WORKING PAPER 2

Developing a Hydrological Model for the Mekong Basin

Impacts of Basin Development on Fisheries Productivity

Geoff Kite

INTERNATIONAL WATER MANAGEMENT INSTITUTE

FUTURE HARVEST
IWMI is a Future Harvest Center
Supported by the CGIAR

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This report describes the hydrological aspects of a CGIAR project to model the effects of water flows on aquatic resource production in the Mekong Basin. The project was carried out by the International Centre for Living Aquatic Resources Management (ICLARM, Penang, Malaysia) and the International Water Management Institute (IWMI, Colombo, Sri Lanka) in cooperation with the Mekong River Commission (MRC, Phnom Penh, Cambodia) together with other institutes and national and regional agencies working in the riparian countries of Cambodia, Lao PDR, Thailand and Vietnam. The project commenced in January 2000 and finished in December 2000. The land cover analysis for the Tonle Sap area was carried out, and the data on existing and proposed dams were collated, by Dilkushi De Alwis, IWMI, Colombo.

Contents

Developing a Hydrological Model for the Mekong Basin

Introduction

The Mekong River, with a basin of almost 800,000 square kilometers and a length of 4,500 kilometers, ranks among the world's great rivers. Flowing from China's Yunnan Province, between the Salween and Yangtze Rivers, through Burma, Thailand, Laos and Cambodia, it reaches the South China Sea in Vietnam. The 50 million residents and numerous species of plant and animal depend on the river's annual cycle of flood and drought. The many wetlands along the river, including Cambodia's Tonle Sap (Grand Lac), are significant sources of fish for the riparian peoples and form an important part of the regional economy. Fish supply 50–80 percent of total protein intake for basin residents (Mekong Secretariat 1992a). It is thought this resource may be affected by proposed developments in the basin.

Such effects can be studied using distributed hydrological models. These models, however, generally require large numbers of data, which, in many countries, are not always available. However, global datasets (including the International Water Management Institute (IWMI) World Water and Climate Atlas) are becoming increasingly available and data from the Internet can sometimes be used to substitute 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 2000) for simulation of basin hydrology and water resources development.

This report describes the application of this model to simulate the hydrology of the Mekong Basin using mainly publicly available data from the Internet and with a particular emphasis on generating data of use to the fisheries of the basin. The study was conducted as part of a joint project by IWMI, ICLARM (International Centre for Living Aquatic Resource Management) and MRC (Mekong River Commission) funded by the Technical Advisory Committee of the Consultative Group for International Agricultural Research (CGIAR).

The Mekong Basin

One of the earliest written descriptions of the hydrography and geography of the Mekong Basin was produced by Lagrée's 1866–68 expedition seeking a river route to China (Osborne 1996). The source of the Mekong River is on the Tibetan Plateau from where it flows to the South China Sea. The river is believed to rise at an elevation of about 5,100m in the Thang Hla mountains. It falls over 2,000m to Chamdo where it is crossed by the road from Kanting, China, to Lhasa. The river then passes through virtually unexplored gorges until it is seen again at Paoshan on the Burma Road. From there, the river flows through further inaccessible gorges until reaching Chaing Saen upstream from the Laotian cultural capital of Luang Prabang. From Luang Prabang the Mekong is navigable in reaches separated by major waterfalls until reaching Kratie upstream of the Cambodian capital, Phonm Penh. From Phnom Penh, the river divides into two main channels and many smaller channels flowing through the Delta to the South China Sea.

The river provides food, water, transportation and economic sustenance to more than 50 million people, and supports a unique and rich ecosystem. Each year the Mekong overtops its banks, providing water and nutrient-rich sediment for the rice-based agriculture of the riparian countries. Annual floodwaters also inundate wetlands and bottomland forests, creating spawning and nursery grounds for the roughly 700,000 metric tons of fish harvested from the Mekong each year.

Approximately five percent of the annual flow of the Mekong is regulated by dams (Piper et al. 1991). However, the pace of hydro-development on the Mekong is accelerating. It is estimated that only 20.5 terawatthours per year are developed out of a potential of 1090 terawatthours/year in the Mekong countries (Plinston and Daming 1999). While these figures are for the countries of the basin in their entireties (except for China which is for Yunnan Province alone) they do give an indication of the possible scale of development. China alone intends to complete eight large mainstem dams (Plinston and Daming 1999) and Laos has started construction on several of the 23 projects planned for completion before 2010. In 1990, the Mekong Secretariat released a study proposing nine mainstem "run-of-river" dams (Mekong Secretariat 1990). Since the first comprehensive survey of the Mekong in the 1950s, more than 180 dams and diversion projects have been proposed for the basin. Earlier plans envisioned a cascade of ten mainstem storage projects, with more than 6,000 square kilometers of reservoir area and over 10,000 megawatts of generating capacity. For political, social, economic, and environmental reasons, planners no longer consider projects of such scale viable and dam proponents have scaled down the mainstem project proposals, to pursue sites on Mekong tributaries in Laos, Thailand, and Vietnam (Rothert 1995).

Many aspects of the Mekong River system remain poorly understood. Most studies have focused on detailing the benefits of proposed hydropower projects and seldom surpass a perfunctory treatment of potential environmental and social repercussions. Many questions related to fish ecology, tributary and mainstem hydrology, sediment dynamics, and the river's importance to local communities are left unanswered. Moreover, the available literature indicates scientists have paid scant attention to the cumulative effects of the numerous projects.

The lower Mekong Basin area (basically, excluding China), containing most of the riparian population, represents 77 percent of the total basin area and 3,000 km of its total length. The average gradient of the Lower Mekong River is 0.15 m/1,000 m, or 0.015 percent, and the width ranges from 500 meters at the Chinese border to more than 1,200 meters in the lower reaches (Mekong Secretariat 1992b).

The climate is dominated by two distinct monsoon seasons: the rainy southwest monsoon, which occurs between mid-May and early October; and the dry northeast monsoon, which occurs between October and March. The precipitation contributes to the Mekong both as snowmelt in Tibet and China and as monsoon rain in the lower basin. Ninety percent of the precipitation falls between the months of May and October. Rainfall in the Lower Mekong Basin ranges from 1,000 millimeters in northeast Thailand to more than 3,200 millimeters in the mountainous regions of Laos (Rothert 1995).

The river flow reflects the seasonal variation in precipitation. At the farthest downstream gauging station near Phnom Penh, Cambodia, the river usually begins rising in May, and peaks in September or October, with the average peak flow greater than 45,000 cubic meters per second. Flows taper off after November and reach their lowest levels of roughly 1,500 m^3/s in March and April. At more upstream locations, the peak flows occur earlier and with less volume than at Phnom Penh. Average annual total discharge is roughly 450 billion cubic meters, and ranks sixth in the world. The average flow at Chiang Saen, at the top of the Lower Mekong Basin, is only about 20 percent of the average flow at Kratie, near Phnom Penh.

The approximate contributions of flow from the riparian countries to the total Mekong River discharge are as follows: China, 20 percent; Laos, 26 percent; Vietnam, 20 percent; Thailand, 12 percent; and Cambodia, 8 percent (Mekong Secretariat 1990).

Cambodia's Tonle Sap, or "Grand Lac," plays a vital role in the Mekong River system and in the Cambodian economy. In the dry season, the Great Lake's shallow waters cover roughly 3,000 square kilometers, and the lake drains slowly into the Mekong River. As the rainy season progresses, the Mekong River rises above the Tonle Sap level, and the flow reverses, filling the lake. The lake typically expands to more than 10,000 km^2. As floodwaters reach the surrounding forest and agricultural areas, the lake receives a massive influx of nutrients that triggers a surge in productivity. The Tonle Sap is renowned as one of the most productive freshwater ecosystems in the world (Pantulu 1981), supporting 60–75 percent of the inland fishery in Cambodia, with harvests that have historically reached 100,000 tons per year. After rice, fish is the most important component of the Cambodian diet, accounting for as much as 80 percent of the animal protein consumed.

The productivity of this system is seriously threatened, with a marked decline in both the annual catch, from 100,000 to 50,000 tons and the catch per unit effort (Mekong Secretariat 1992a). Logging and the need for fuelwood and farmland, have halved the area of seasonally inundated forests to 500,000 ha (Laroche and Wilcox 1992). Deforestation and mining have contributed to a doubling of the siltation rate to 4 cm/yr. As a result, dry season lake depths have decreased from 0.5 m in 1960 to 0.3 m in 1995, causing higher water temperatures and greater juvenile fish mortality (Rothert 1995). Over-harvesting and destructive fishing methods (e.g., explosives, electric shock, and pesticides) compound the pressures on the fishery (Mekong Secretariat 1992).

In addition to serving important functions in the local economy and society, the Tonle Sap also plays at least two key roles in the larger Mekong River system. First, during the rainy season, the natural floodwater storage capacity of the lake lessens the degree of flooding downstream; and during the dry season, the natural release of water from the lake augments irrigation and drinking water supplies downstream. Second, the Tonle Sap provides critical spawning and other habitats to many important migratory fish species, including the giant catfishes, Catlocarpio siamensis and Pangasionadon gigas. Fish known to spawn or rear in the productive flooded areas of the Tonle Sap are caught by subsistence and commercial fishermen far up the Mekong River (Pantulu 1986).

The 50,000-square-kilometer Mekong Delta at the mouth of the river in Vietnam and Cambodia is considered the "rice bowl" of Vietnam. Although it represents only 12 percent of Vietnam's area, the Delta produces roughly half of the country's annual rice harvest of 20 million tons (Mekong Secretariat 1990). Of the Delta's 14.6 million residents, only 16 percent live in urbanized areas, while the rest live among the complex network of river channels and canals criss-crossing the Delta plain. The Delta's average elevation of only one meter above sea level subjects large areas to annual flooding. Overtopped riverbanks and heavy rain falling on saturated soils begin to inundate land in July. The flooding will often persist until December in some areas.

In 1993, the Mekong Secretariat estimated that the 310,000 tons of fish caught in the Delta and the 170,000 tons cultured in ponds and cages amounted to over half of Vietnam's fisheries exports. An estimated 13 million people and 6 million metric tons of cargo were transported on the Delta's waterways (Mekong Secretariat 1994).

The Delta fauna include some 23 species of mammals, 386 species of birds, 35 species of reptiles, six species of amphibians, and 260 species of fish (USAID 1995). The Delta is of particular importance as a wintering habitat for migratory birds. Large breeding colonies of herons, egrets, storks and ibises are found in the Delta. Although the Delta's once extensive mangrove forests have been reduced to just 15 percent of their original extent, the remaining forests still provide critical habitats to juvenile and adult shrimp and fish species, as well as terrestrial animals (Rothert 1995).

The Mekong Fisheries

Mekong River fisheries are a tremendously valuable resource to the 50 million residents of the basin. Fishers harvest more than 700,000 metric tons of over 300 commercially important species each year (Mekong Secretariat 1992a). The Mekong discharge into the South China Sea also supports a productive coastal fishery. Estimates of annual per capita consumption of fish range from 30 kilograms in Vietnam to 15.3 kg in Thailand, 13.3 kg in Cambodia, and 6.5 kg in Laos. Fish supply 50–80 percent of the total protein intake for basin residents (Mekong Secretariat 1992a.).

The Mekong Basin fishery remains a poorly understood system, despite its importance. After a comprehensive review of Mekong fisheries data, Hill and Hill (1994) concluded that "many fundamental questions regarding Mekong River fish ecology are unanswerable at this time and ... currently available data would not support a detailed assessment of the impacts of hydropower development on the resource." It is generally believed that the Mekong basin supports one of the most biodiverse aquatic ecosystems in the world with more than 1,000 indigenous species. The river system provides an access route to important feeding, spawning, and rearing habitats in main channel and floodplain locations, and serves as a refuge in the dry season.

Migrations are a common and important feature of Mekong Basin fish ecology (Mekong Secretariat 1992a; Roberts 1993). Research suggests entire fish communities migrate great distances on a seasonal basis, prompted by subtle environmental cues such as water temperature, depth, and turbidity (University of Michigan 1976; Roberts 1993). These migrations appear to follow three general patterns: from one mainstem location to another; from the mainstem in the dry season to tributaries and wetlands (e.g., the Great Lake) in the rainy season; and from one tributary to another (Roberts 1993; Baird 1995).

Fishers and scientists have documented a critical link between the Mekong main channel and its floodplain wetlands and agricultural land (Pantulu 1988). During periods of high water, flooded areas serve as primary breeding and nursing grounds for 90 percent of Mekong fish species (Woodruff et al. 1993). Nutrients stored in floodplain vegetation are made available to the river food chain when inundated, causing a surge in productivity. Floodplain areas produce three times as much fish per area as the main channel, and of the estimated 700,000 metric tons caught annually, roughly 236,000 tons are attributed to floodplain areas (Pantulu 1988).

