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Research Report

Using Datasets from the Internet for Hydrological Modeling: An Example from the Küçük Menderes Basin, Turkey

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and
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International Water Management Institute

Research Reports

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Contents

Summary

Increased competition for water will be amongst the most important issues of the next few decades. As a result, water scarcity for agriculture and the resulting problem of food security must be addressed. Hydrological modeling can be used to assess basin water resources and to study alternative water allocations amongst competing demands. Such modeling endeavors usually require a large amount of data. Conventionally, government departments maintain such data and, in many countries, these can be difficult to obtain due to bureaucratic constraints. Furthermore, cutbacks in government budgets in recent years have resulted in reductions in the data collection network, in data quality, and in increased processing time.

Public domain datasets have become increasingly available on the internet. These data are free, easy to obtain, and often more up-to-date than those from local sources. These data can be used as inputs into hydrological models. This simplifies the modeling process and increases our ability to model basins anywhere in the world, from anywhere with internet access. Although not all types of data are available and some conversions may be needed, the information provided does allow for quick and easy simulations of basins.

The SLURP (**S**emi-Distributed **L**and-**U**se **R**unoff **P**rocess) hydrological model has been designed to take advantage of such data sources. This report describes the application of the model to the Küçük Menderes Basin in western Turkey using public domain data from the Internet for topography, land use, seasonal variation in leaf area index (for transpiration), and climate data—all without calibration of parameters.

The model was verified using locally available monthly streamflows. For 3 out of 4 years, the simulated streamflow agrees well with the recorded data but for the fourth year the agreement is poor. However, the recorded data for that year have not been quality-controlled by the producer and they do not follow the recorded precipitation pattern. On these grounds, we believe the model is performing well and is able to simulate the hydrology of the basin.

To demonstrate the usefulness of such a quickly derived model we investigated the possible behavior of a large dam and reservoir planned to supply water for a new irrigation scheme. The model showed that the planned reservoir would be unable to satisfy the total water demands of the irrigation scheme.

The application is an example of how public domain data from the Internet could be used for water-resources planning in basins around the world.

Using Datasets from the Internet for Hydrological Modeling: An Example from the Küçük Menderes Basin, Turkey

Martin Lacroix, Geoff Kite, and Peter Droogers

Introduction

Distributed hydrological models are often used to investigate basin water resources. Such models generally require a large amount of data, which are not always available in developing countries. However, global datasets of climate data (including the International Water Management Institute's World Water and Climate Atlas) are becoming increasingly available and data from the Internet can often be substituted for ground-based data. The Semi-Distributed Land-Use Runoff Process (SLURP) hydrological model has been designed to take advantage of such data sources (Kite 1997) for simulation of basin hydrology and water resources development.

The first objective of the study was to see if a hydrological model could successfully simulate the hydrology of a river basin using only data from the Internet. As an example, the model was used to simulate the Küçük Menderes Basin in western Turkey (figure 1). The Küçük Menderes River, approximately 107 km long, has a drainage area of 3,617 km^2 and flows from east to west into the Aegean Sea, just south of Izmir, in western Turkey. The average total annual precipitation in the basin, as derived by the stations used in this study, is about 570 mm/yr., and the mean annual temperature is 16.7 ^{0}C. Precipitation occurs mainly in the winters while during the summer irrigation period there is very little rain.

The second objective of the study, assuming successful completion of the first objective, was to investigate, as an application of the model, a new reservoir and irrigation scheme proposed for the Küçük Menderes Basin. A reservoir at Beydağı is planned for development by the Government of Turkey to provide water for an 18,200-hectare irrigation scheme. Using data provided by the Government of Turkey, the SLURP model was used to simulate the performance of this reservoir and irrigation scheme.

The study demonstrates IWMI's remote sensing and modeling capabilities and shows how studies on basin water resources can be conducted using public domain datasets.

Method

The following paragraphs give a brief description on how the digital elevation model (DEM) was prepared, how a land cover image was created, and how climate data were taken from the Internet. Appendices A, B, and C explain in more detail how each task was performed.

FIGURE 1.
Map of Turkey showing the location of the Küçük Menderes Basin.

Definition of the Basin, Subbasin, and Physiographic Characteristics

In order to route water down a basin, the SLURP model needs information on the distribution of distances and changes in elevation for each point in the basin. For the Küçük Menderes Basin we used the United States Geological Survey (USGS) public domain digital elevation database (DEM) GTOPO30 from the Internet[1][1] to define the basin, subbasins, elevations, and distances needed for the hydrological model. Other global DEMs such as GLOBE (Hastings 1996) are also available.

The United States Department of Agriculture/ University of Saskatchewan's digital terrain analysis model (TOPAZ) (Garbrecht and Martz, 1997) was used to process the 30 arcsecond (approximately 1 km) resolution GTOPO30 DEM.

The number of subbasins in the basin is determined from TOPAZ by specifying two parameters, the critical source area (CSA) in hectares, and the minimum source channel length (MSCL) in meters. A continuous drainage network is delineated by selecting cells with a drainage area that exceeds the specified CSA value and additional pruning of the network is performed to eliminate extraneous links that are shorter than the specified MSCL.

Table 1 shows the number of subbasins produced using various combinations of CSA and

[1]Digits within square brackets, as [1], [2], etc., refer to Internet literature cited, given at the end of this report.

TABLE 1.
Number of subbasins generated by manipulating user-specified CSA parameter.

CSA (ha)	MSCL (m) (ASAs)	Number of subbasins
50,000	1,000	5
40,000	1,000	5
30,000	1,000	5
20,000	1,000	9
15,000	1,000	9
14,000	1,000	11
13,000	1,000	11
12,000	1,000	11
11,000	1,000	15
10,000	1,000	17
5,000	1,000	41

MSCL values. Based on past experience, it was decided to use 12 subbasins for the SLURP simulations. Running TOPAZ with a CSA value of 14,000 hectares produced 11 subbasins. A further run of TOPAZ was used to create another subbasin for the proposed Beydağı reservoir at the eastern end of the basin. In the SLURP model, subbasins are known as Aggregated Simulation Areas (ASAs).

Any topographic analysis is only as accurate as the input data used and it is always important to check the logic of the derived basin and stream network. In this case, the initial results from TOPAZ showed a subbasin at the western end of the basin, which did not agree with other sources of information such as the stream network included in Encarta (Microsoft 1998). Inspection of the DEM showed that the resolution was not adequate to show the divide between two basins and confirmed that a portion of the westernmost subbasin should be removed from the DEM of the Küçük Menderes Basin. One kilometer is a convenient scale for a global DEM but we have found that averaging elevations over 1 km^2 will often miss narrow gorges or narrow watershed divides. The USGS is now developing a hydrologically corrected version of GTOPO30 known as HYDRO1K [2] that will reduce this problem.

Figure 2 shows the topographic map and stream network derived by TOPAZ from

FIGURE 2.
Topographic map and river network of the Küçük Menderes Basin.

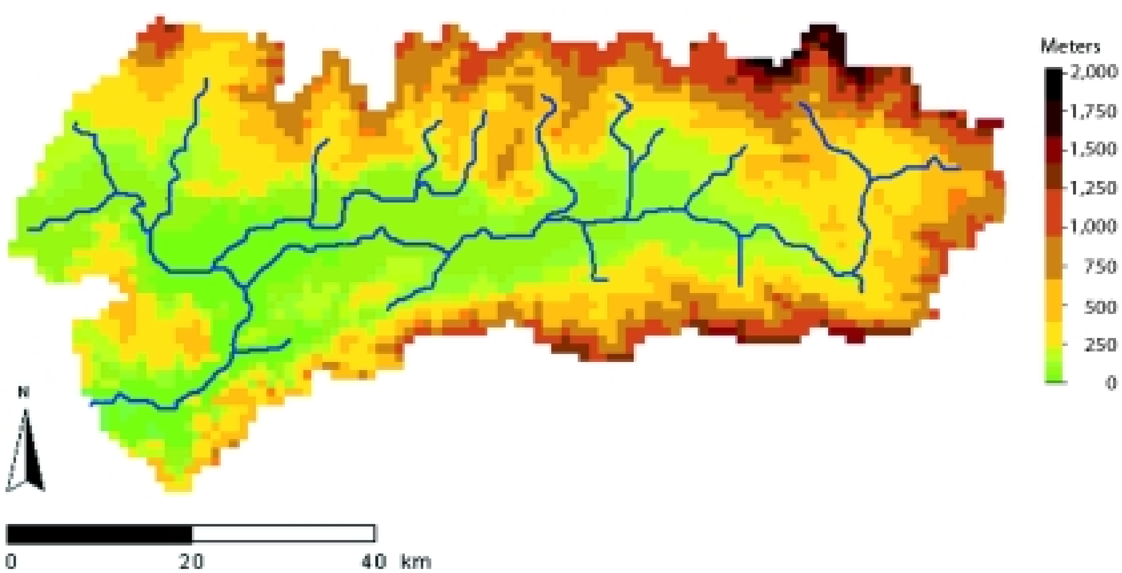
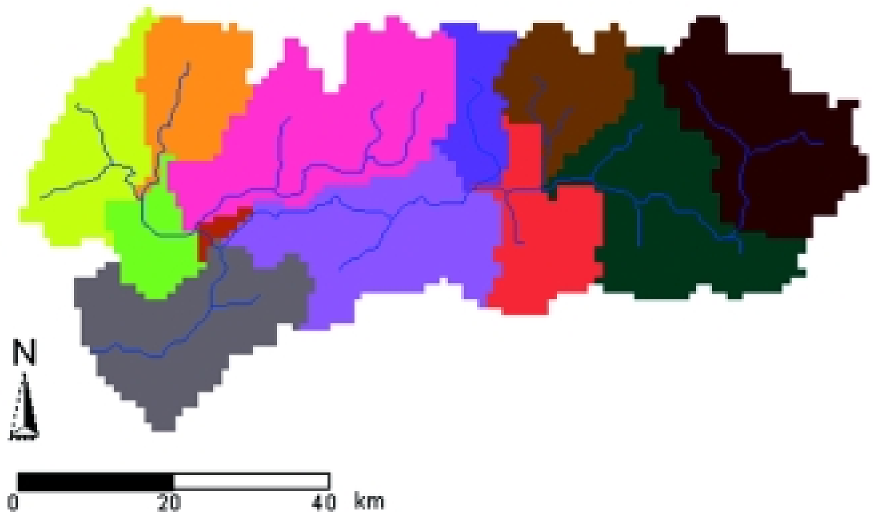


FIGURE 3.
Subbasins determined from topographic analysis of the USGS DEM.



