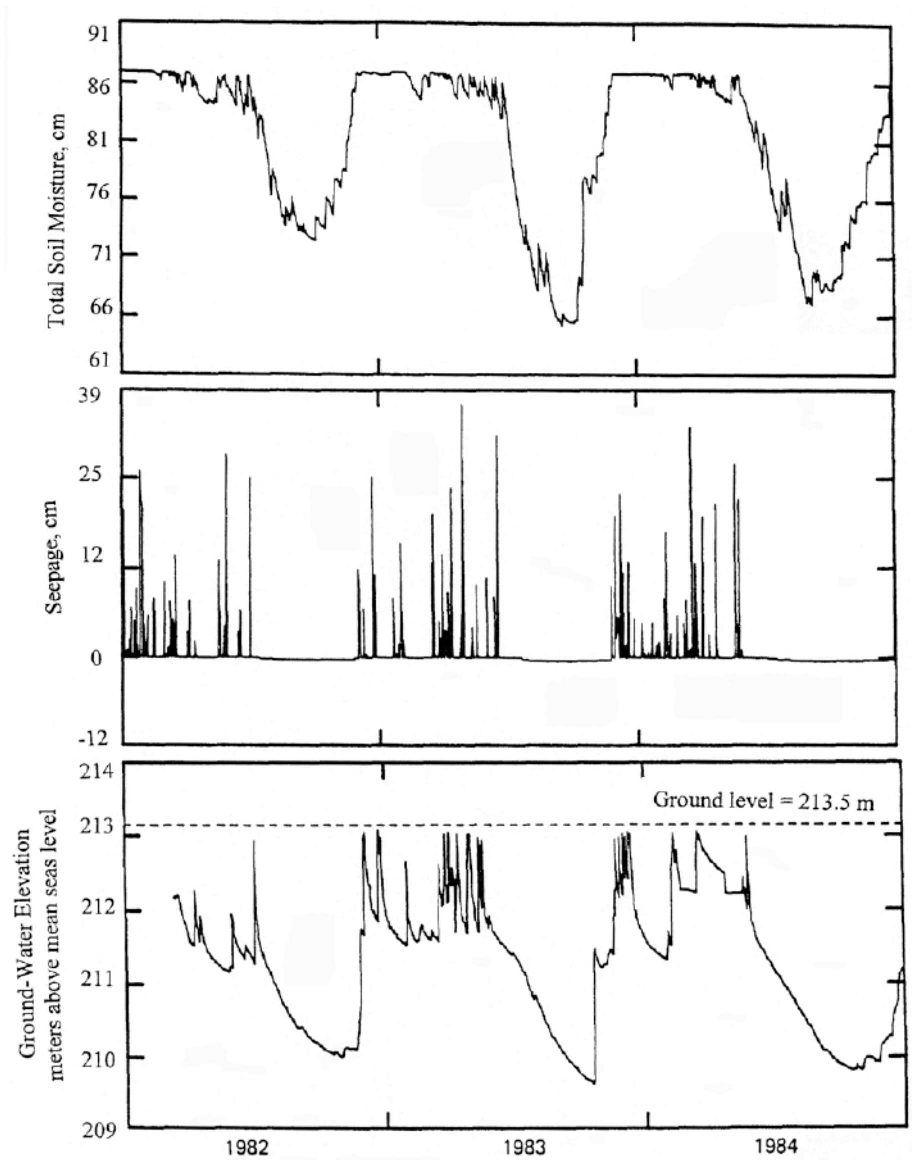

Figure 4. Observed and estimated streamflows for the Upper Kaskaskia River Basin in 1953 (upper) and 1973 (lower).