Existing Hydrologic and Hydraulic Models

The Mekong River Commission and its predecessor organizations have a long history of using hydrologic and hydraulic models. The US Army Corps of Engineer's Streamflow Synthesis and Reservoir Routing (SSARR) model (US Army 1972) was installed in 1967 to simulate flows in the main river from Chiang Saen to Pakse. In 1970, use of this model was extended to flood forecasting during the wet season. According to a review by Delft Hydraulics (Vreugdenhil 1987), the hydraulic routing used in this model is not adequate for its purpose and the model has difficulty in forecasting the short-duration peak flows. In addition, the model cannot be used outside of its calibrated range. Despite these limitations, the SSARR model is still being used successfully (Tanaka 1999).

A detailed (268 mesh) model of the Mekong Delta was developed by SOGREAH between 1962 and 1965 to study possible flood-control measures (UNESCO/UNDP 1969), including a dam across the Tonle Sap. This model was the first operational mathematical model for flow simulation in a Delta area in the world and was used to develop weekly flood forecasts. According to Delft Hydraulics (Vreugdenhil 1987) it is cumbersome to change, the schematization was already out of date in 1987, and it suffers from having a very unsatisfactory supply of upstream boundary data. The same model was also used to develop hydrodynamic models of the Mun and Nam Songkhram Rivers to assess proposed flood control works (Kreuze 1998).

Since the SOGREAH model includes only a rudimentary coastal region and is unable to simulate tidal effects in the Delta , a separate model for tidal flow up to Phnom Penh was developed in 1974 (van Parreeren 1977). This model, however, considers only the channels, is only for low flows, and does not include over-bank flooding. It is therefore incompatible with the detailed Delta model. This model has been used to provide flow patterns for salinity intrusion although Vreugdenhil (1987) describes it as inflexible and not user-friendly. The model is also out of date because of new canals, dykes and roads in the Delta area (Hien 1999).

Other models have been developed to study salinity intrusion (e.g., MEKSAL; Nguyen Tat Dac et al. 1987) and models such as HYSSR (Choung Phanrajsavong 1986) and MITSIM (WMO 1984) have been used to evaluate reservoir operations in specific locations.

In 1991, Delft Hydraulics developed a one-dimensional hydraulic model of the Lower Mekong from Chiang Saen to the South China Sea to simulate flow and salinity intrusion (van Mierlo and Ogink 1991). This Master Model includes a physical representation of the main river and its flood plain to allow the investigation of the effects of natural and man-made interferences in the river basin. The model has three components; a river model, a Delta tidal model, and a Delta flood model. The river model does not include any rainfall-runoff simulation, relying on recorded river flows at Chiang Saen as inputs. Tributary inflows are included only as water balance residuals. The Delta tidal model was based on the earlier MEKSAL model and used output flows at Pakse from the river component as upstream boundary conditions. The Delta flood model used the same cross sections as the tidal model with hydraulic data updated from the SOGREAH study (UNESCO/UNDP 1969). A separate model was used for the Tonle Sap, simulating the lake as a river reach of 150 km with 11 lateral inflows representing tributary flows, precipitation and evapotranspiration. This model was calibrated for the period from April 1962 to March 1963 but was not verified. The study noted that accurate calibration of the models was hampered by lack of up-to-date topographic, hydraulic, and hydrologic data. Kreuze (1998) noted that this model was no longer operational.

The VRSAP model, developed at the Vietnam Sub-Institute of Water Resources Planning and Management, covers the Mekong River system from Kratie to the sea including the Tonle Sap. The model uses the finite difference method of solving the Saint-Venant equations and includes salinity intrusion. With 1,560 segments, 1,278 nodes and 333 storage basins, the model has been calibrated using high flood years from 1978 to 1996 (Hien 1999).

Huang and Tamai (Internet 14) describe an initial attempt to apply the MIKE 11 model to the main branches of the river from Phnom Penh to the sea. The tributaries in the Plain of Reeds and Long Xuen are not included. The recorded flows at Phnom Penh are used as upstream boundary conditions and the observed water level at the river mouths are used as downstream boundaries. Calibration is achieved by adjusting the Manning roughness coefficient and by changing lateral inflows.

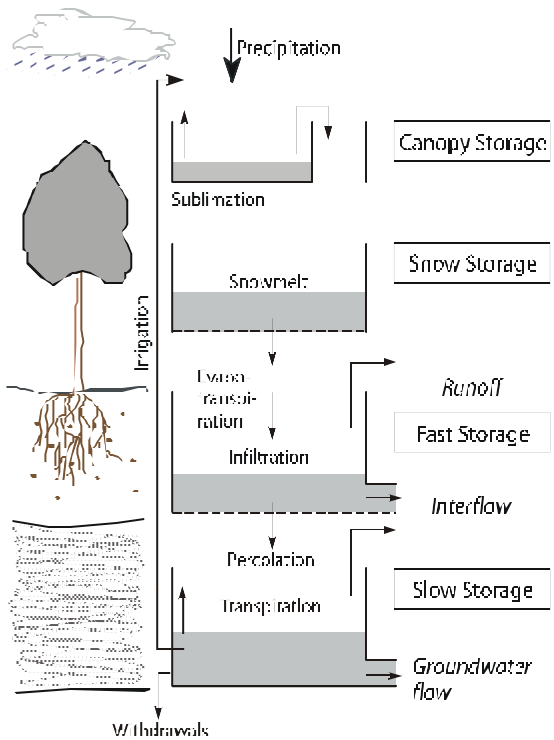
The Mekong Secretariat is currently evaluating the IQQM (Integrated Quantity and Quality) model developed by the Department of Land and Water Conservation, New South Wales, Australia, for the main river between Chiang Saen and Kratie. This is a model developed mainly for irrigated agriculture so it is questionable how appropriate this will be.

The SLURP Hydrological Model

SLURP (Kite 2000) 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 first divides a basin into sub-basins using topography from a digital elevation map. These sub-basins are further divided into areas of different land covers using data from a digital land cover classification. Each land cover class has a distinct set of parameters in the model. If the model is applied to a basin that contains land covers used in previous studies, no calibration of the parameters is needed. If the basin contains a land cover that has not been used before, then the parameters for that land cover must be estimated or calibrated. For the Mekong, a first estimate of the parameters for comparable land covers was taken from a previous application of the model (Kite and Droogers 1999).

The hydrological model simulates the vertical water balance for each land cover within each sub-basin at a daily timestep. That is, the model approximates the physical processes controlling the transformation of precipitation into evapotranspiration and runoff separately for each land cover within each sub-basin. Each element of the sub-basin/land cover matrix is represented by four nonlinear reservoirs or tanks representing canopy interception, snowpack, fast storage, and slow storage. The outputs of each vertical water balance include evaporation, transpiration, runoff, groundwater flow and changes in canopy storage, snowpack, soil moisture and groundwater.

FIGURE 1



Vertical water balance of sub-basin/land cover element (Kite 2000).

The model has previously been applied in many countries for basins ranging in size from prairie sloughs measuring only a few hectares (Su, Stolte, and Kamp 1997) to large basins such as the Mackenzie with an area of 1.8 million square kilometers (Kite, Dalton, and Dion 1994) and has been designed to make maximum use of remotely sensed data. Applications of the model have included studies of climate change (Kite 1993), hydropower (Kite, Danard, and Li 1998), water productivity (Droogers and Kite 1999), irrigation (Kite and Droogers 1999) and wildlife refuges (de Voogt et al. 2000).

The precipitation data for each sub-basin were derived from the Internet data from 17 climate stations within the Mekong Basin using nearest neighbor algorithms and then adjusted to the mean elevation of each land cover using a 5 percent increase per 100 m rise in elevation, with a maximum possible change of 50 percent above that recorded.

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

$$? \; ?ET \; ? \; \frac{s(Q^{*} \; ? \; G)}{s \; ? \; ?(1 \; ? \; \frac{r_s}{r_a})} \; ? \; \frac{? _a c_p \frac{e_s \, ? e_a}{r_a}}{s \; ? \; ?(1 \; ? \; \frac{r_s}{r_a})} \qquad (1)$$

where, ? 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, ? 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, $?_a$ is the air density, and c_p is the heat capacity of moist air.

The net radiation and vapor pressures for each site are interpolated from data available on the Internet. The resulting evapotranspirative demand is 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 leaf capacity by the leaf area index (LAI) for a particular crop and date. The LAI data are derived from NDVI (Normalized Difference Vegetation Index) data obtained from NOAA AVHRR (National Oceanic and Atmospheric Administration, Advanced Very High Resolution Radiometer) satellite images from the Internet. 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 that soil water storage, which provides the rapid-response part of the streamflow hydrograph.

$$Inf \; ? \; ?1 \, ? \, \frac{S_1}{S_{1,\max}} ? ? Inf_{\max} \qquad (2)$$

Here, 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}) specified for the particular land cover. If the current infiltration rate is not sufficient to transmit all the excess 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 sub-basin 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 sub-basin. For first-order sub-basins (those that 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 sub-basins, either the Muskingum or Muskingum/Cunge routing method is used to describe the relationship between inflow, outflow and storage of the channel reach. The Muskingum weight function, x, is set to a default value of 0.25 and the time of travel, K, is computed from the change in elevation along the stream channel, DZ, (Institute of Hydrology 1995) as:

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

Applying the SLURP Hydrological Model

The SLURP hydrological model was applied in two stages. First the model was applied to the entire Mekong Basin using only data available from the Internet or from public-domain datasets. Such data included elevations, land cover, vegetation indices, climate and streamflow. However, one of the most interesting features of the Mekong Basin is the fact that flows in the Tonle Sap River, between the Mekong River and the Tonle Sap or Great Lake in Cambodia, change direction during the year. Not sufficient data were available on the Internet to model this phenomenon and so a second phase of development used hydrologic and hydraulic data made available by the Mekong Basin Secretariat to model the Tonle Sap.

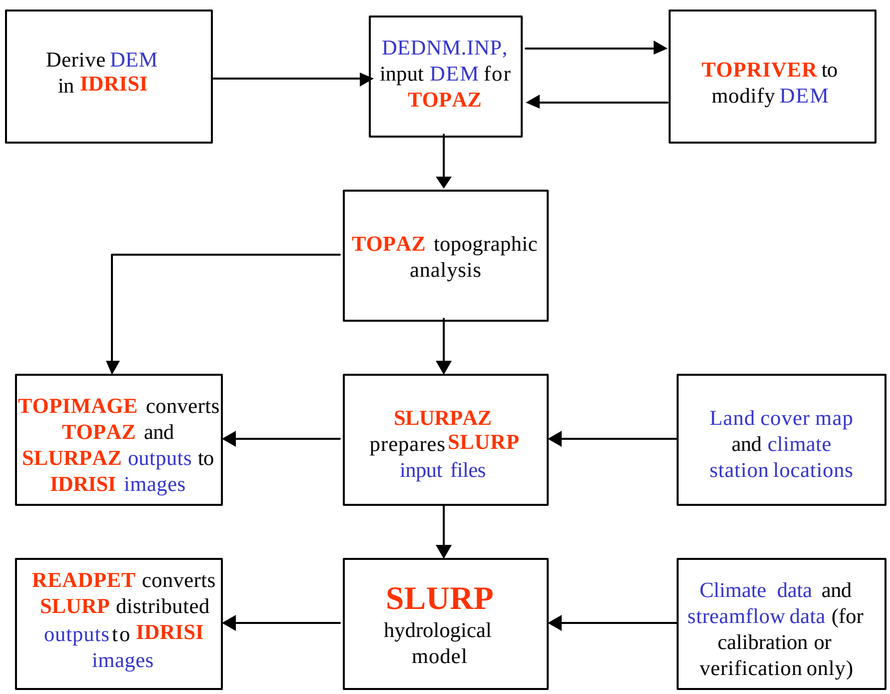
FIRST PHASE: MODELING THE MEKONG USING PUBLIC-DOMAIN DATA

The first phase of model development used only data from the Internet and from public-domain datasets. The following paragraphs briefly describe how the various types of data needed to run the hydrological model were prepared and how the model was applied.

The general sequence of programs and data are shown in figure 2, starting from the preparation of a digital elevation model (DEM) and its analysis using topographic software to the development of a land cover map, the derivation of climate data, running the SLURP model and the preparation of output data.

More details of the derivation of the digital elevation model (DEM), the land cover map, the climate, streamflow, and soil data are given in the appendices to this report.

FIGURE 2.



Definition of the basin, sub-basins, 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 Mekong Basin we used the United States Geological Survey (USGS) GTOPO30 public-domain DEM on the Internet (Internet 1) to define the basin, sub-basins, elevations and distances needed for the hydrological model.

The 30 arc-second resolution DEM was first prepared in a geographic information system (GIS) where elevations may be adjusted, if necessary to ensure channel continuity. In this case we used IDRISI (Eastman 1997).

The United States Department of Agriculture/University of Saskatchewan digital terrain analysis model TOPAZ (Garbrecht and Martz 1997) was used to derive the basin topography from the DEM. Figure 3 shows the programs and datasets used in TOPAZ.

Figures 4 and 5 show the basin outline and sub-basins derived by TOPAZ and the stream network derived by TOPAZ.

Note that the derived stream network includes only a single path through the Mekong Delta. This is because the entire Delta lies within a 1 m contour, the vertical accuracy of the DEM. If necessary, further detail could be added.