GTOPO30 while figure 3 shows the layout of the subbasins.

Derivation of Land Cover Classification

The SLURP model carries out a vertical water balance for each land cover within each subbasin separately and, therefore, it needs information on the distribution of the various land covers within the basin. In many cases, local land use maps are available but for the Küçük Menderes Basin our objective was to use data available on the Internet.

There are several global land cover classifications available. For example, the USGS 1 km land cover [3] divided the entire globe into 24 land classes. However, a previous study in western Turkey (Droogers, Kite, and Bastiaanssen 1998) has shown this classification to be inappropriate for this area, and so we decided to derive our own land cover map from public domain data. Following the procedure used for the nearby Gediz River Basin (Droogers, Kite, and Bastiaanssen 1998) we derived the land cover classification using 1 km resolution US National Oceanic and Atmospheric Administration (NOAA) satellite images with the Advanced Very High Resolution Radiometer (AVHRR) sensor from the Internet [4] together with a DEM. The AVHRR images are freely available and have the advantages of being radiometrically calibrated, atmospherically corrected, and geometrically registered. These types of data have been used successfully in the past to derive ecologically homogeneous land units (Maselli et al. 1996).

We used three data types to derive the land use composite map of the area:

- the temporal variation in land cover
- the spatial variation of land cover at one particular time
- information on the variation of land cover with basin physiography

We derived the temporal variation in land cover using near-infrared data from eight images from February to October 1995. Principal components analysis using the TSA module in the IDRISI geographical information system (GIS) (Eastman 1997) was used to derive an image of the most important components.

The spatial variation in land cover was defined by using normalized difference vegetation indices (NDVI) derived from an August 1995 NOAA AVHRR image. The August NDVI image was selected since it showed the greatest variation in NDVI across the image.

The physical environment was included by using the USGS DEM described earlier to represent variation in elevation of the basin.

A composite image was prepared using the result of the time series analysis of the near-infrared images, the NDVI image for August, and the DEM, and this was used in an unsupervised classification procedure. This procedure enables users to uncover or classify land cover differences where field verification is impractical or when information about expected land covers is lacking. The classes identified can then be assigned to land covers using information from other areas or by field verification.

The unsupervised classification of this composite image was carried out using the CLUSTER module in IDRISI. As in the Gediz study, a simple linear stretch and seven clusters gave satisfactory results providing seven land cover types (Droogers, Kite, and Bastiaanssen 1998). Figure 4 shows the procedure used in the analysis.

Figure 5 shows the resulting spatial distribution of land cover types within the Küçük Menderes Basin, and table 2 lists the percentage of each land cover type within the basin.

FIGURE 4.
Procedure to derive the land cover map for the Küçük Menderes Basin.

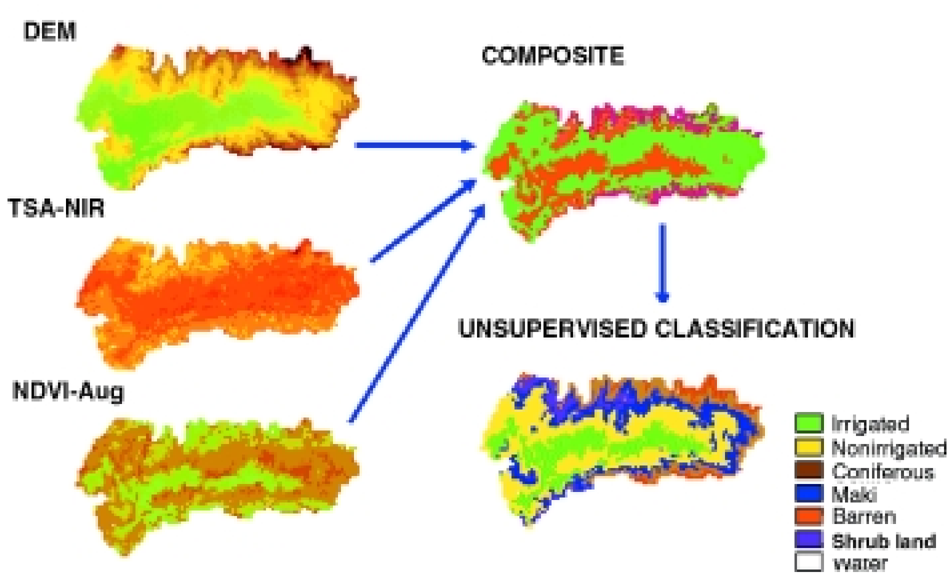


FIGURE 5.
Land cover map of the Küçük Menderes Basin.

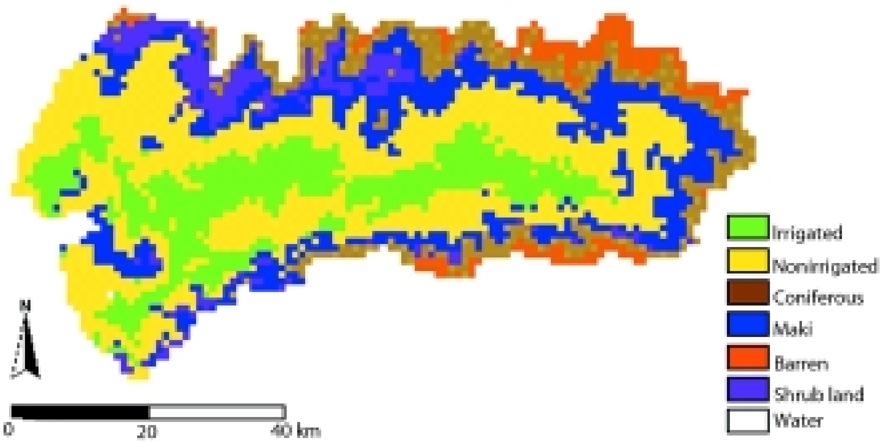


TABLE 2.
Land cover classes and percentages of the basin area.

Land cover class	Area %
Irrigated	18.9
Nonirrigated	37.8
Coniferous	11.7
Maki	19.9
Barren	5.3
Shrub land	6.3
Water	0.1

The physiographic outputs from TOPAZ together with land cover data, river routing information (assumed widths, depths, and roughnesses for each Strahler stream number), and climate station coordinates were analyzed using the SLURPAZ interface program (Lacroix and Martz 1997) to produce input files for the SLURP hydrological model. These input files include information on basin and subbasin areas and elevations, land cover percentages within each subbasin, distances and changes in elevation both to stream and downstream, and the sequence of flows from subbasin to subbasin. Figure 6 shows the data flow.

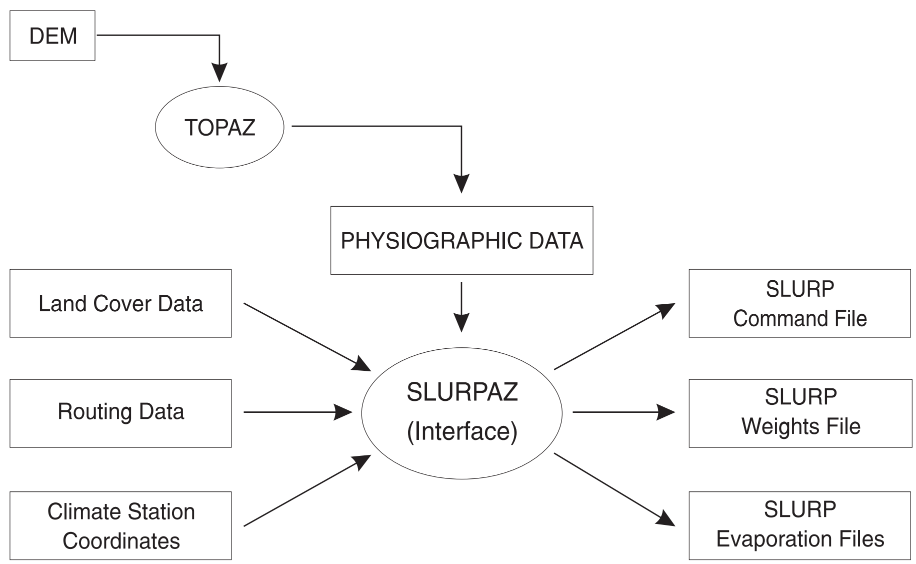
Obtaining Climate Data

The SLURP model requires precipitation, temperature, humidity, and radiation data for each subbasin in the basin. Conventionally, these would be obtained from the government departments of the country concerned. In this case, however, in line with our objective we obtained the climate data from public domain datasets available on the Internet.

Two global climate databases are available online from the US National Climate Data Center (NCDC). The first, Global Daily Summary (GDS) [6], contains daily precipitation and maximum and minimum temperatures for 10,000 stations worldwide for the period 1977 to 1991 (also available from IWMI [10] and USDA's Hydrolab [12]). The second, NCDC dataset, Global Surface Summary of the Day (GSOD) [7], contains 13 daily parameters including precipitation, temperature, dew point, and wind velocity for 8,000 global stations for the period 1994 to date. This database is updated each month and is also available from the University of Miami [8].

There is also a website for Med-Hycos [5], an organization with climate data for stations around

FIGURE 6.
Flowchart of the physiographic analysis programs.



the periphery of the Mediterranean. However, these data are available only from the subscribing governments. Global datasets derived from climate models are also available on the Internet such as those provided by the University of East Anglia on behalf of the International Panel for Climate Change (IPCC) [9].

Table 3 compares the periods of record available from GDS and GSOD for the stations closest to the Küçük Menderes Basin and figure 7 shows the station locations relative to the Küçük Menderes River. Note that none of the stations available from GDS/GSOD are within the basin; one station is on the Greek island of Samos while the other three are on the Turkish mainland. The distribution of the stations is far from ideal; all are located at low elevations and, therefore, they may not be good representatives of climatic patterns in the higher, eastern end of the basin.