FIGURE 3.

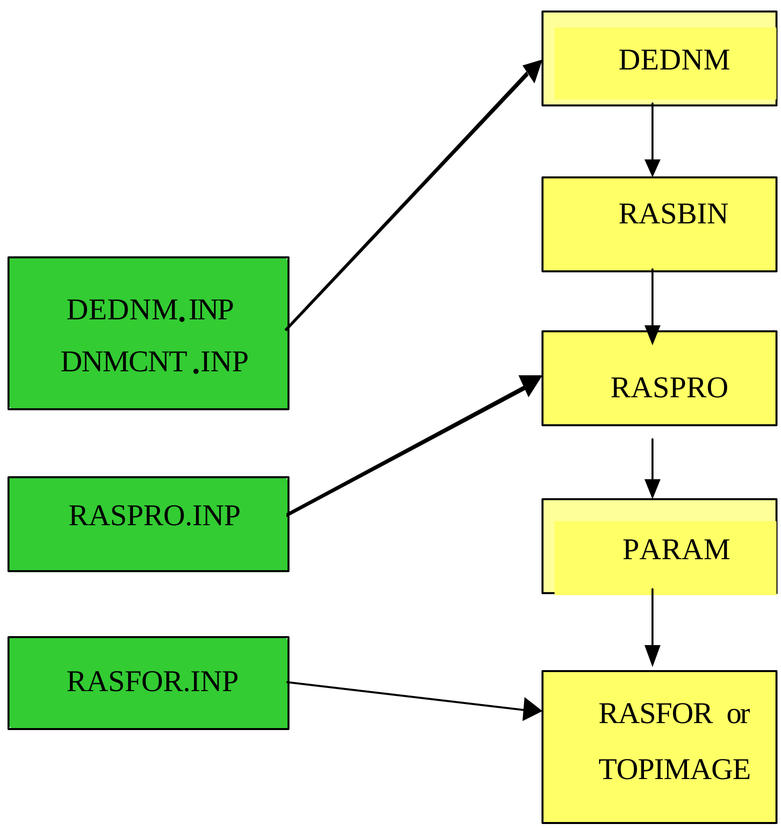
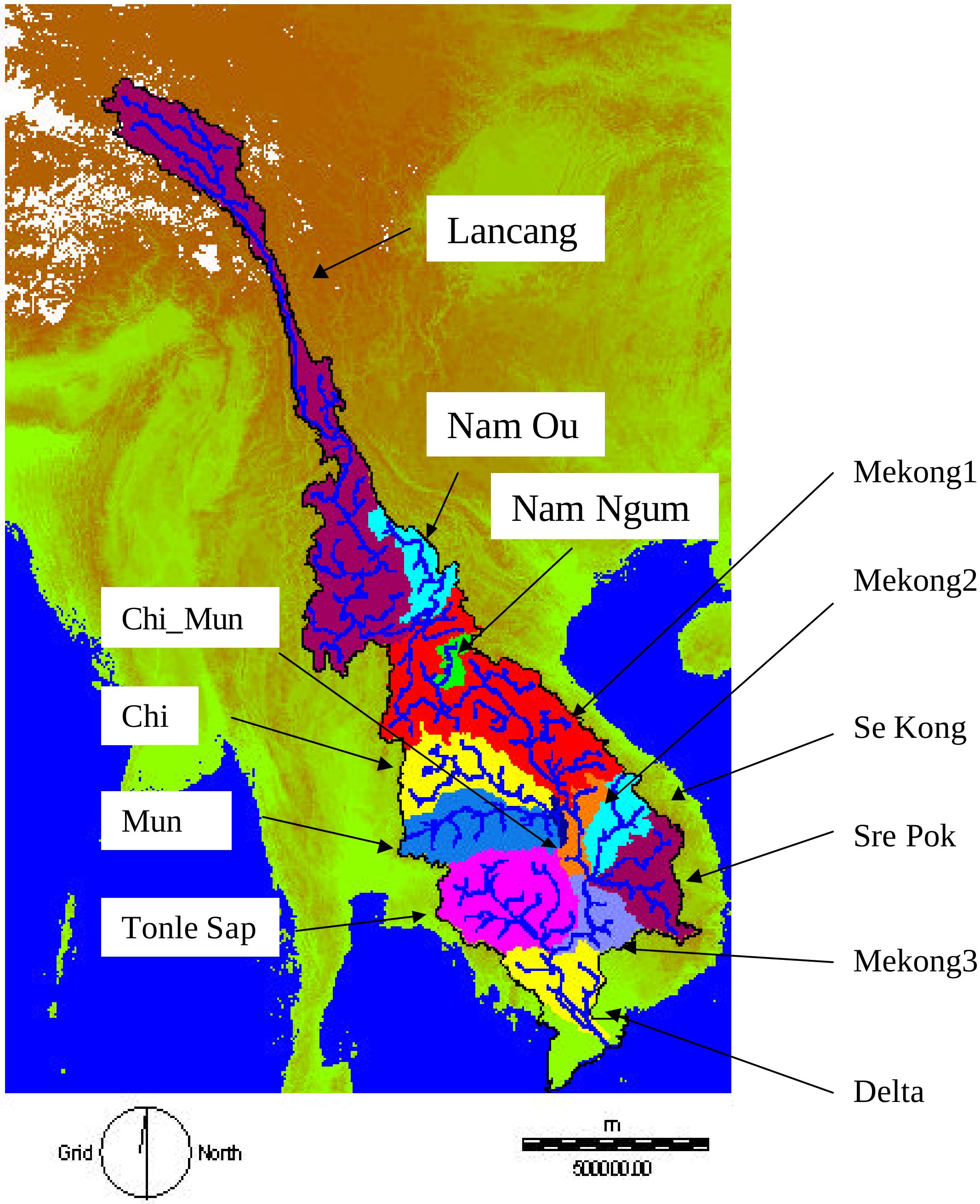


FIGURE 4.


Lancang
Nam Ou
Nam Ngum
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Mekong2
Chi_Mun
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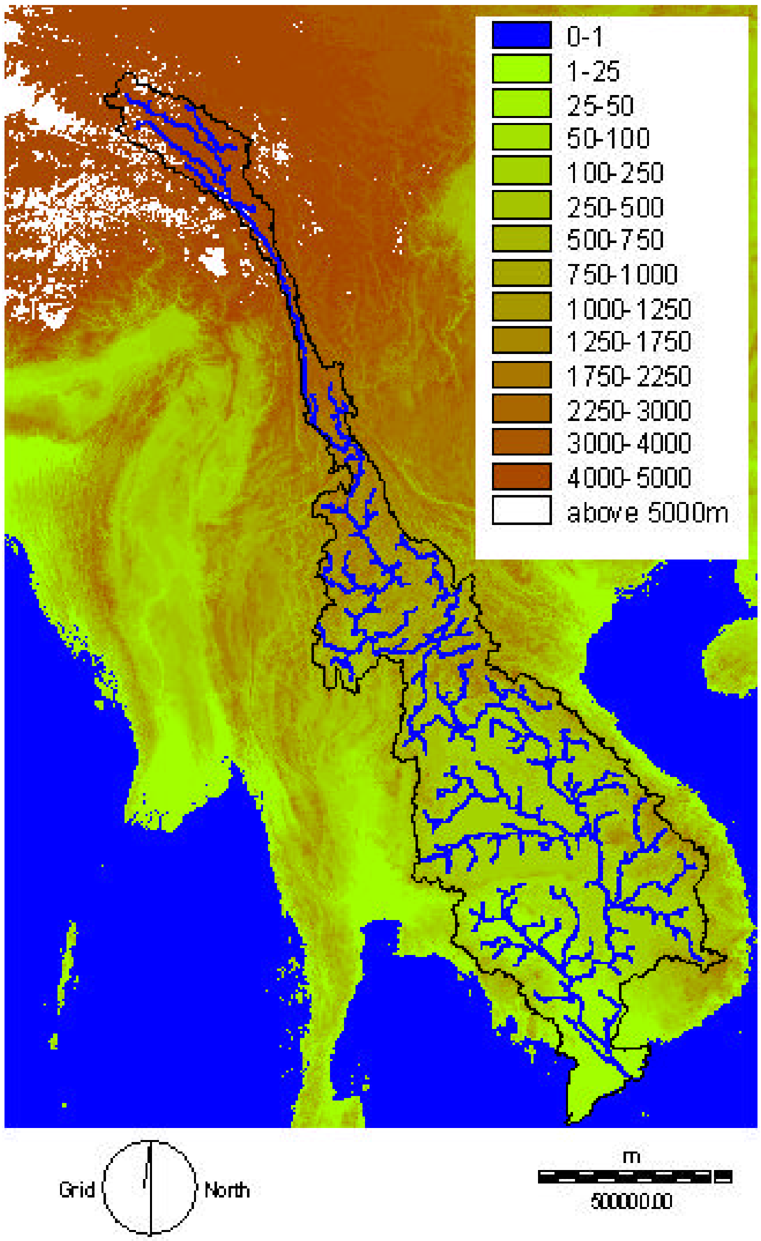
F IGURE 5.

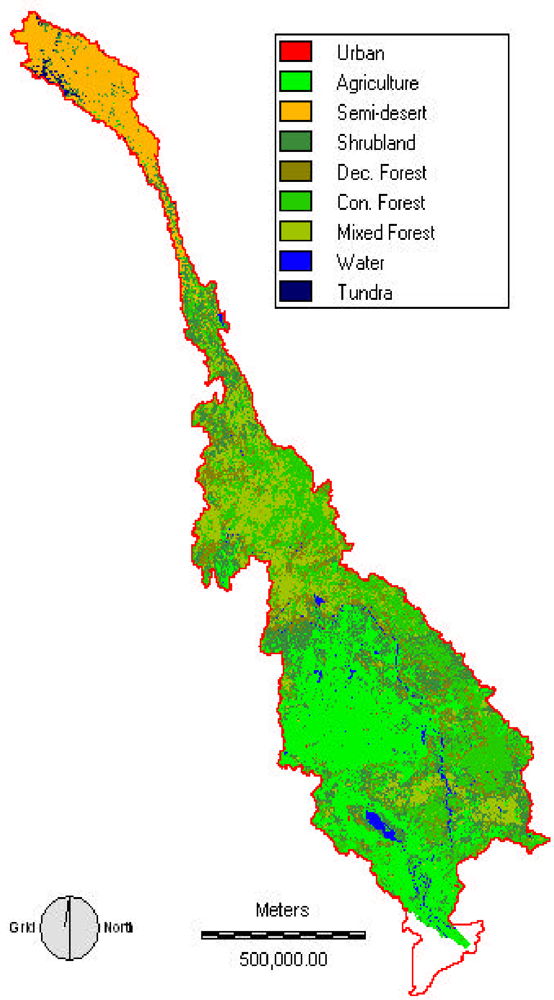

0-1
1-25
25-50
50-100
100-250
250-500
500-750
750-1000
1000-1250
1250-1750
1750-2250
2250-3000
3000-4000
4000-5000
above 5000m
Grid
North
m
500000.00

Derivation of land cover classification

The SLURP model carries out a vertical water balance for each land cover within each sub-basin separately and therefore needs information on the distribution of the various land covers within the basin. For the Mekong Basin, the USGS 1km digital land cover map of the world (Internet 2) was used. This divides the entire globe into 24 land classes. For the Mekong, we reclassified the number of land classes down to 7. The final land classification is shown figure 6.

Although SLURP does not use soil data directly, soil information may be used to derive some of the model parameters such as wilting point and field capacity through pedotransfer functions (Droogers and Kite 1999). For the Mekong Basin, the FAO Digital Soil Map of the World (FAO 1998) was used.

FIGURE 6.



Obtaining climate data

The SLURP model requires precipitation, temperature, humidity, and radiation data for each sub-basin 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 U.S. National Climate Data Centre (NCDC). The first, Global Daily Summary (GDS), contains daily precipitation, maximum temperature and minimum temperature for 10,000 stations worldwide for the period 1977–1991. The second NCDC dataset, Global Surface Summary of the Day (GSOD) (Internet 3), contains 13 daily parameters including precipitation, temperature, dew point and wind for 8,000 global stations for the period 1994 to date.

For the Mekong Basin, it was decided to use data from January 1994 to December 1998 from the GSOD database. A program was written to extract the data from the GSOD database for the required stations and convert them to metric units. Since no radiation or sunshine hours data 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 given 0 hours of bright sunshine, days with zero precipitation were assumed to have the maximum theoretical hours of bright sunshine and, for those days with precipitation between 0 and 25 mm, hours of bright sunshine were computed proportionately. These approximations have been used in other studies (Kite, Dalton, and Dion 1998) but no sensitivity analyses have been performed.

Figure 7 shows the sequence of programs and data used to extract the climate station data from the GSOD archive. From the GSOD list of 901 stations in or close to the Mekong Basin, it was found that only 17 stations actually had significant data. The station locations are shown in figure 8.

If stations have short records or many missing data then they may need to be replaced by other stations when computing the distributed climate data. For example, for the Mekong, stations 561250 and 568560 in Sichuan sub-basin were replaced by 560180 and 569770, respectively. The replacement stations were selected because they are at elevations similar to the original stations and have more complete records.

It can be seen that the distribution of the stations is far from ideal; only those parts of the basin in China and Thailand have data available in GSOD. The mean annual distribution of precipitation over the basin derived from the IWMI Atlas (see figure 9) shows high rainfall areas in Laos that will not be correctly simulated from the stations shown above.

In the second phase of the modeling study, further climate data were obtained from the Mekong River Commission and used to improve the performance of the model.

FIGURE 7.

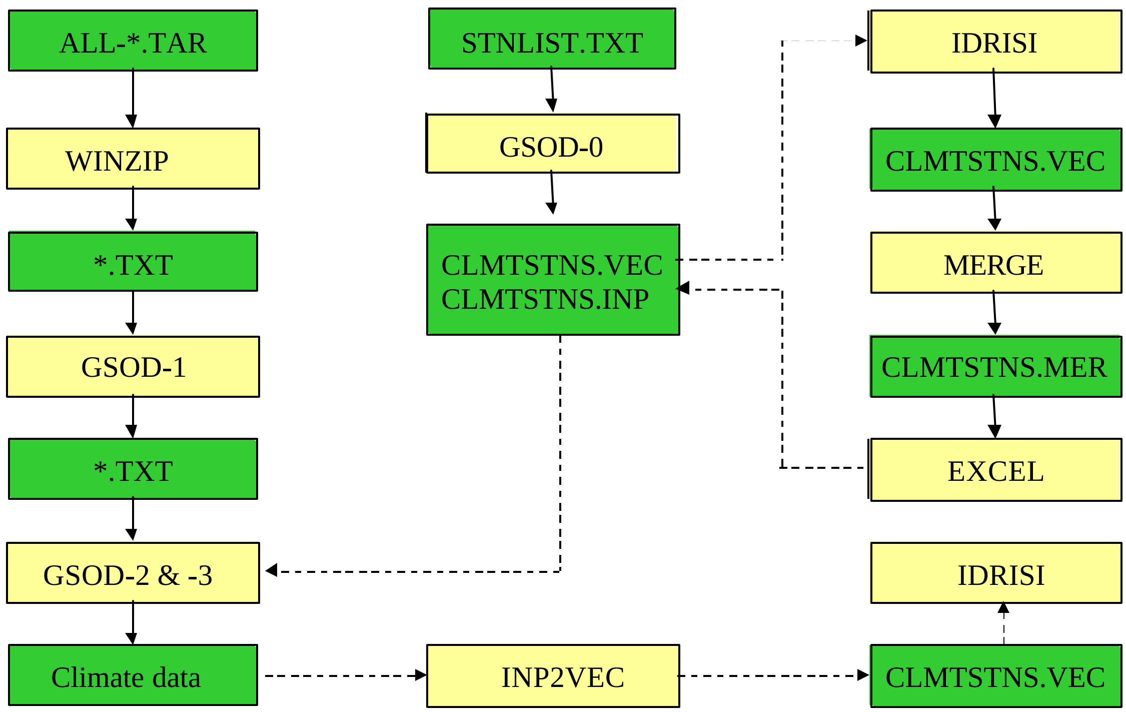

ALL-*.TAR
WINZIP
*.TXT
GSOD-1
*.TXT
GSOD-2 & -3
Climate data
STNLIST.TXT
GSOD-0
CLMTSTNS.VEC
CLMTSTNS.INP
INP2VEC
IDRISI
CLMTSTNS.VEC
MERGE
CLMTSTNS.MER
EXCEL
IDRISI
CLMTSTNS.VEC

FIGURE 8.

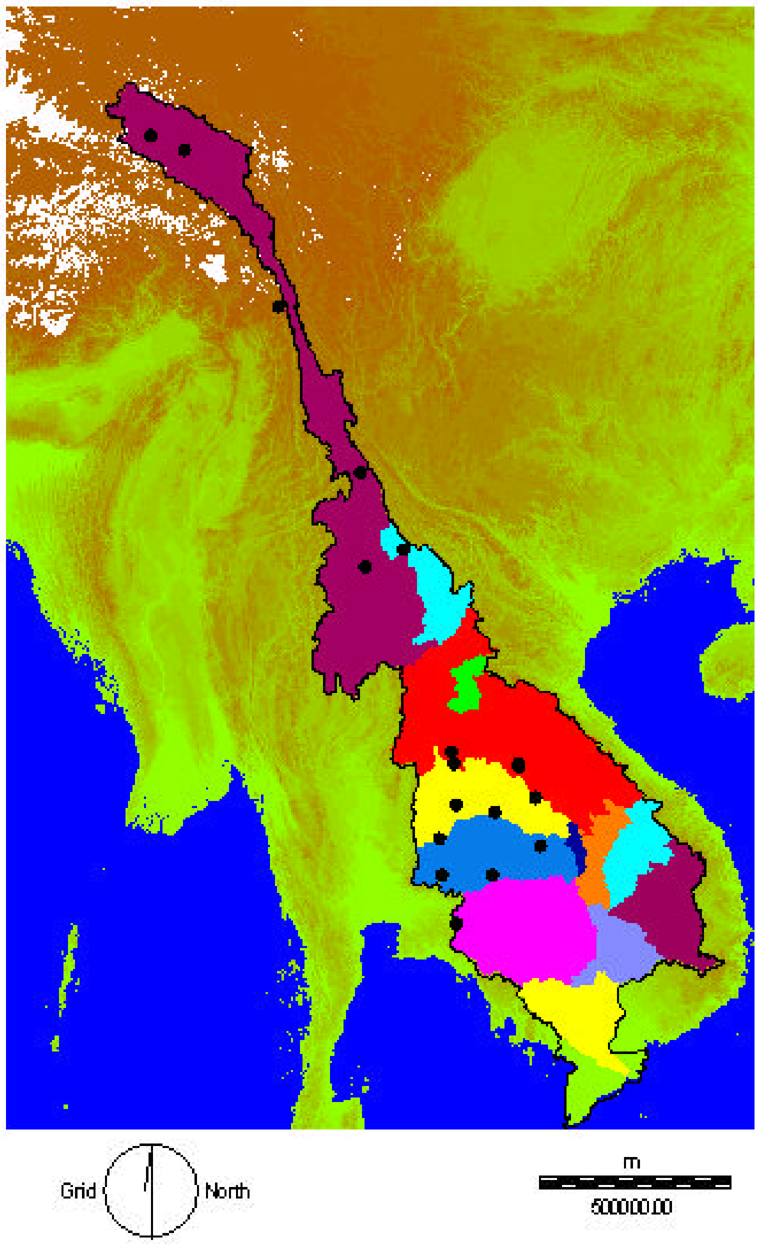
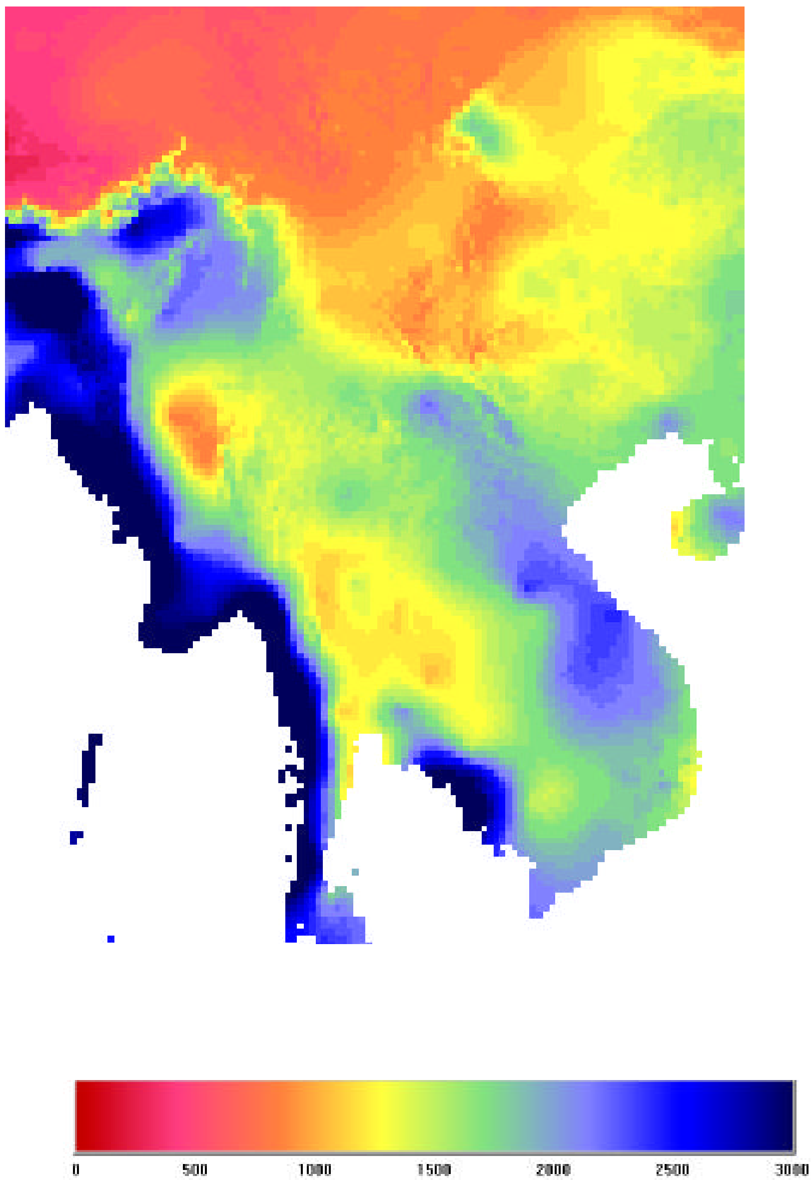


FIGURE 9.



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 sub-basin areas and elevations, land cover percentages within each sub-basin, distances and changes in elevation both to stream and downstream and the sequence of flows from sub-basin to sub-basin.

The output files from SLURPAZ will be given the default names TEMP.CMD, TEMP.WTS, TEMP.MOR, TEMP.SB, and TEMP.GRA, which must be changed to some more meaningful name using Windows Explorer or a similar program.

SLURPAZ assigns default sub-basin names such as ASA00002 in the output files. For convenience, these should be replaced by appropriate names in the .CMD, .WTS and .MOR files using an editor or using Option 3 of the SLURP main menu. The replacement names will then be used in all subsequent analyses. If the names are longer than 8 characters, they will be abbreviated to 8 in the model outputs. Table 1 lists the equivalencies for the 12 sub-basins used in the Mekong Basin.

Table 1.

Default name	Replacement name
ASA00002	Delta
ASA00003	Tonle Sap
ASA00004	Mekong3
ASA00006	Mekong2
ASA00007	Chi_Mun
ASA00008	Mun
ASA00009	Chi
ASA00010	Mekong1
ASA00011	Lancang
ASA00012	Nam Ou
ASA00013	Se Kong
ASA00014	Sre Pok

Similarly, the topographic analysis will name the land covers, LCOVR----A, etc. These names should be replaced in the .PM, .SB and .GRA files using an editor or Option 3 of the SLURP main menu. The replacement land cover names will then be used in all subsequent analyses. If the names are longer than 10 characters, they will be abbreviated to 10 in the model outputs. Table 2 lists the equivalencies used for the Mekong Basin.

Table 2.

Default Land Cover	Replacement Name
LCOVR----A	Urban
LCOVR----B	Crop/grass
LCOVR----C	Crop/pasture
LCOVR----D	Semi-desert
LCOVR----E	Shrubland
LCOVR----F	Deciduous forest
LCOVR----G	Evergreen forest
LCOVR----H	Mixed forest
LCOVR----I	Water
LCOVR----J	Tundra

The parameters of the SLURP model, such as the maximum infiltration rate, are related to the land covers. If the land covers have been used before in another basin, then we assume that the same parameters should be applicable in the new basin. For the Mekong Basin, parameters for crop/grassland, crop/pasture, shrubland, evergreen forest, and water were used from other basins previously modeled. Parameters for urban areas, deciduous forest, semi-desert and tundra were estimated. All parameters can be revised during the model runs.

Obtaining streamflow data

No daily streamflow to validate or calibrate the Mekong model are available on the Internet or from public domain data CDs. However, monthly streamflow data are available from the International Satellite Land Surface Climatology Project (ISLSCP 1995) and from the Oak Ridge National Laboratory (ORNL 1999 and Internet 4). For the Mekong Basin, the following stations (table 3) are available:

Table 3.

Station No.	Location	Country	Period of record	Closest sub-basin
2469260	Mekong at Pakxe	Laos	1980–1990	Pakxe
18900	Mekong at Chiang Saen	Thailand	1960–1987	Sichuan
391000	Mekong at Mukdahan	Thailand	1924–1987	Vientiane
43100	Chi at Yasothon	Thailand	1953–1987	Chi
10667	Mun at Ubon Rachathani	Thailand	1955–1987	Mun

It is emphasised that SLURP is a hydrologic/hydraulic model and does not include the hydrodynamic components that would be needed to model the multiple channels and braided channels of the Mekong in Cambodia nor the tidal influence and multiple channels of the Delta in Vietnam. In SLURP, the river is considered a single channel.