For the Küçük Menderes Basin, it was decided to use data from October 1994 to September 1998 for the stations at Samos, Menderes, and Aydin from the GSOD dataset. Çiğli was eliminated because of missing data. A program was written to extract the data from the GSOD database for the required stations and convert the data back to metric units. Since no data on radiation or sunshine hours are available in GSOD, we estimated the ratio of observed sunshine hours to potential sunshine hours from the daily precipitation data. Days with more than 25 mm were assumed to be totally sun-free and days with zero precipitation were 100 percent sunshine while days with 0.25 precipitation would have proportionate hours of sunshine. These approximations have been used in other studies (Kite, Danard, and Li 1998) but no sensitivity analyses have been performed.

It is also possible to use the IWMI Atlas Synthesizer [10] to derive GDS and GSOD daily climate data for selected regions (see appendix C).

TABLE 3.
Climate stations from GDS/GSOD close to the Küçük Menderes Basin.

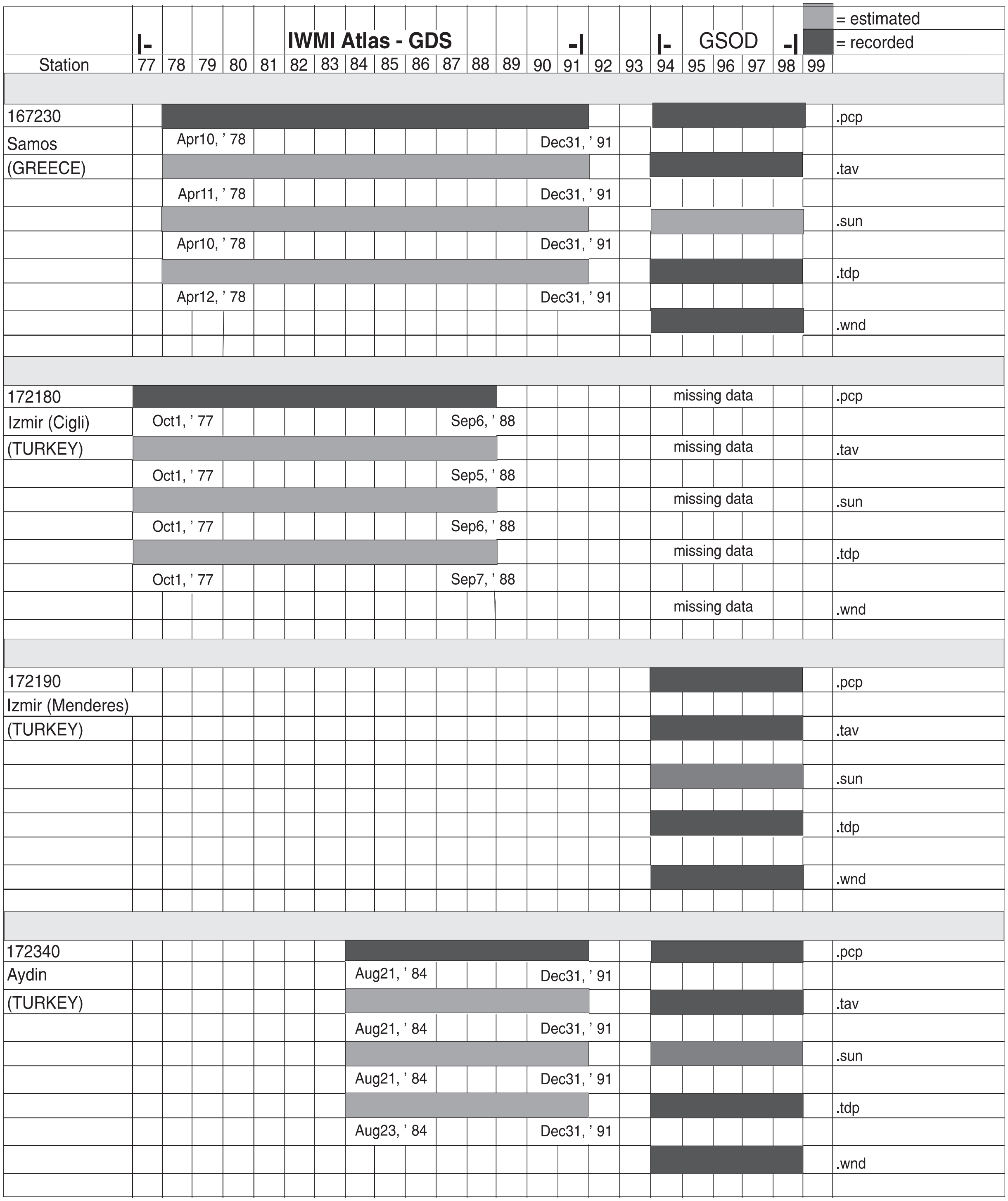
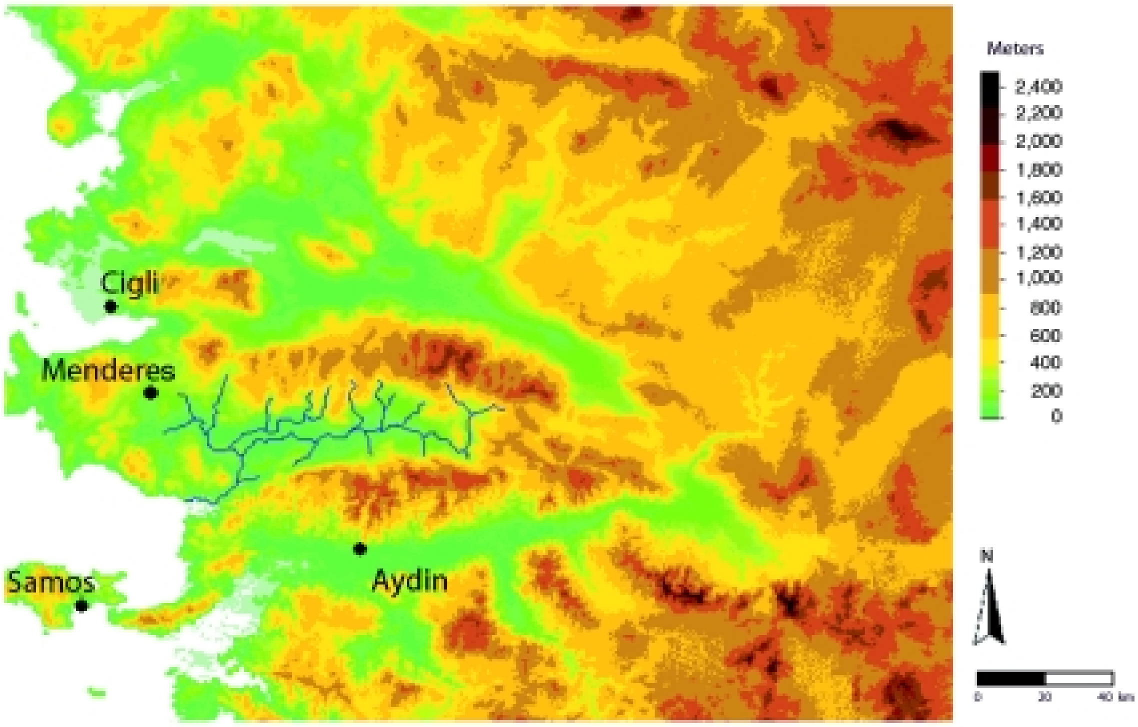


FIGURE 7.
Locations of climate stations closest to the Küçük Menderes Basin.



Running the SLURP Model

SLURP is a hydrological basin model that simulates the hydrological cycle from precipitation to runoff including the effects of reservoirs, regulators, water extractions, and irrigation schemes. It divides the basin into subbasins on the basis of topography. These subbasins are further subdivided into areas of different land classes. In the SLURP model, the parameters are related to the land covers used. If the model is applied to a basin with a land cover that has not been used before, then the parameters must be estimated. In this case, the model had previously been applied to a nearby basin (Kite and Droogers 1999) and we were confident in transferring the parameters for comparable land covers from that basin (table 4).

The hydrological model simulates the vertical water balance for each land cover within each subbasin at a daily timestep. Each element of the subbasin/land cover matrix is simulated by four nonlinear reservoirs or tanks representing canopy interception, snowpack, fast storage, and slow storage (figure 8).

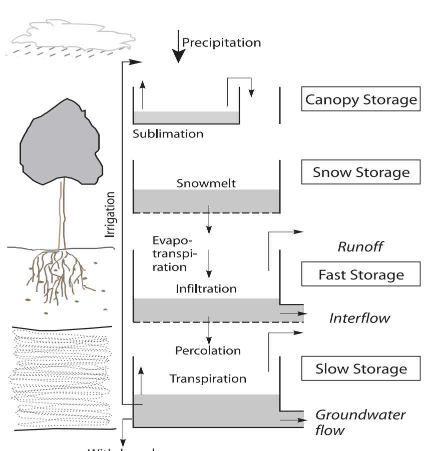
Precipitation data for each subbasin were derived from the three meteorological stations using nearest neighbor algorithms within SLURPAZ and then adjusting to the mean elevation of each land cover using a 5 percent

TABLE 4.
Model parameters for each land cover.

Parameter	Maki	Nonirrigated cropland	Coniferous	Irrigated	Shrub land cropland	Barren land	Water
Initial contents of snow store (mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Initial contents of slow store (%)	5.0	5.0	5.0	7.0	7.0	5.0	50.0
Maximum infiltration rate (mm/day)	89	171	93	174	140	92	200.0
Manning roughness, n	0.0678	0.027	0.057	0.059	0.031	0.001	0.0
Retention constant for fast store	3	41	4	20	21	45	1.0
Maximum capacity of fast store (mm)	448	473	226	489	300.0	199	0.0
Retention constant for slow store	9,019	8,609	6,339	8,986	7,000	5,487	100,000
Maximum capacity of slow store (mm)	5,725	6,352	2,290	9,252	7,611	9,060	100,000
Precipitation factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rain/snow division (°C)	0.0	0.0	0.0	0.00	0 0	0 0	0 0

increase per 100 m rise in elevation with a maximum possible change of 50 percent above that recorded.

FIGURE 8.
Vertical water balance of a subbasin/land cover element (Kite 1997).