For the Mekong, river routing was carried out using the Muskingum method. Table 4 shows, for the river reach within each sub-basin, the drainage area, channel length and change in elevation and the parameters x and K of the Muskingum method.

Table 4

.Sub-basin	Area, km^2	Length, km	? H	x	K
Delta	40,930	344	6	0.25	15
Tonle Sap	87,530	247	7	0.25	20
Mekong3	28,000	337	63	0.25	10
Mekong2	20,780	260	38	0.25	10
Mun	48,830	238	30	0.25	10
Chi	53,270	317	39	0.25	10
Chi_Mun	20,290	142	9	0.25	5
Mekong1	167,200	1,189	224	0.25	25
Lancang	228,000	2,201	3,451	0.25	30
Nam Ou	31,040	196	165	0.25	12
Se Kong	28,910	141	12	0.25	10
Sre Pok	48,840	210	47	0.25	15

During the second phase of the study, daily streamflow data were obtained from the Mekong River Commission and used to improve the hydrological model.

Dams

Appendix F lists 21 existing and 38 planned dams on the Mekong River and its tributaries using data from Rothert (1995), ICOLD (1988), Plinston and Daming (1999), MRC(1994), Kreuze (1998), Oud and Muir(1999), and Long [13]. Much information is unavailable and some of the data (particularly reservoir areas) are of doubtful accuracy.

Plinston and Daming (1999) list the dams planned and built in the Lancang cascade in China. The Mannwan was completed in 1993, the Dachaoshan will be completed in 2000, the Xiaowan in 2012, and five other dams are planned. Only when the Nuozhadu dam is completed in 2017 will there be sufficient storage volume to completely control seasonal flows and, at this stage, 23 percent of the interannual variation could also be controlled.

In northeast Thailand there are large irrigation projects on the Chi River at Nam Pong/Nong Wai and at Lam Pao. Lam Pao was constructed in the early 1970s (Jacobs 1998). The Institute of Hydrology (1988) estimates that the mean annual flow of the Chi has been reduced by 28 percent since construction began in 1965. There is also a large dam and reservoir at Shirinthom on the Mun River but no information is available. By the time the flows from the Chi and the Mun are combined and routed to the Mekong, no effects of the irrigation can be detected.

Laos has constructed several dams on tributaries to the Mekong such as Nam Theun, Nam Ngum, Nam Leuk, Houay Ho, Xe Kaman and Xe Pian-Xe Namnoi but, again, little information is available on the regulatory effects of these structures.

Dams on the Mekong and its tributaries affect not only the river flows but also the sediment load, which is important for riparian agriculture and fisheries. Plinston and Daming (1999) note that although China supplies only 16 percent of the long term average annual flow in the Mekong (as measured at its outlet to the South China Sea), over 50 percent of the estimated 150-170 million tons per year of sediment load carried in the lower Mekong comes from China. Dams and reservoirs will trap sediment. It is expected, for example, that the dead storage of the Manwan reservoir (662 million cubic metres) will be filled within 15-20 years. However, since the sediment-free river below the reservoirs will scour the bed and erode more sediment, it is not clear that the planned dams and reservoirs will significantly affect sediment loads in the Lower Mekong.

Appendix F details how existing reservoirs were included in the SLURP model. The procedure involved many assumptions since almost no real data were available on operating procedures.

FIGURE 10

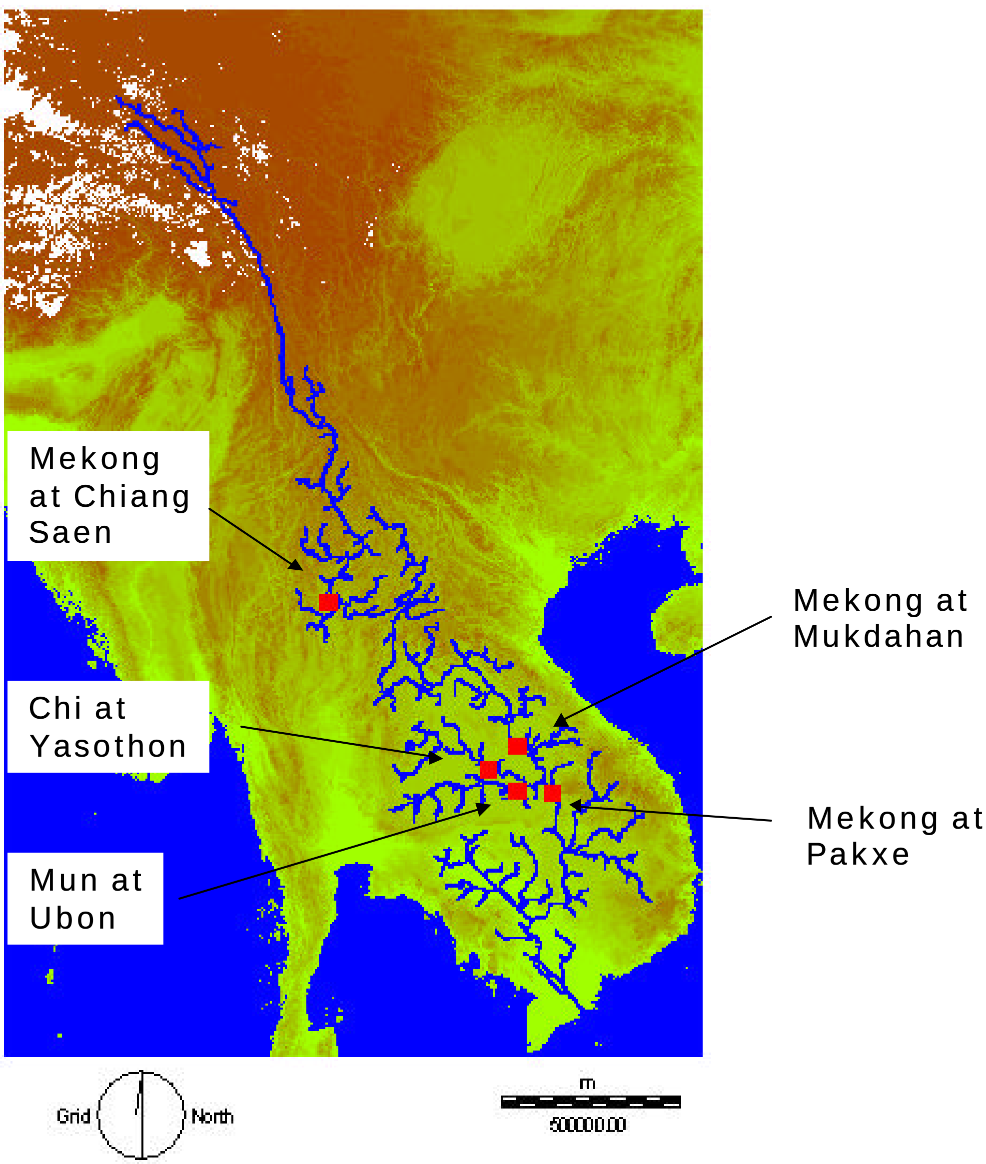
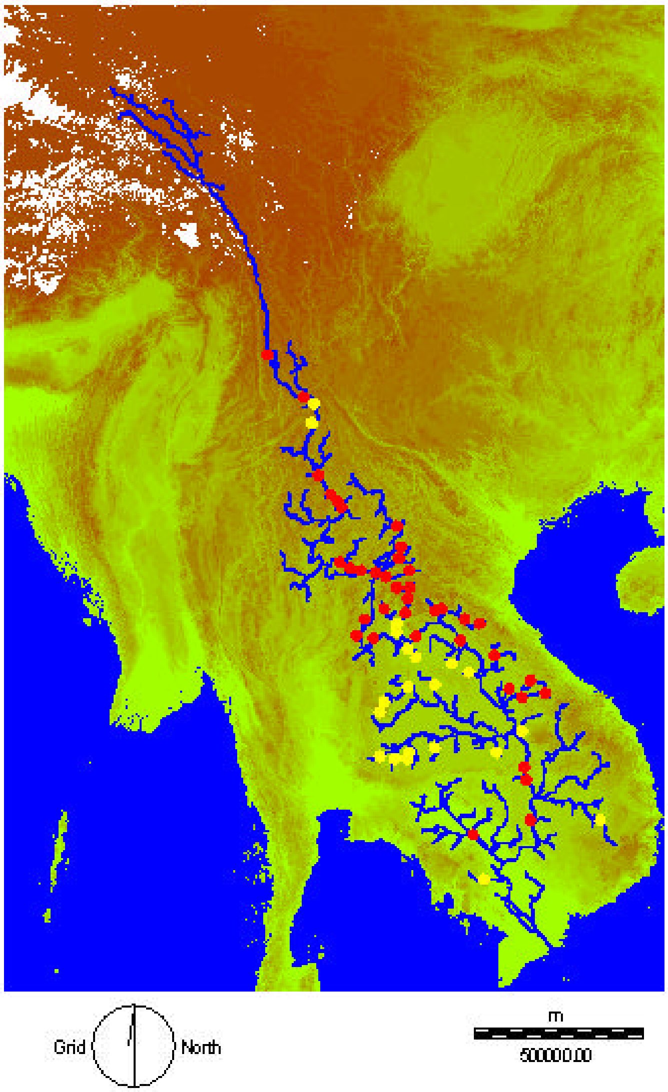


FIGURE 11.



Existing dams (yellow) and planned dams (red) on the Mekong River and its tributaries

SECOND PHASE: MODELING THE TONLE SAP

The first phase of this study applied the SLURP hydrological model (Kite 2000) to the Mekong River using only data from public-domain databases . In the second phase, the initial model was refined using additional data made available by the Mekong River Secretariat in Phnom Penh and a more detailed model of the Tonle Sap area was prepared in order to derive hydrologic and hydraulic data that can be used to investigate fisheries productivity. Further details of the modeling procedures are given in the appendices.

The Tonle Sap

Cambodia's Tonle Sap, or "Grand Lac," plays a vital role in the Mekong River system and in the Cambodian economy. In the dry season, the Great Lake's shallow waters cover roughly 3,000 square kilometers, and the lake drains slowly into the Mekong River. When the Mekong floods, from June to October, the flow in the main river backs up and forces water "upstream" into the Tonle Sap River and lake. The lake typically expands to more than 10,000 km^2 with an area at maximum recorded elevation (11 m) of 13,000 km^2. The flooded area around the Tonle Sap is constrained by the roads from Prek Kdam to Kompong Cham, Krator and Kompong Chen. As floodwaters reach the surrounding forest and agricultural areas, the lake receives a massive influx of nutrients that triggers a surge in productivity. When the Mekong flood subsides, the flows in the Tonle Sap River change direction and flow normally downstream to the confluence with the Mekong at Phnom Penh. The Tonle Sap is renowned as one of the most productive freshwater ecosystems in the world (Pantulu 1981), supporting 60-75 percent of the inland fishery in Cambodia, with harvests that have historically reached 100,000 tons per year. After rice, fish is the most important component of the Cambodian diet, accounting for as much as 80 percent of the animal protein consumed.

In addition to serving important functions in the local economy and society, the Tonle Sap plays a key role in the larger Mekong River system. During the rainy season, the natural floodwater storage capacity of the lake lessens the degree of flooding downstream; and during the dry season, the natural release of water from the lake augments irrigation and drinking water supplies downstream. In addition, the Tonle Sap provides critical spawning and other habitat to many important migratory fish species, including the giant catfishes, Catlocarpio siamensis and Pangasionadon gigas. Fish known to spawn or rear in the productive flooded areas of the Tonle Sap are caught by subsistence and commercial fishermen far up the Mekong River (Pantulu 1986).

Figure 12 shows the relationship between the main Mekong River flowing southwards through Kratie to Phnom Penh and the Mekong Delta, the Tonle Sap lake and river and the Bassac River. Figure 13 shows the seasonal changes in flows in the Mekong River at Kratie (Compagnie Nationale du Rhone 1994) and the Tonle Sap River at Prek Kdam (Institute of Hydrology 1988) with the level of the Tonle Sap lake at Kompong Luong (Sopharith 1996). Since these data are not all from the same year, they should be regarded as indicative only.

FIGURE 12.