The evapotranspirative demand for each land cover in each subbasin was calculated using the Food and Agriculture Organization's (FAO) version of the Penman-Monteith method (Verhoef and Feddes 1991):

$$\lambda \cdot ET = \frac{s(Q^* - G)}{s + \gamma(1 + \frac{r_s}{r_a})} + \frac{\rho_a c_p \frac{e_s - e_a}{r_a}}{s + \gamma(1 + \frac{r_s}{r_a})} \qquad (1)$$

where, λ is the latent heat of vaporization, *ET* is the potential transpiration rate (mm), *s* is the slope of the vapor pressure curve, *Q** is the net radiation, *G* is the soil heat flux, γ is the psychrometric constant, r_a is the aerodynamic resistance, r_c is the crop resistance, e_s is the saturated vapor pressure, e_a is the actual vapor pressure, ρ_a is the air density, and c_p is the heat capacity of moist air.

The evapotranspirative demand will be met by evaporation from intercepted precipitation stored on the canopy, from soil evaporation, and from crop transpiration.

The canopy capacity is computed by multiplying a specified maximum depth of water on a leaf by the leaf area index (LAI) for a particular crop and date. The LAI data are derived from NDVI obtained from NOAA AVHRR satellite images throughout the year. Precipitation is intercepted by the canopy and any excess falls to the ground or to a snowpack depending on the air temperature.

If a snowpack exists and the temperature exceeds a critical value, snowmelt will be computed using either a simple degree-day method or a modified energy balance approach.

Excess precipitation and any snowmelt will infiltrate into a fast groundwater store at a rate computed by equation 2. The fast store represents the soil water storage that provides the rapid-response part of the streamflow hydrograph.

$$Inf = \left(1 - \frac{S_1}{S_{1,max}}\right) \cdot Inf_{max} \qquad (2)$$

where, S_1 is the current contents of the fast store (mm), $S_{1,max}$ is the maximum possible contents of the fast store (mm), *Inf* is the current infiltration rate (mm day^{-1}), and Inf_{max} is the maximum possible infiltration rate (mm day^{-1}). If the current infiltration rate is not sufficient to transmit all the precipitation, then the surplus will be spilt as surface runoff.

The fast store generates outflow, $Q_{1,out,}$ using equation (3):

$$Q_{1,out} = \frac{1}{k_1} . S_1 \qquad (3)$$

where, k_1 is the retention constant for the fast store. The outflow $Q_{1,out}$ is then separated into deep percolation, RP, flowing to a lower (slow) store and to interflow, RI, using equations (4) and (5):

$$RP = \frac{Q_{1,out}}{1 + \frac{S_2}{S_{max}}} \qquad (4)$$

$$RI = Q_{1,out} - RP \qquad (5)$$

where, S_2 is the current contents of the slow store (mm) and S_{max} is the maximum possible contents of the slow store (mm). The slow store contains groundwater that contributes to the baseflow of the stream hydrograph.

Finally, the slow store generates groundwater flow, RG, using equation (6). If the slow store overflows, the surplus water will be added to the interflow (RI):

$$RG = \frac{1}{k_2} * S_2 \qquad (6)$$

where, k_2 is the retention constant for the slow store.

From each land cover in a subbasin the surface runoff, interflow, and groundwater runoff are accumulated using a time/contributing area relationship for each land cover and the combined runoff is converted to streamflow and routed between each subbasin. For first order subbasins (those which directly discharge to the river), the streamflow is routed by simply accumulating the flows down the basin with no delay or attenuation. For second order or higher subbasins, Muskingum routing is used, which describes the relationship between inflow, outflow, and storage of the channel reach. The Muskingum weight function (x) was set to 0.25 and the time of travel, K, was computed from the change in elevation along the stream channel, DZ, (Institute of Hydrology 1995) as:

$$K = 1.5 * e^{-DZ/250} \qquad (7)$$

Results

The SLURP model produces two types of output: i) point data such as streamflow at different locations in the basin, and ii) spatially distributed data such as basin-wide evaporation, transpiration, or net runoff. As an example of point output, figure 9 shows the simulated daily stream hydrograph at the outlet of the basin for the hydrological years 1994/95 to 1997/98. The hydrograph displays typical flows for this part of the country, where flows are high during the rainfall events of the winter period and low during the dry summer period. Due to its distributed nature, SLURP is able to generate values of all components of the hydrologic cycle for each pixel of the basin for any period. Figure 10 shows, as an example, the total transpiration for 1995. We could equally have produced maps for potential evapotranspiration, actual crop transpiration, actual soil evaporation, precipitation, surface irrigation, runoff, and crop yield.

The results show that we can apply a hydrological model to a basin using only data from the Internet and can obtain results that would be, first of all, useful for those cases where there are no local data or where local data are too difficult to obtain and, second, useful for rapid studies of water management scenarios where using detailed local data would be too time-consuming.

FIGURE 9.
Simulated hydrograph, m^3/s, Küçük Menderes River at the outlet, October 1, 1994 to September 30, 1998.

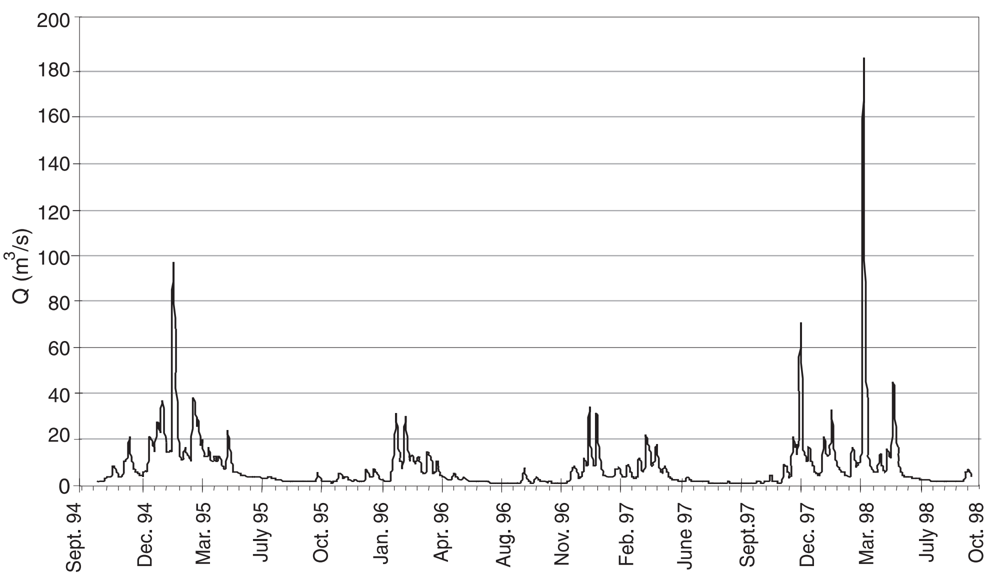
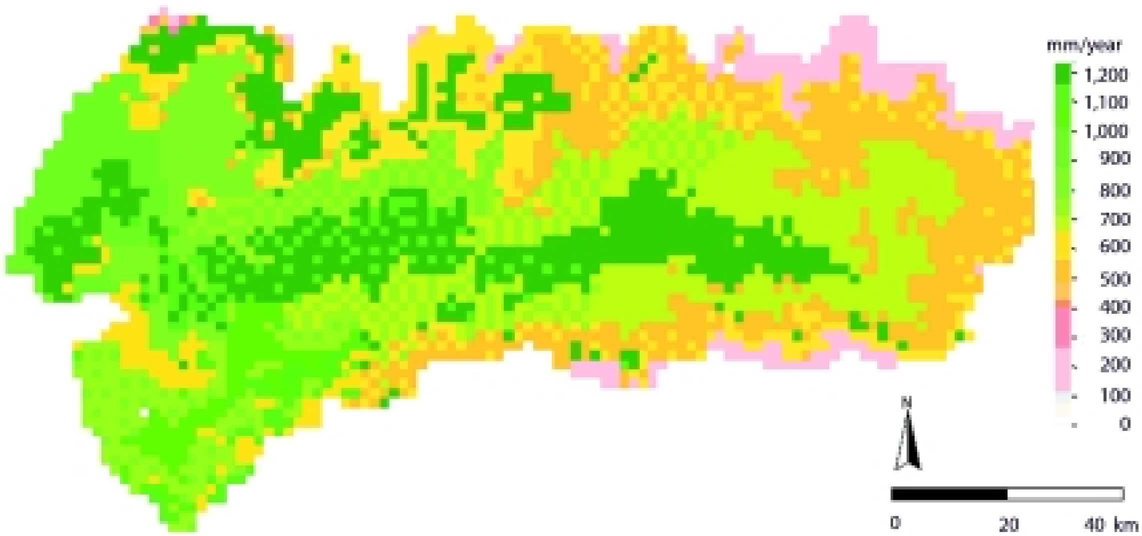


FIGURE 10.
Simulated transpiration, mm/yr., Küçük Menderes Basin, 1995.



Verification

The model was run using only data available on the Internet; no locally obtained data were used and no calibration was made. Parameter values were assumed to be the same as those for the same land covers in an adjacent basin. The previous section has shown the results and the next step was to see if we could verify the data from the Internet and the consequent performance of the model.

As previously noted, the DEM had to be corrected because the 1-km lateral resolution of the data did not detect the watershed divide at the western end of the basin and so the topographic analysis package derived a larger-than-correct basin outline. This was first suspected by looking at the stream network shown in Encarta (Microsoft 1998) and was confirmed by a field visit. The DEM was corrected and TOPAZ then gave the correct basin outline.