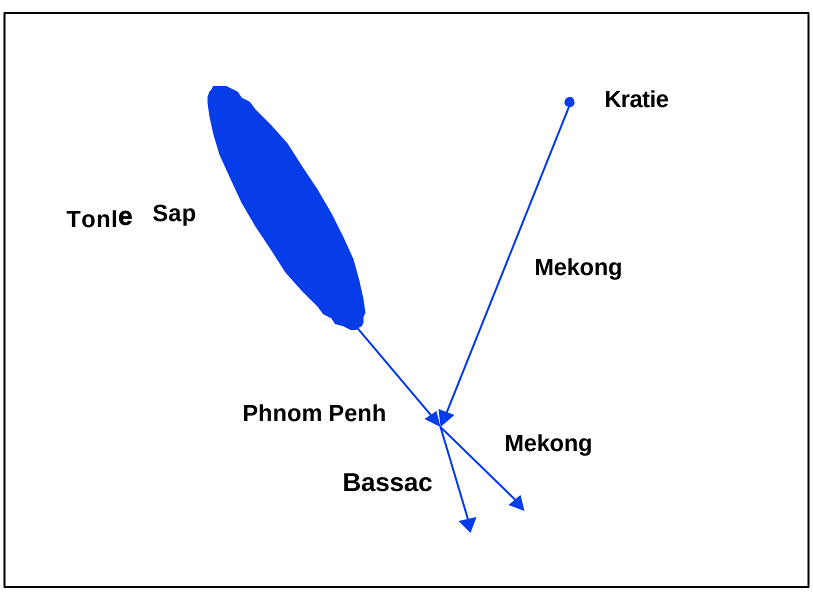
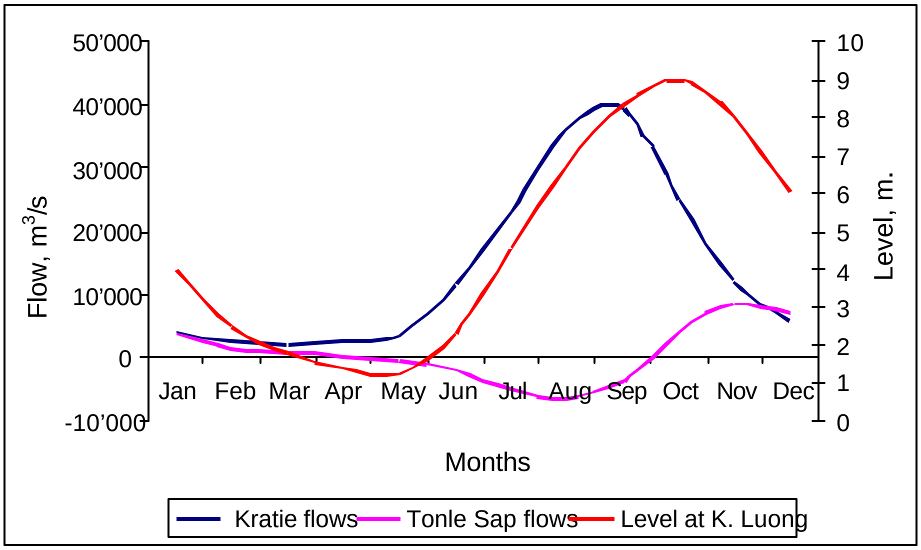


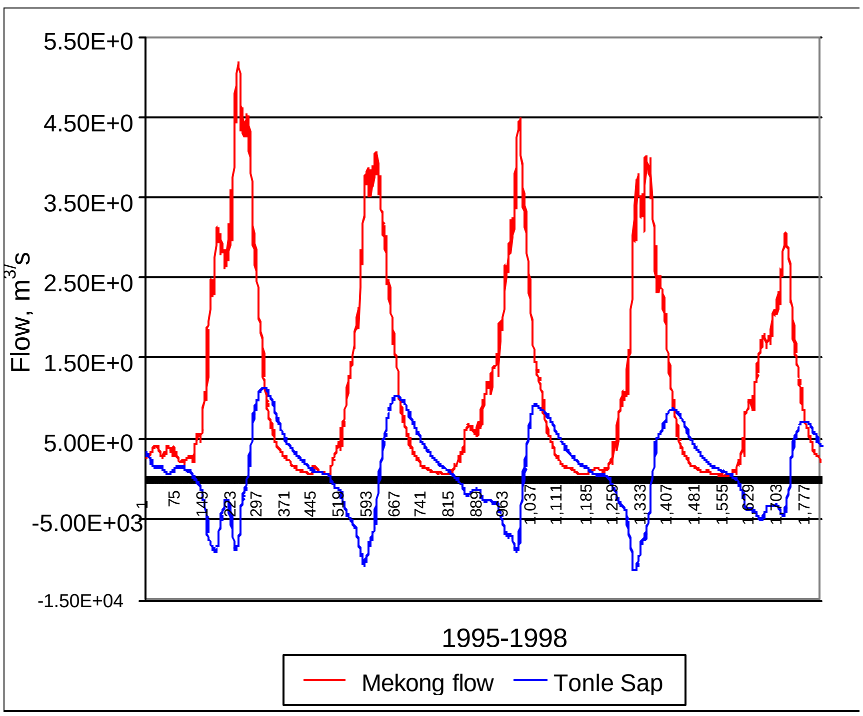
FIGURE 13.



Results

The SLURP hydrological model has been applied at a daily time interval from 1 January 1994 to 31 December 1998. The model simulates streamflow at many points along the length of the Mekong and its tributaries and includes the effects of many existing dams. Figure 14 shows the simulated flows of the Mekong at Pakxe and the Tonle Sap River, as examples. Note the reversing flows in the Tonle Sap.

FIGURE 14.

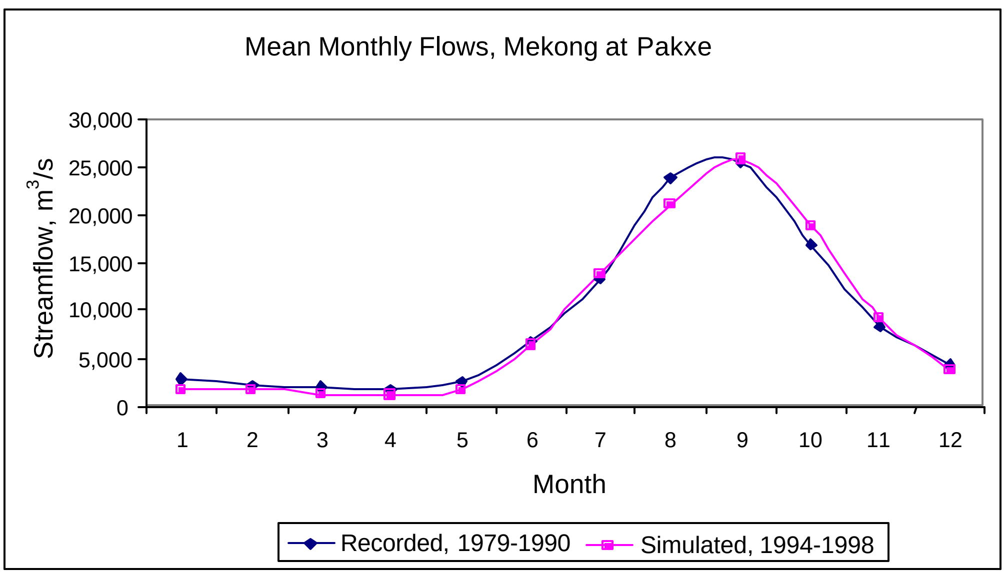


To verify the performance of the model we would need to compare the simulated streamflow with recorded data. However, none of the periods of recorded streamflow available on the Internet coincides with the period of SLURP simulation. Therefore, the model was validated by comparing the mean monthly simulated hydrographs for 1994–1998 with the mean monthly observed hydrographs for the periods of record of each station.

The hydrometric stations are usually not located at the outlets of the sub-basins used in the model and so simulated flows must be adjusted on the basis of the upstream areas.

Figure 15 shows a comparison between the observed and the area-adjusted simulated flows for the Mekong at Pakxe. It can be seen that the annual volumes are comparable but that the simulated flows peak earlier in the year than the observed flows. This may reflect flow differences between the different periods used (it is known that no discharge measurements have been made at Pakxe since 1992) or may be an error in the model.

FIGURE 15.



Similarly, figure 16 compares the recorded flows in the Tonle Sap with those simulated by the SLURP model for the year 1962. Similar comparisons could be done using the data from the other recorded streamflow stations available on the Internet.

The simulated flows in the Tonle Sap river are converted to levels in the Tonle Sap lake and, using the digital elevation model described in the appendix, converted to flooded area, shown in figure 17.

Combining the level-area relationship shown above with a land cover classification for 1992-1993 based on Landsat TM 30m. pixels (figure 18), the flooded area of each land cover can be determined at each lake level.

FIGURE 16

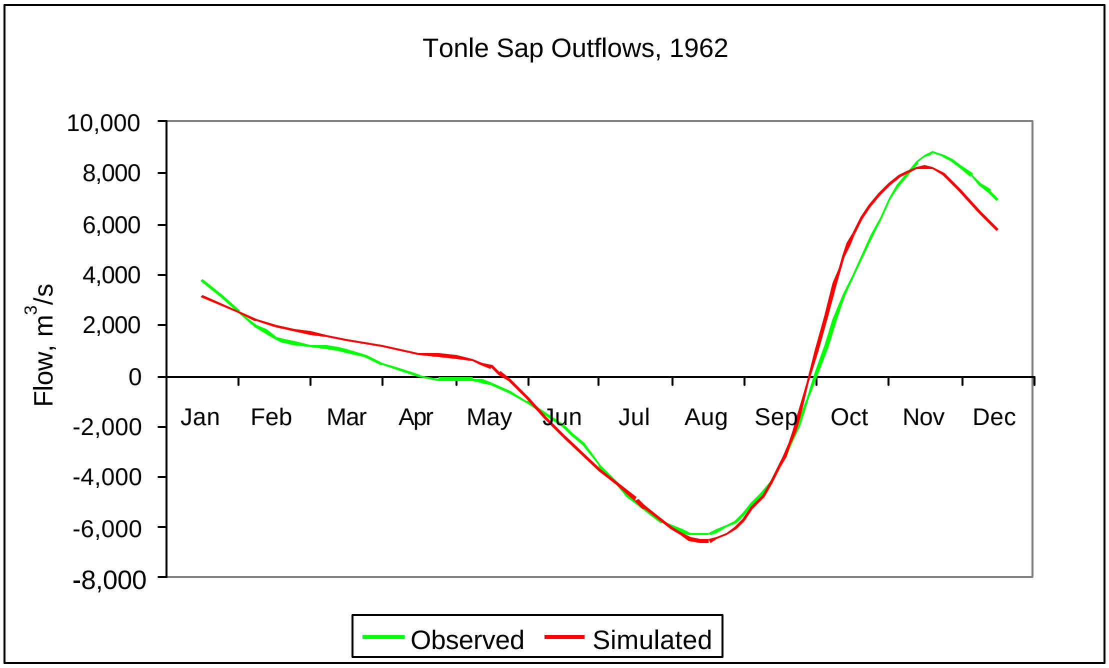


FIGURE 17.

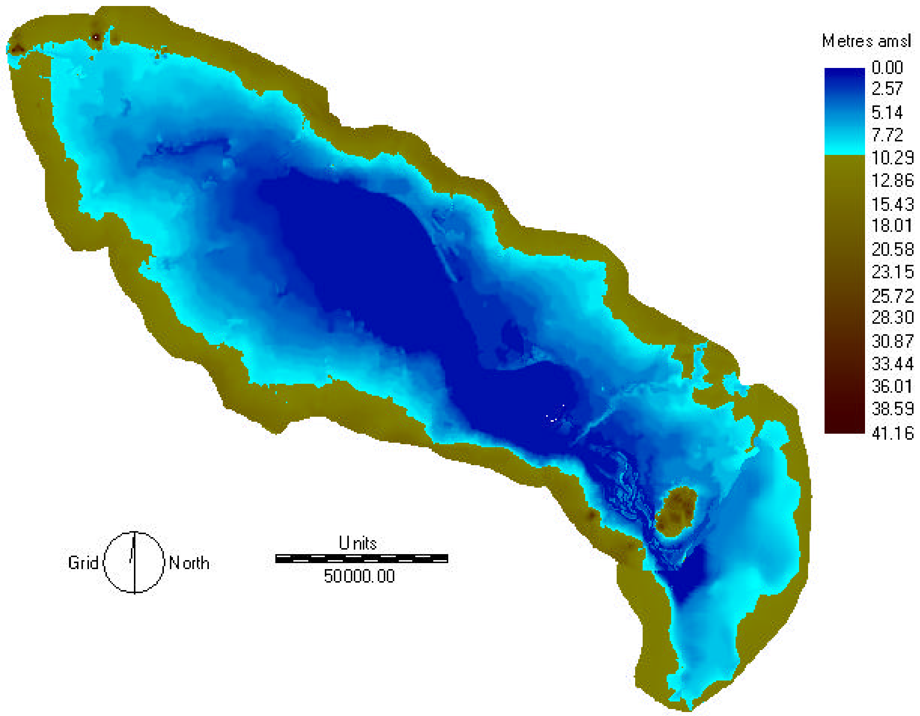


FIGURE 18.

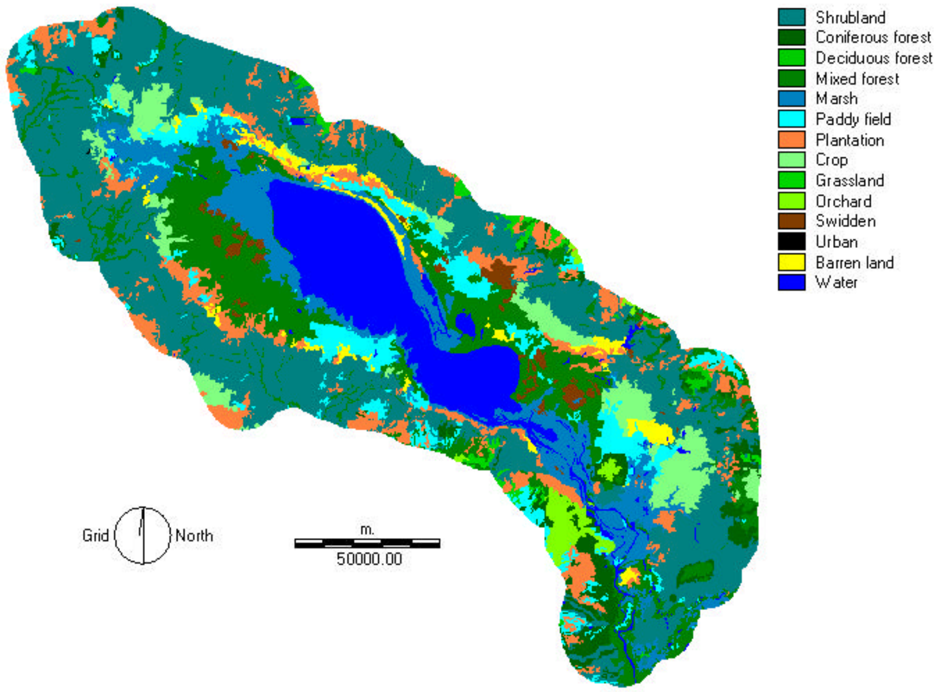
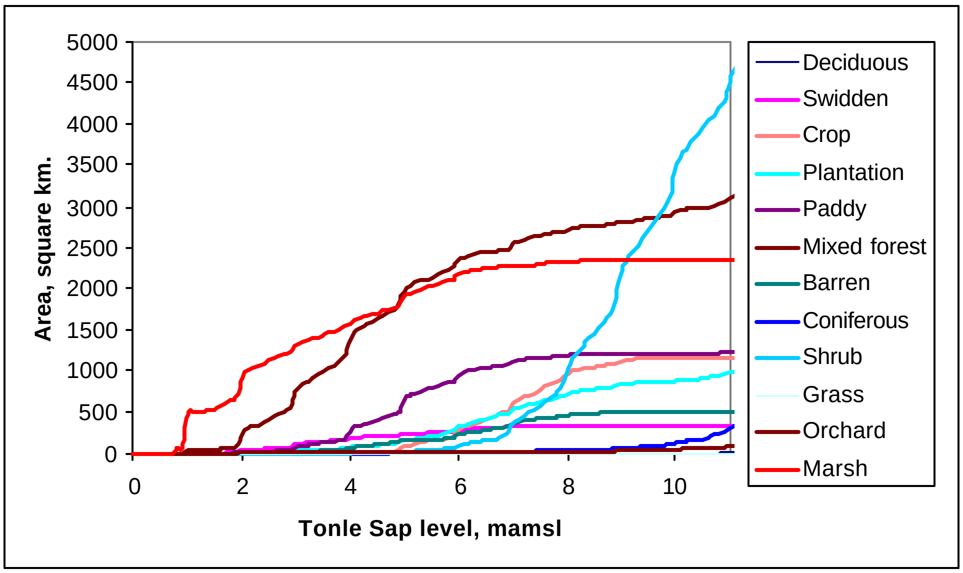


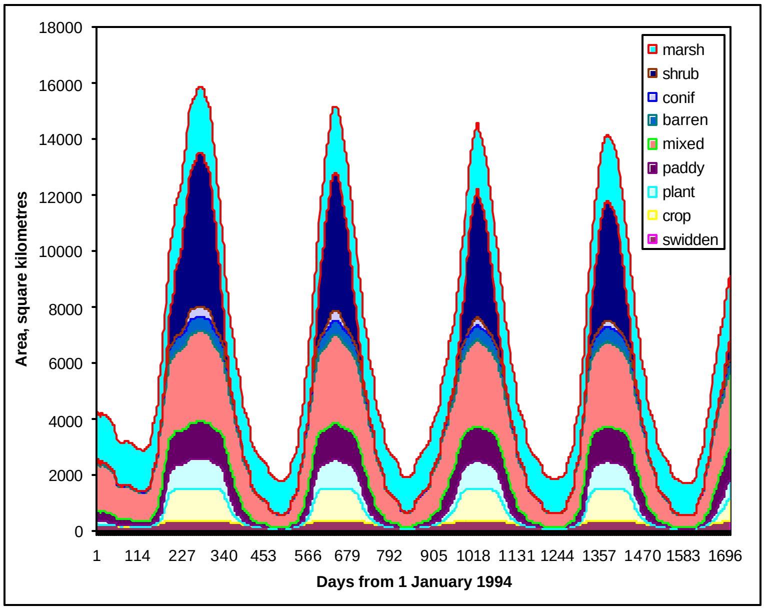
FIGURE 19.



Note: mamsl = meters above mean sea level.

Combining the simulated lake levels with the level vs. flooded area relationships for each land cover, we can produce time series of flooded areas for each land cover as shown in figure 20. This information may then be used to determine fisheries productivity.

FIGURE 20.



Stacked areas of land cover flooded by Tonle Sap.

CONCLUSIONS

This study has shown that the SLURP hydrological model can be successfully applied to simulate a large river basin using mainly data available on the Internet. A previous study (Lacroix, Kite, and Droogers 1999) has shown that the same model can be applied equally successfully to smaller basins in the same way.

There are two limitations to this type of application. The first is that not all types of data are available on the Internet. For the Mekong River study, in particular, the important types of missing data are fluvial hydraulics and information on river regulation. Fortunately, the fluvial hydraulics data such as levels and flows of lakes and connecting channels were available from the Mekong River Secretariat and were used to develop the routing procedures needed to simulate the reversing flows of the Tonle Sap River in the model..

Operating rules and reservoir characteristics for the existing dams on the Mekong and its tributaries were not available on the Internet nor from the Mekong River Commission. The model includes the effects of many existing dams (see Appendix F) by making many assumptions. Once the real data are available it will be a simple matter to change the data files used by SLURP to model the reservoirs more realistically. With the assumptions used, no major effects of the existing reservoirs on the levels of the Tonle Sap or on the outflows from the Mekong Delta were found.

The second limitation with the use of Internet data is that the available data are not always accurate or sufficient. For example, as described in the appendices, the 30 arc-second (approximately 1 km) resolution USGS DEM had to be modified before the topographic analysis software could correctly define the river channel in the Delta area and in the mountain gorge area of Yunnan Province. Also, it was found that the available climate stations were not well distributed across the basin. The climate data available on the Internet do not include radiation or sunshine hours which we had to interpolate from other variables.

Because of these shortcomings, the data available from the Internet were supplemented by data made available by the Mekong River Secretariat and the combined sets of data were used in the modeling. The model developed can be used to provide a useful water resources tool for the entire Mekong Basin. The model can be used to investigate issues such as water allocation between various interests, the effects of land use change or climate change on water resources, and the effects of dam construction on fisheries and other interests.

Appendix A

PREPARING A DEM

This appendix describes a suitable procedure to derive digital elevation data for a river basin. The example used and all data quoted are for the Mekong Basin using the USGS GTOPO30 (Internet 1) digital elevation model (DEM) and all references to GIS procedures use IDRISI 32 (Eastman 1997).

1. Download the DEM from the Internet:

   - determine the latitude and longitude range required for the basin (from Encarta or similar map), 8-35Nº latitude, 95-110ºE longitude. Allow plenty of room at this stage.

   - select the appropriate tile(s). GTOPO30 tiles are 40 degree longitude by 50 degree latitude rectangles. A list of tiles is provided in the file, README.TXT on the USGS website. The Mekong Basin falls into two tiles, E100N40.TGZ (10ºS - 40ºN latitude, 100-140º longitude), and E060N40.TGZ (10ºS - 40ºN latitude, 60-100º longitude). For this example, both were downloaded.

   - the tiles are in compressed and “tar” form and each contains 8 individual files. Uncompress the .TGZ file using TAR and GUNZIP programs or use Windows Commander or similar. Out of the 8 files per tile only the .DEM is required. The .HED will give information about the tile.

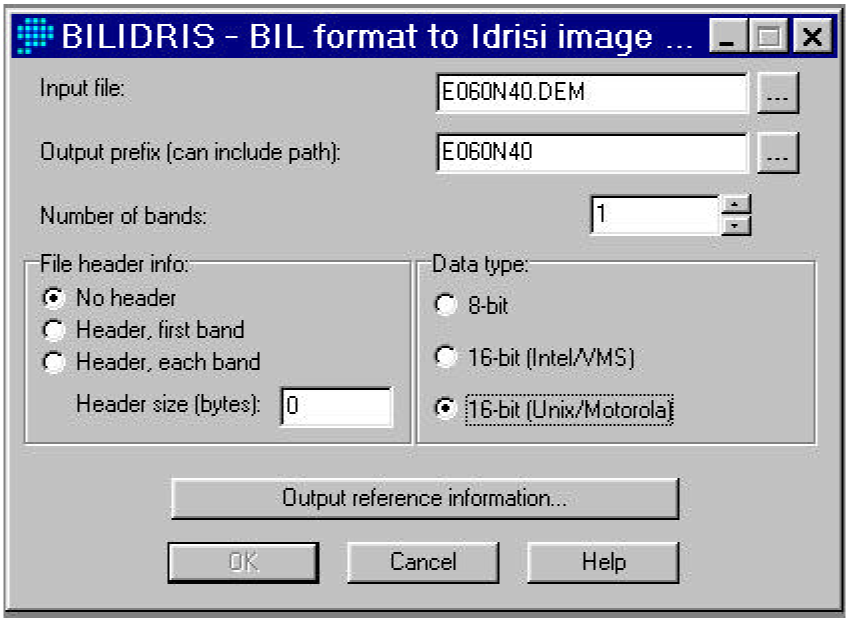
2. Import the DEM tile into IDRISI.

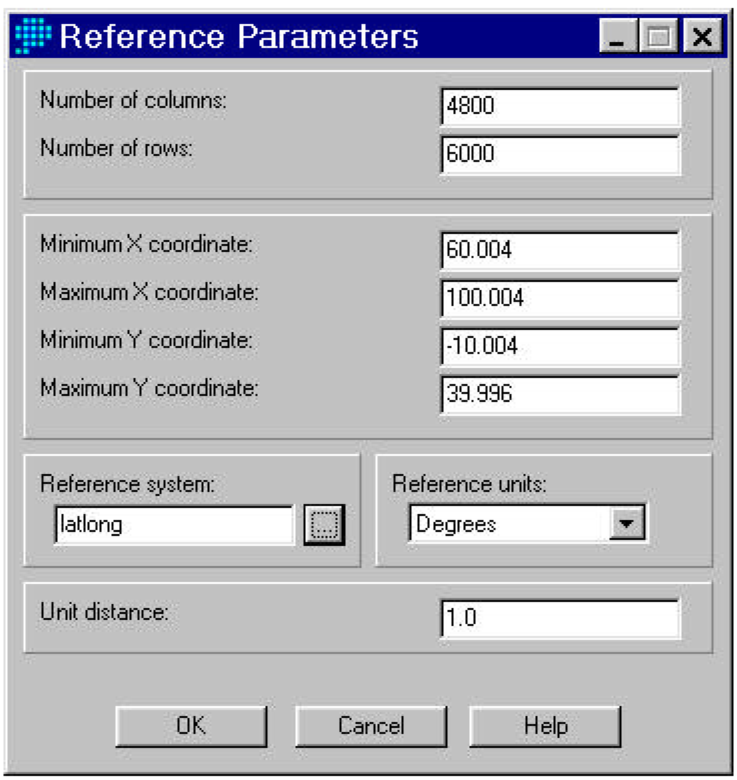
   - set the IDRISI environment to your working directory with:

     \File\Data Paths\Project environment.