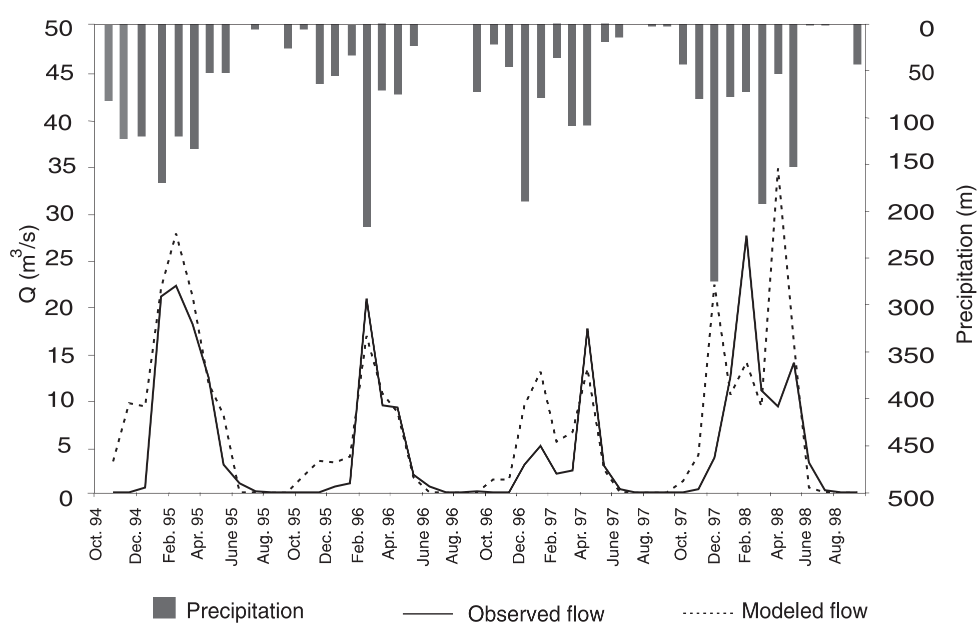
The field visit also confirmed a discrepancy in the land cover classification. Several high elevation areas with high water availability were classified by our analysis as 'irrigated' whereas the field visit showed that these areas should have been classified as *maki,* the typical Mediterranean land cover consisting of bay, myrtle, shrub, oak, and juniper trees. In total, 4.5 percent of the basin was reclassified to rectify this error.

For the verification, we attempted to obtain streamflow from public domain datasets on the Internet. The only site available was the Global Runoff Data Center [11] and on reviewing their CD we found no data for the Küçük Menderes River.

We were able to obtain observed monthly mean streamflow at Station 601 from EIE (the Turkish electricity company) for the period 1994–1998 to compare with the outputs from SLURP. The daily SLURP outflows from the Küçük Menderes Basin were converted to monthly flows and the EIE flow data were adjusted for drainage area, as their station is upstream from the outlet used in the SLURP simulations. The drainage area upstream of the EIE station is 3,255 km^2 while the area above the outlet to the Aegean Sea simulated by SLURP is 3,617 km^2. The EIE data were adjusted proportionally. Figure 11 shows the comparison between the observed and simulated monthly flows after correcting for drainage areas.

The fit is generally good, especially for the first 2 years of simulation. The overestimation of discharge during the autumn months (October-November) of each year is most likely because the measured flows take account of the diversion and consumption of water by irrigation schemes whereas, for the model simulations, we assumed diversion only for June-September. The simulated flows for 1998 do not look as good as, and even appear to have peaks at different times to, the observed flows. However, if we look at the monthly precipitation events (top of figure 11), we see that the model correctly simulates high flows after high precipitation events while the recorded hydrograph does not follow these same precipitation events. As examples, the precipitation events of 14 December 1997 (60 mm) and 31 March 1998 (82 mm) are reflected in high-simulated streamflows but low-recorded streamflows while the very high-recorded streamflow on 4 February 1998 (141 m^3/s) has only very low associated precipitation. There is a negligible snow effect in this basin. The errors could be attributed to changes in weather patterns for the 1997/1998 hydrological year, or to the fact that the precipitation stations used no longer adequately represent the basin precipitation conditions. However, we also know that the streamflow data for 1996–1998 have not been quality-controlled by EIE and it is possible that there are errors in the recorded streamflows.

FIGURE 11.
Mean monthly recorded (EIE, station 601 adjusted for area) and simulated (SLURP) streamflows, and monthly precipitation, Küçük Menderes Basin.



The standard error over the full period is comparatively high at 121 percent of the mean observed flow (table 5). But if we omit the doubtful year (1998), the standard error is reduced to 73 percent of the mean.

The standard errors here are acceptable but it would be interesting to see what reduction could be obtained if local (climate, particularly) data were used instead of the data from the Internet and if we had better information on withdrawals for irrigation.

TABLE 5.
Standard error between recorded and observed streamflows, Küçük Menderes River.

Period	Observed mean flow	Standard error	Standard error as % of observed mean
1994–1998	4.89	5.94	121
1994–1997	4.27	3.57	73

Sample Application of the Model

We have described the application, results, and verification of the SLURP hydrological model for the Küçük Menderes Basin using only data from the Internet. The second objective of the study is to show that a model derived in this way can be used to investigate a practical water management problem. It was noted earlier that while precipitation in the Küçük Menderes Basin occurs mainly in winter, the main irrigation season is in summer. To provide the storage necessary to conserve high winter streamflows, a reservoir is being constructed at Beydaği to supply water for an 18,200-hectare irrigation scheme (Alpaslan 1999). The main crops in the irrigation scheme will be cotton (22%), potato (22%), watermelon (10%), and vegetables (10%) as well as lesser amounts of fruit, cereals, citrus, and tobacco. There is also a much smaller secondary cropping season. The mean annual water requirement of the irrigation scheme is estimated (Alpaslan 1999) at 1.6 x 108 m^3/yr. with a peak requirement of 16.4 m^3/s in July. The Beydaği reservoir would be expected to satisfy 60 percent of this demand, the remainder being met by groundwater pumping.

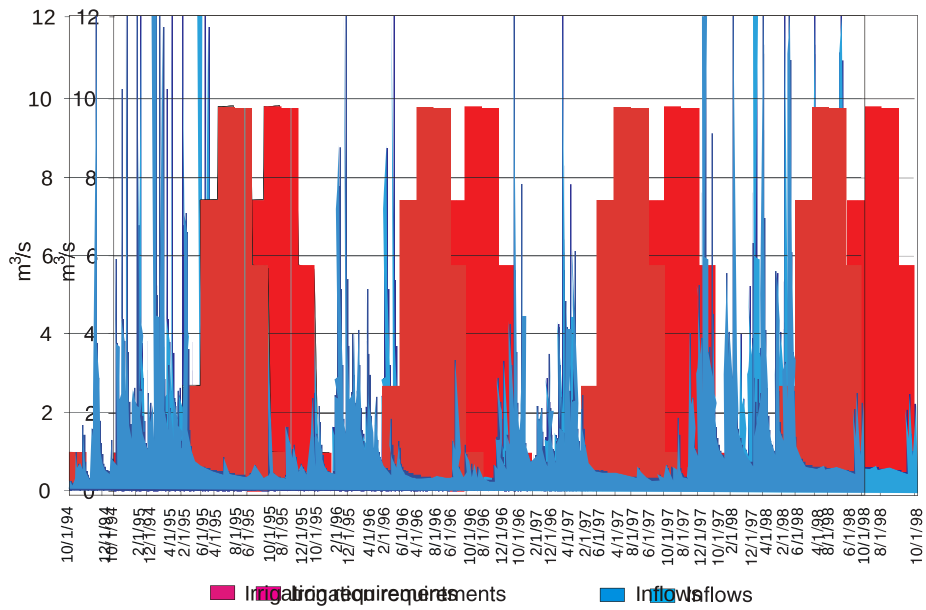
The hydrological model was used to simulate inflows to the reservoir. Figure 12 compares the daily simulated reservoir inflows (blue) and the monthly irrigation demand (red). Note that the reservoir inflows have a much greater range (0-180 m^3/s) than the irrigation demand (0-16.4 m3/s) and so, in order to show both on the same graph, reservoir inflows above 12 m^3/s have been cut off. The seasonal shift between supply and demand is clear.

Next, stage-area and stage-volume curves were included in SLURP to simulate the behavior of the reservoir. The model then needs to know the starting level of the reservoir. We investigated two options.

First, we assumed that the reservoir had been completed in time for the 1994-1995 hydrological year, and that the reservoir would start from empty at a water level of 173.0 meters (Alpaslan 1999). Figure 13 shows that, using the simulated reservoir inflows shown in figure 12, in a real-world situation starting from an empty reservoir in October 1994, there would only be enough water to satisfy the irrigation demand for the first few months every year. In no year could the total irrigation demand be satisfied.

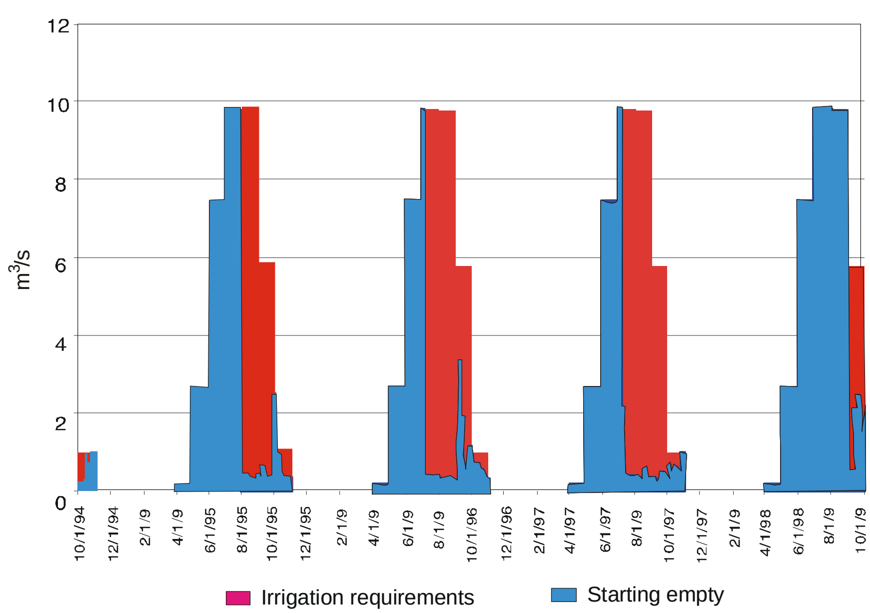
Second, we assumed that on October 1, 1994, the reservoir was complete and had been filled to its specified "normal water level" at a height of 221.18 meters (Alpaslan 1999). In this case, with the reservoir starting 48.8 meters higher than in the first option, the irrigation demand could be met satisfactorily.

FIGURE 12.
Irrigation surface water requirements (red) and simulated inflows to Beydaği reservoir (blue).



Note: Inflows greater than 12 m^3/s have been truncated for clarity of presentation.

FIGURE 13.
Surface water demand (red) and water supply (blue) for the Beydaği irrigation scheme assuming an empty reservoir on October 1, 1994.



Conclusions and Recommendations

We have shown that we can apply a distributed hydrological model to a basin using only data from the Internet and using no calibrations. The implications for modeling are that we can do the same thing for any basin in the world and that we can do the modeling from any location with Internet access. This implication assumes, as discussed below, that climate stations are available from the Internet at a comparable density for all basins and that parameters for each land cover are available or can be derived.

This capability will be useful for studies aimed at ameliorating the likely crises in water scarcity and food shortages over the next few decades. Computer models allow for rapid parameterization of a drainage basin and can be used quickly and cost-effectively to evaluate management alternatives such as reallocation of limited water, reservoir development, irrigation development, and so on.

The verification of the model by a field visit disclosed two limitations. First, the 1-km resolution of the DEM was shown to create a problem in an area with rapidly varying topography. For global DEMs the 1-km resolution is appropriate and convenient to use in terms of storage space and computer speed and is unlikely to be improved on in the near future. Improvements would seem to lie in hydrologically correcting the DEM as with the USGS HYDRO1K now in progress [2].

The second limitation shown by the field visit was that, although over 95 percent of the basin area was correctly classified, several small parts of the basin were classified as irrigated land instead of maki. This occurred despite using a fairly sophisticated classification scheme and this level of inaccuracy would seem unavoidable at this time. There are global land classification schemes available but these have been shown (Droogers, Kite, and Bastiaanssen 1998) to be sometimes inappropriate.

The global climate datasets do not have sufficient stations to provide very good coverage of small basins and can sometimes create anomalies when the available climate stations fall outside or are far from the basin of interest. For example, coastal climate variations will differ greatly from the inland climate, especially in mountainous areas. The GSOD database does not contain radiation data and we had to interpolate radiation from precipitation data. This should improve in the future as datsets proliferate.

As explained earlier, the SLURP model uses parameters that are related to the land covers. For example, infiltration rates will obviously vary depending on the land cover. It is, therefore, necessary when applying the model to have parameter sets for all relevant land covers. In this application, the parameter set used was the same as that used in a previous study of a nearby basin. As the model is used around the world, different land covers are encountered and a database of parameters for many different land covers is being built up. Research is also being carried out to derive the necessary parameters from digital soil maps using pedo-transfer functions.

Preparing a Digital Elevation Model (DEM)

This appendix describes the procedure to follow to derive a digital elevation dataset for a river basin prior to running SLURPAZ. The example used is for the Küçuk Menderes Basin, Turkey and all references to GIS procedures use IDRISI.

1. Download a DEM tile from the Internet. For this study the USGS GTOPO30 DEM [1] tile e020n40 was used.

2. Extract a window from the original DEM tile that covers the project area (figure A1). This window has been named tk_dem1.img:

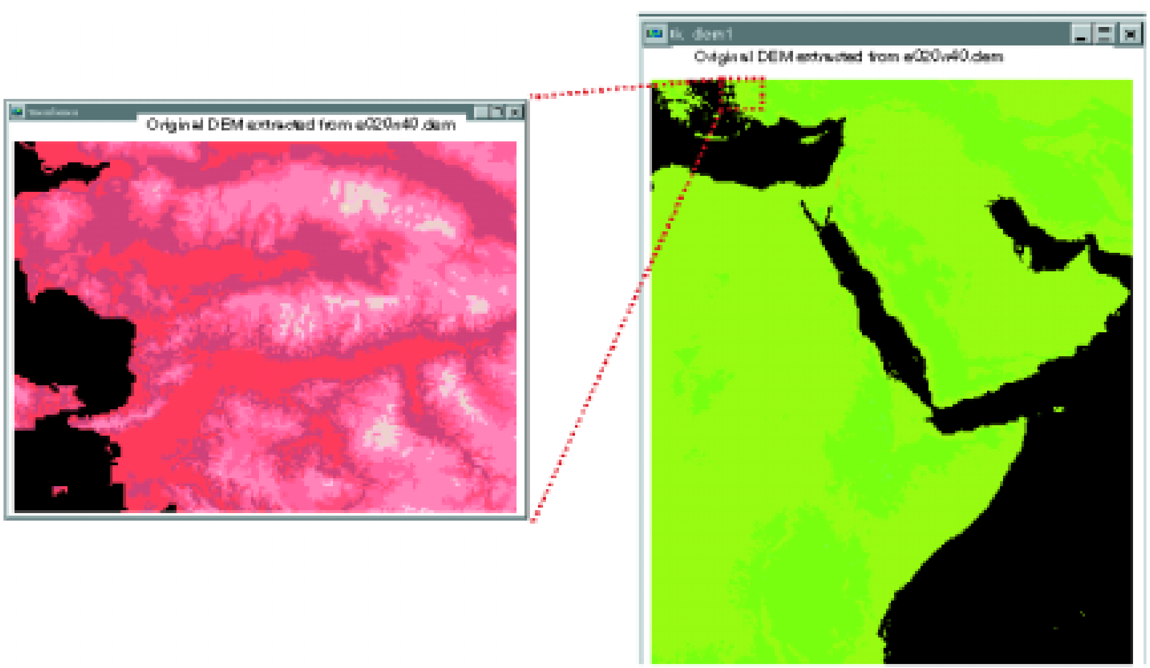
- set the new window coordinates: min_x, max_x, min_y, max_ in IDRISI (figure A2) using REFORMAT-PROJECT with the following coordinates:

  min_x 483000
  max_x 653000
  min_y 4138000
  max_y 4265000

Note: X values are Easting (or columns) and y are Northing (or rows) in meters.

- convert from Lat/Long to UTM coordinates using zone -35n
- make into 1-km grid

FIGURE A1.
Window for Küçük Menderes River from original DEM tile.



Note: The initial window contained 135 rows and 230 columns. Once resampled to a 1-km grid and 'zoomed-in' to encompass only the study area the new image contains 126 rows and 170 columns.

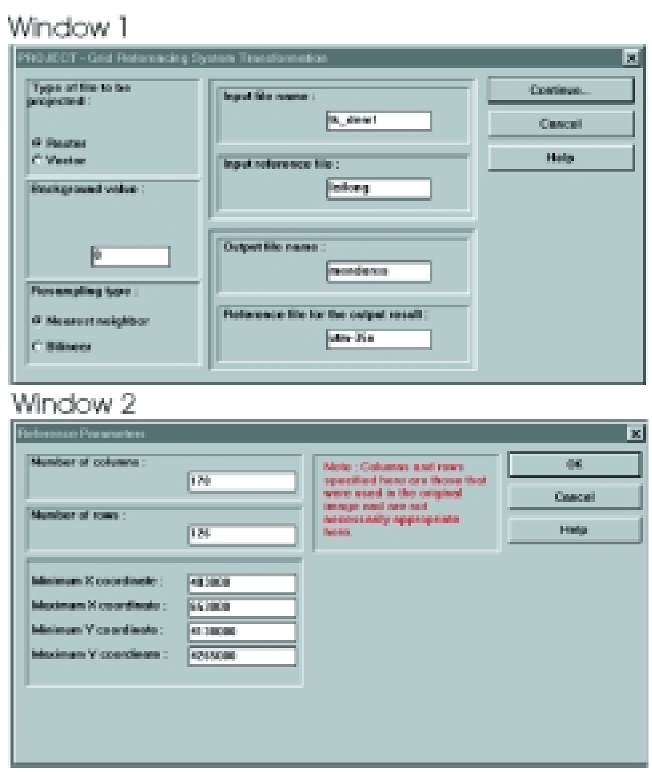
1. Convert the image from BINARY format to ASCII (REFORMAT-CONVERT).

2. Rename the DEM image (.img) to DEDNM.INP. Prepare DNMCNT.INP and other .INP files used in TOPAZ (see TOPAZ user manual and/or SLURP manual).

3. Run TOPAZ modules (DEDNM; RASBIN; RASPRO; RASFOR; RASPROX; RASFORX). Make several runs changing the CSA/MSCL parameters to derive output files with different numbers of subbasins (see table 1).

To select the lowest point on the river (the outlet) in TOPAZ, first zoom in to the approximate location of the outlet using IDRISI and select the approximate row and column to include in file DNMCNT.INP (e.g., row=62; column=41). Then, when running module DEDNM, you can choose the exact outlet (e.g., row=62; column=42) from the DOS display (figure A3). This display shows the channel route with each cell containing the number of upstream area in cells (for river cells), and containing a 0 (for non-river cells). At this stage in DEDNM, the user can change the row and column for the river outlet. For subsequent runs of DEDNM, the user can enter the corrected

FIGURE A2.
Windows under REFORMAT-PROJECT procedure.



outlet row/column values in the file DNMCNT.INP and avoid this interactive step.

TOPAZ selects the subbasins solely on the basis of topographic information. In some cases, the user will want to force subbasins at specific locations. For example, if the SLURP model is to be calibrated using recorded streamflow data then at least one subbasin will need to end at the site of a streamflow recorder. TOPAZ is unable to force subbasins to end at specified points automatically, but there are procedures that can be used to rectify this. In the case of the Küçük Menderes Basin, we wanted to have a subbasin, which would correspond to the catchment area of the planned Beydağı reservoir.

By applying multiple TOPAZ runs, the subbasins can be forced to specific points. The following steps should be taken:

1. Start at the point of interest furthest upstream (in this case row/column = 46/124 at the position for the outlet of the user-selected subbasin).

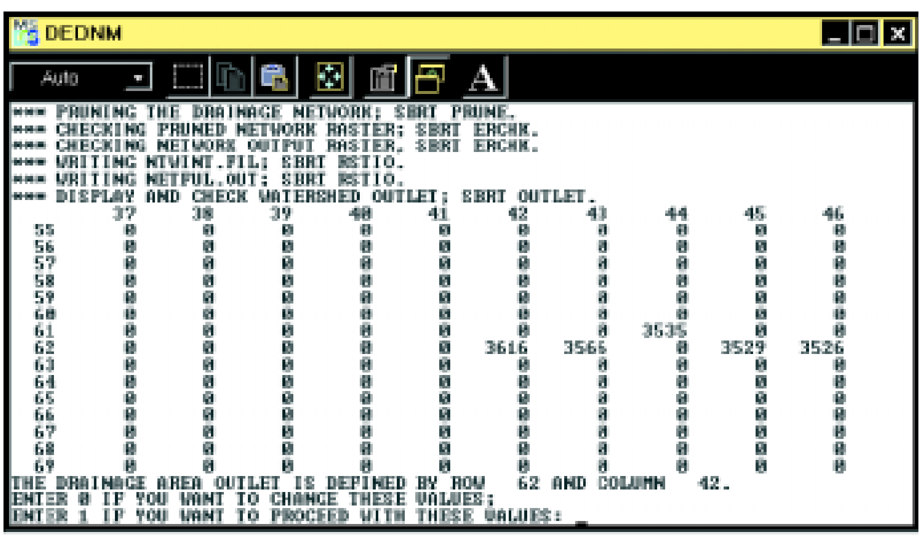
2. Define the coordinates of this point as the outlet point in the DNMCNT.INP file or run DEDNM and enter the coordinates interactively when requested. Run the remaining programs RASBIN, RASPRO, RASPROX and SLURPAZ to compute the characteristics (.CMD, etc.) of this first subbasin. Rename the TEMP.* output from SLURPAZ to some other name.

3. Make a copy of the original DEM and convert this to IDRISI .IMG and .DOC files by copying DEDNM.INP to DEDNM.IMG and copying an existing .DOC file (for example RELIEF.DOC) to DEDNM.DOC.

4. In IDRISI, change the attribute of the completed subbasin to -1 using (i.e., in file subwtb.img): DISPLAY/DISPLAY LAUNCHER ANALYSIS/DATABASE QUERY/RECLASS Save this reclassified image.

5. Now cut this subbasin from the main DEM using: ANALYSIS/DATABASE QUERY/OVERLAY/ FIRST COVERS SECOND EXCEPT WHERE ZERO with the image of the first subbasin as "first" and the main DEM as "second."

FIGURE A3.
DEDNM window when selecting stream outlet.



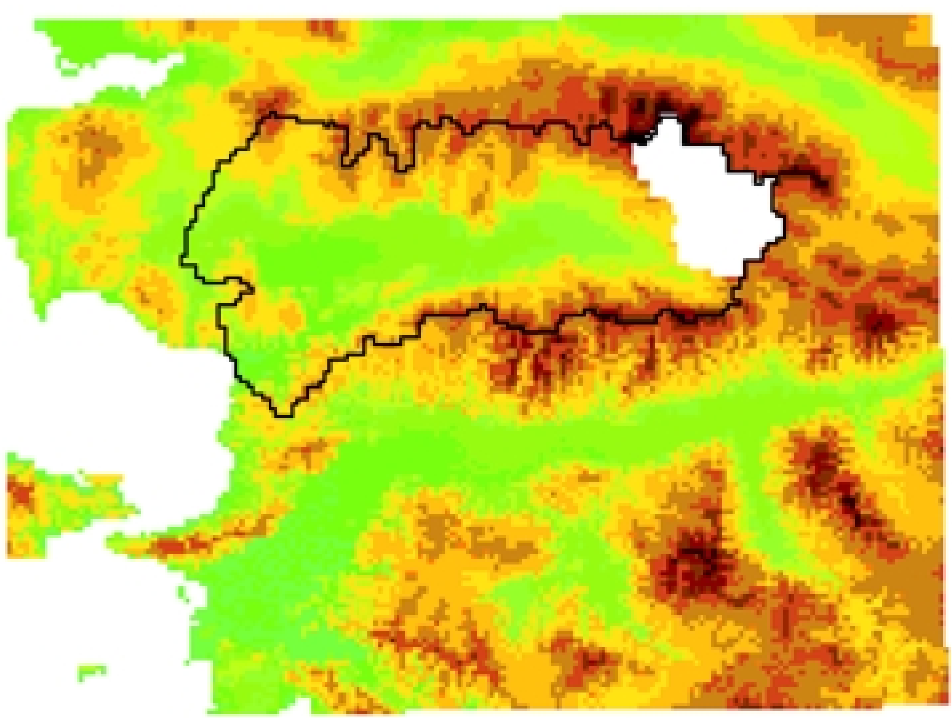
6. Change the attribute -1 in the modified DEM to the value of the indeterminate elevation (unknown elevation, default for TOPAZ is 0) in the original DEM (TOPAZ input file DEDNM.INP). The value of the indeterminate elevation is specified by the user in the file DNMCNT.INP. Use: ANALYSIS/DATABASE QUERY/RECLASS

7. Convert .img file from binary to ASCII and rename the modified DEM to DEDNM.INP.

8. The DEM has now been modified for further analysis and you can repeat the process outlined above, taking successive points downstream, until the whole basin is analyzed. Note that when running SLURPAZ the land cover LCLASS.INP must be for the same area as the DEM. Finally, the output files obtained from the different SLURPAZ runs should be combined manually using a text editor. Note that, in some cases, it may not be desirable to force intermediate subbasins exactly to streamflow station locations (i.e., where a station is located just upstream of a river junction it may be better to have the subbasin start at the junction rather than just upstream since otherwise TOPAZ will create a small subbasin between the actual junction and the hydrometric station).

For the Küçük Menderes example, figure A4 shows the DEM after the reservoir subbasin has been removed and before running TOPAZ for the rest of the basin downstream.

FIGURE A4.
Küçük Menderes DEM with values for upstream reservoir set to zero.



Preparing a Land Cover Image

The TOPAZ topographic analysis package (appendix A) derives the parameters needed for SLURP from a DEM. Before running SLURPAZ to prepare the input files for SLURP we need to have a land class map.

Three sets of data are used to prepare the land cover map. First, a series of monthly NDVI or near-infrared images from the NOAA AVHRR [4] satellite sensor over a full year are used to capture the change of time-variation in the bands for the different land covers. For example, in a winter or spring NDVI image, irrigated and nonirrigated land may appear the same but, in a summer image of the same area, the NDVIs for the two land covers would be very different. Second, a single NDVI image is used to capture the spatial variation in land cover. Third, a DEM is used to include the influence of elevation on land cover. These three sets of data are all used in the preparation of the final image of land cover.

1. For the Küçuk Menderes Basin we wanted to use the same land covers as in an earlier study of the Gediz Basin and so, the first step was to create a new DEM window that included both basins. The new window selected was as follows (rows/columns: 212/280):

min_x:	470000 (Gediz)
max_x:	750000 (Gediz)
min_y:	4138000 (Menderes)
max_y:	4350000 (Gediz)

2. Once the DEM was created, the following NOAA AVHRR images used for the land cover classification were downloaded from the Internet:

   - Band 2 (NIR): Feb., Mar., Apr., May, July, Aug., Sept., Oct. (1995)

   - Band 6 (NDVI): Aug. (1995)

   These images were georeferenced with the DEM. First, a correspondence file (*ndvi-dem.cor*) was created in IDRISI using the combined basin DEM image with one of the NOAA images (table B1). This is done by manually or visually selecting the same points from the DEM and from the NOAA images. The more the points selected over the widest area

TABLE B1.
Points used to georeference the land cover map to the DEM.

Point #	Old X	Old Y	New X	New Y
1	474438.5	4255535.0	479402.3	4255504.0
2	472478.7	4164484.0	482456.6	4164415.0
3	614724.1	4164570.0	621567.7	4164391.0
4	607784.6	4269517.0	612644.2	4269517.0
5	562592.3	4275628.0	566576.8	4275423.0
6	495511.4	4300596.0	500456.5	4301530.0

possible on the images, the more the precision of the georeferencing.

3. The next step was to RESAMPLE all the NOAA images using the ndvi-dem.cor file in order to georeference all the images. An IDRISI batch (i.e., *.iml)* file was used (table B2).

4. The following step was to OVERLAY the 9 NOAA images with the DEM outline of both the Gediz and the Küçük Menderes River basins. Again, an IDRISI batch file was used (table B3).

5. A principle component analysis is done using the time series analysis (TSA) module in IDRISI. The eight monthly NOAA AVHRR images may be analyzed in IDRISI using either a Principle Component Analysis (PCA) or TSA:

PCA: Analysis/Image processing/Transformation/PCA

- calculate covariances directly
- input: 8 bands only
- number of components = 3 (because most of the information is in the first 2–3 components)
- prefix: pca
- standardized... integer

TABLE B2.
Batch file used to georeference NOAA images.

RESUME	x	i	950201b2	c50201b2	ndvi-dem	utm-35n	m	1	0	470000	750000	413800	435000	280	212	1	1
RESUME	x	i	950301b2	c50301b2	ndvi-dem	utm-35n	m	1	0	470000	750000	413800	435000	280	212	1	1
RESUME	x	i	950401b2	c50401b2	ndvi-dem	utm-35n	m	1	0	470000	750000	413800	435000	280	212	1	1
RESUME	x	i	950501b2	c50501b2	ndvi-dem	utm-35n	m	1	0	470000	750000	413800	435000	280	212	1	1
RESUME	x	i	950701b2	c50701b2	ndvi-dem	utm-35n	m	1	0	470000	750000	413800	435000	280	212	1	1
RESUME	x	i	950801b2	c50801b2	ndvi-dem	utm-35n	m	1	0	470000	750000	413800	435000	280	212	1	1
RESUME	x	i	950901b2	c50901b2	ndvi-dem	utm-35n	m	1	0	470000	750000	413800	435000	280	212	1	1
RESUME	x	i	951001b2	c51001b2	ndvi-dem	utm-35n	m	1	0	470000	750000	413800	435000	280	212	1	1
RESUME	x	i	ndvi-g-m	ndvi-cor	ndvi-dem	utm-35n	m	1	0	470000	750000	413800	435000	280	212	1	1

TABLE B3.
Batch file used to overlay NOAA images on to the DEM.

overlay	x	7	2bounds3	C50201b2	050201b2
overlay	x	7	2bounds3	C50301b2	050301b2
overlay	x	7	2bounds3	C50401b2	050401b2
overlay	x	7	2bounds3	C50501b2	050501b2
overlay	x	7	2bounds3	C50701b2	050701b2
overlay	x	7	2bounds3	C50801b2	050801b2
overlay	x	7	2bounds3	C50901b2	050901b2
overlay	x	7	2bounds3	C51001b2	051001b2
overlay	x	7	2bounds3	ndvi-cor	Ondvicor

A) RECLASS: - equal-interval
B) CONVERT from integer/binary to byte/binary
C) Use pcamp1

TSA:Analysis/Change/Time Series/TSA

or - Data entry/Edit/Time Series Analysis, i.e., tsabnd2 (selected 8 band2 images)

- Analysis/Change/Time Series/TSA

  - tsabnd2
  - 3 components
  - DIF format
  - store as integer
  - Use tsacmp1

6. Select the NOAA image with the greatest variation in NDVI (usually a summer image, e.g., August)

7. Produce a composite image from the first TSA component (i.e., tsacmp1), the DEM and the image selected in step 6 (i.e., Aug NDVI) Analysis/Image processing/ Enhancement/ Composit

   Blue: TSA image (1st component)
   Green: DEM
   Red: NDVI image
   simple linear -omit 0 -grey scale=0

8. Carry out an unsupervised classification on the resulting image: Analysis/Image processing/Hard classifier/Cluster

9. Check the result in the field and change as necessary.

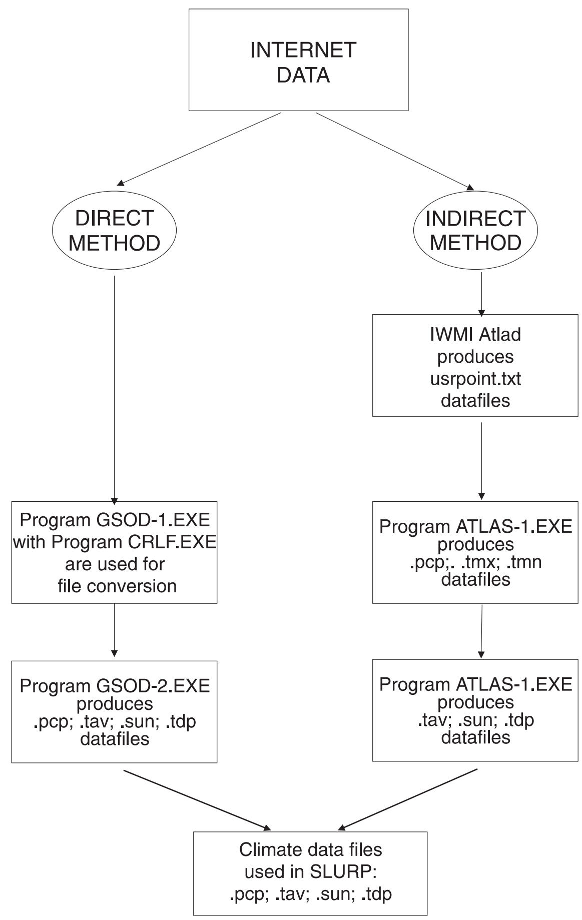
Processing Climate Data from the Internet

Traditionally, hydrological models have depended on locally collected climate data. However, in many countries, such data are becoming difficult to obtain either because of lengthy processing times or high data costs. Instead, we can obtain many data from databases held on the Internet. Currently, there are two main global datasets of daily climate data, GDS (Global Daily Summary) [6] (also available from IWMI [10]) and GSOD (Global Surface Summary of the Day) [7] (also available from the University of Miami [8]), both provided by NOAA from NCDC data collections. GDS contains daily maximum and minimum temperatures and daily precipitation from over 10,000 stations for the period 1977–1991 in metric units. GDS data are also available from the USGS Hydrolab website [12], although the format is uncertain. GSOD contains 13 parameters for over 8,000 stations for the period 1994 to date, is updated on the web every month, and is in imperial units.

In addition, there are many datasets containing monthly climate data such as those of the Climate Research Unit, University of East Anglia [9], the NCEP/NCAR reanalysis project (Jenne 1999), and the IWMI World Water and Climate Atlas [10].

SLURP uses daily average air temperature, dew point (or relative humidity), precipitation, and net radiation or hours of bright sunshine. GDS has neither radiation nor humidity data and GSOD does not have radiation data. For the Küçük Menderes study, we investigated both datasets and incorporated approximations for humidity and radiation where necessary. The flow chart in figure C1 summarizes the following two procedures that will be described.

FIGURE C1.
Direct and indirect methods for deriving climate data.



A. Procedure to Use GSOD Data (1994–1998)

The GSOD dataset is available for more recent years and includes dew-point data. The procedure used to process these data is as follows:

1. Download and unzip the .tar files from the Internet site (~65MB each) for the years required:

   all-1994.tar
   all-1995.tar
   all-1996.tar
   all-1997.tar
   all-1998.tar

2. For each of the annual files, unzip the individual month files that are of interest (~5.5MB each):

   september-97.txt.Z
   october-97.txt.Z
   november-97.txt.Z
   december-97.txt.Z
   january-98.txt.Z
   february-98.txt.Z

3. Include in the working directory a file named 'STATIONS.TXT' that includes a listing of the station numbers for which you wish to extract data. Ensure that you include the full DOS 8 characters for the station numbers (i.e., add 00s to the end if necessary). The station numbers can be found in file *stnlist.txt* that is provided with the GSOD/NCDC data.

4. Run program GSOD-1.EXE specifying the path to the directory containing the data files, the month and year of the first data file, and the month and year of the last data file. This program converts the data files from UNIX to DOS format and changes the file names from long form with the year as 2 digits (e.g., september-98.txt) to short names with the year as 4 digits (e.g., G199809.txt). Note that the program CRLF.EXE must be in the same directory as GSOD-1.

5. Specify the path to the directory containing the data files, the month and year of the first data file, and the month and year of the last data file. This program will create data files of average temperate, .tav, and the ratio of actual sunshine hours to maximum possible sunshine hours, .sun, to be used as inputs to SLURP. To derive the average temperature (.tav), the program takes the average of the minimum and maximum temperatures for each day (i.e., [tmn + tmx]/2); the ratio of sunshine hours (.sun) is derived from the precipitation file (.pcp) in the absence of any other information. If there is no precipitation, we assume that the sky is clear. If the daily precipitation exceeds 25 mm we assume no sunshine hours on that day. For daily precipitation between 0 and 25 mm, the daily hours of sunshine are computed proportionately.

B. Procedure to Use GDS Data (1977–1991)

Data from the GDS database had already been copied from the Internet and written to 3 CD-ROMs as part of the IWMI Atlas project (i.e., one CD each for precipitation, minimum temperature, and maximum temperature). These files were in a proprietary format and had to be imported to the Atlas, processed, and reexported in ASCII text format as follows (capital letters indicate an Atlas procedure):

1. IMPORT POINT DATA FILE, e.g., P0002GDS001.IDX (this is actually an index file associated with the data file P0002GDS001.DAT).

2. LOAD OBJECT, specify the name of the .IDX file. Ignore the message about polygons.

3. OBJECT LIST, select the file from the left-hand window (in this case, "World-GDS daily total precipitation (mm)" under Type-Points-World). Click with the right mouse button on the data you wish, e.g., precipitation.

4. EDIT CUSTOM OBJECT PROPERTIES/ EXPORT, select a period of interest between 1977 and 1991, specify 31 values per line, export all values (even if missing), tab delimited, include the name, year, and month and step by month.

5. EXPORT TO SPECIFIED FILE, check the box for file header.

   This procedure produces an ASCII file for the period selected for one variable and should be repeated for each variable for the same period. We have processed the data in this way* and written the files ATLAS_OUTPUT_PCP.ZIP, ATLAS_OUTPUT_TMX.ZIP, and ATLAS_OUTPUT_TMN.ZIP to CD-ROM.

   **Note that any user going back to the original Atlas input files (i.e., .idx and .dat files) should be aware that the maximum temperature CD and the precipitation CD have incorrect .idx files, and that the user must use the minimum temperature .idx file for all three variables (make sure prior to running the Atlas, that the files have the same name and rename the output files appropriately).*

   These files contain all the GDS data and are large (500 MB) and so the next procedure in using GDS data is to extract data only for those stations in the area of interest. This is done by building a file named 'STATIONS.TXT'. This file includes a list of the station numbers for which data are required. Ensure that all station numbers have the full DOS 8 characters (i.e., add 00s to the end if necessary). The station numbers for all the GDS stations can be found in file *stnlist.txt* that is provided with the GSOD/NCDC data on the Internet. This file is more recent and more accurate than the *stations.dat* file provided by Hydrolab. The Hydrolab file contained incorrect longitude coordinates (e.g., for Turkey stations, they were all approximately +3 degrees to the far east).

6. Unzip and rename the Atlas output file to "usrpoint.txt" and run program ATLAS-1.EXE specifying the path to the directory containing files "usrpoint.txt" and "stations.txt" and specifying the variable contained in "usrpoint.txt" (pcp, tmx or tmn) as: ATLAS-1 D:\PATH pcp

   This program will produce individual output files for each station contained in "stations.txt" with the extension .pcp; .tmx; or .tmn as specified. This program should be run with all three .ZIP files.

7. Once all the station files for .pcp, .tmn, and .tmx are created, run program ATLAS-2.EXE specifying the path to the directory containing the .pcp; .tmx; or .tmn as: ATLAS-2 D:\PATH

   This program will create data files of average temperature, .tav, ratio of actual sunshine hours to maximum possible sunshine hours, .sun, and dew point, .tdp, to be used as inputs to SLURP. To derive the average temperature (.tav), the program takes the average of the minimum and maximum temperatures for each day (i.e., [tmn + tmx]/2); the ratio of sunshine hours (.sun) is derived from the precipitation file (.pcp) in the absence of any other information. If there is no precipitation, we assume that the sky is clear. If the daily precipitation exceeds 25 mm we assume no sunshine hours on that day. For daily precipitation between 0 and 25 mm, the daily hours of sunshine are computed proportionately. The dew point (.tdp) for a particular day is set equal to the minimum temperature (.tmn) of the previous day.

C. Additional Notes

The two previous sections have described how to prepare climate data files for input to SLURP. If you are using the Morton evapotranspiration method, then run the MALT.EXE program to derive long-term mean annual precipitation needed for the .MOR file. Ensure that your .pcp file starts on January 1 and ends on December 31 for each year.

The final step is to use the option on the SLURP main menu to convert the climate station data computed in this section to subbasin-average climate data. This step needs a .CMD and a .WTS file (normally prepared by TOPAZ/SLURPAZ from the SLURP main menu).

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