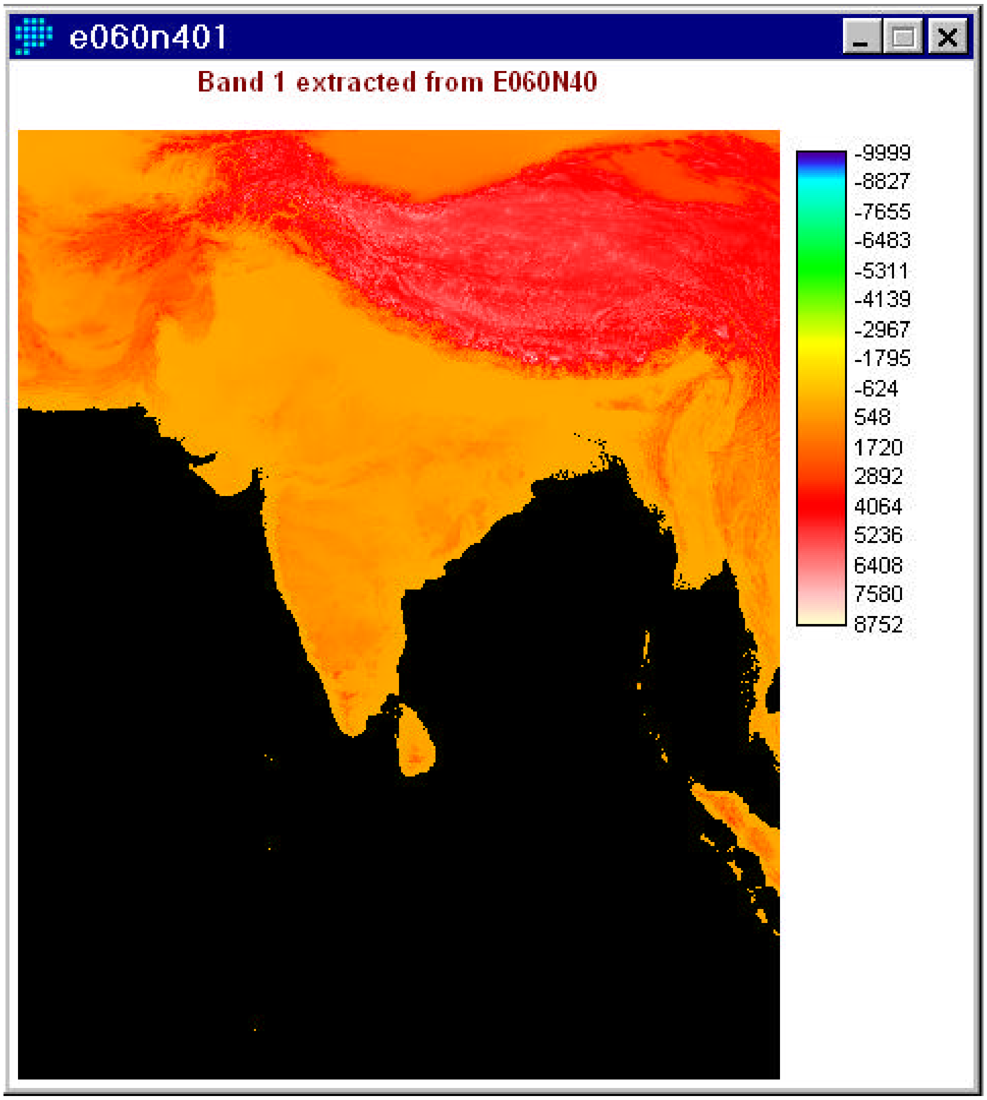
   - use \File\Import\General conversion tools\BILIDRIS. The parameters are shown in the windows below. The minimum and maximum x and y are taken from the following data in the E060N40.HED file:

ULXMAP	60.00416666666667
ULYMAP	39.99583333333333
XDIM	0.00833333333333
YDIM	0.00833333333333

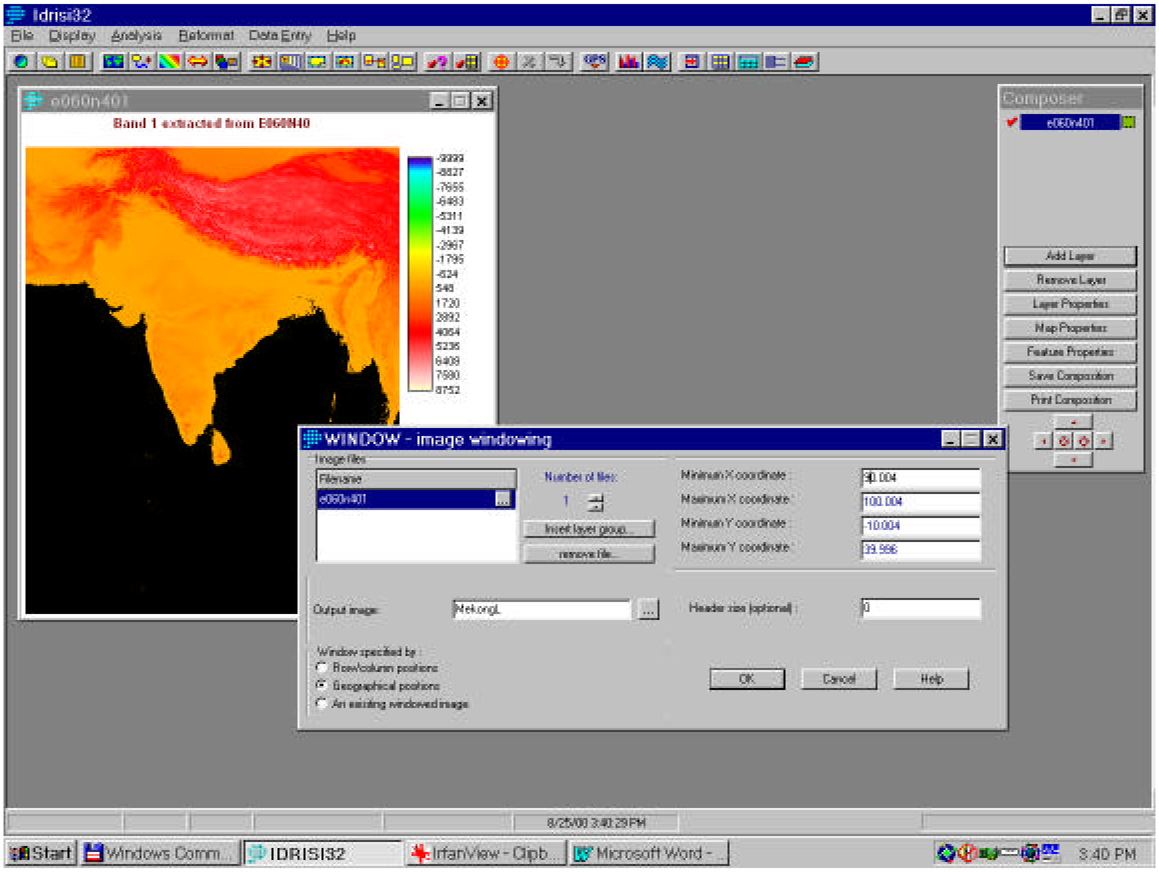

BILIDRIS - BIL format to Idrisi image ...
Input file:
E060N40.DEM
Output prefix (can include path):
E060N40
Number of bands:
1
File header info:
No header
Header, first band
Header, each band
Header size (bytes):
0
Data type:
8-bit
16-bit (Intel/VMS)
16-bit (Unix/Motorola)
Output reference information...
OK
Cancel
Help

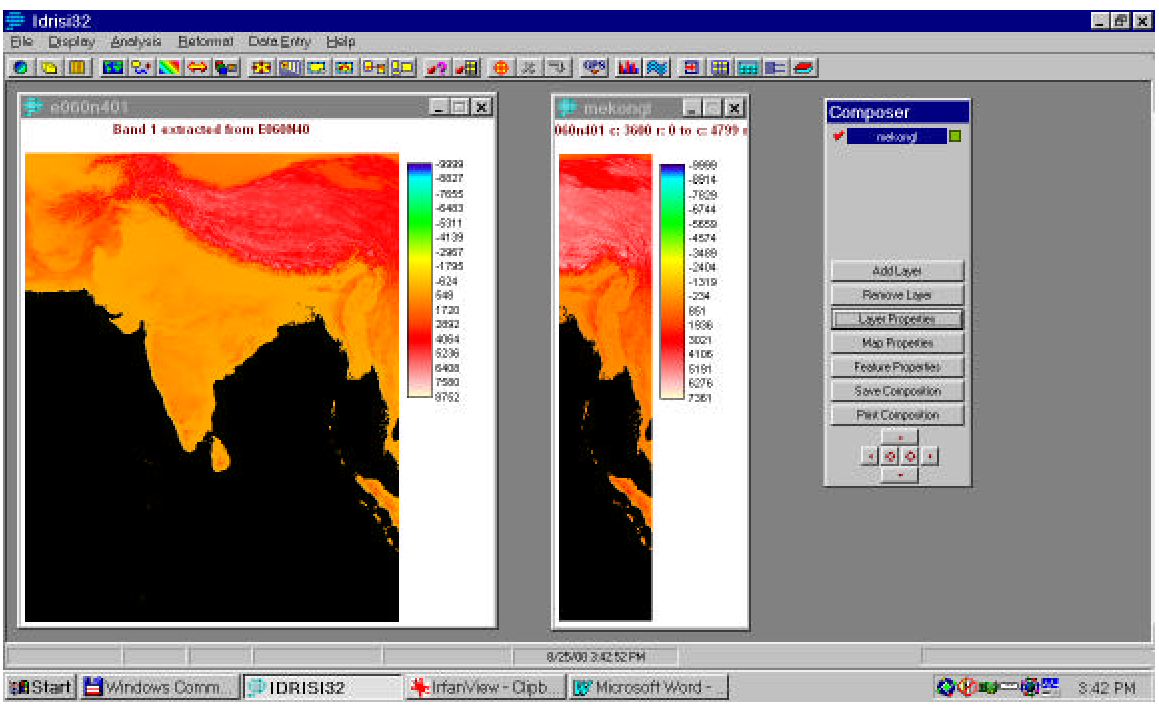

Reference Parameters
Number of columns:
4800
Number of rows:
6000
Minimum X coordinate:
60.004
Maximum X coordinate:
100.004
Minimum Y coordinate:
-10.004
Maximum Y coordinate:
39.996
Reference system:
latlong
Reference units:
Degrees
Unit distance:
1.0
OK
Cancel
Help

- Display the resulting DEM file using DISPLAT\DISPLAY LAUNCHER.

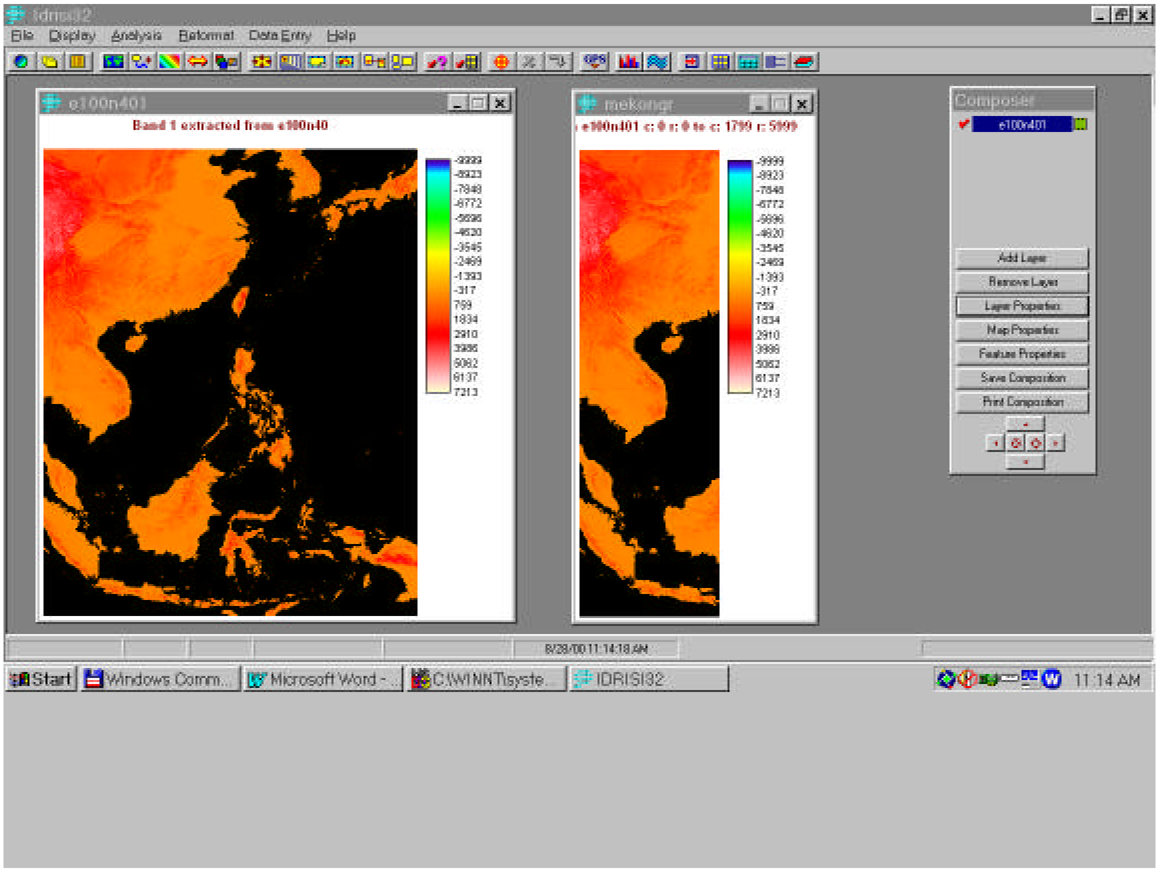


3. Extract a window from the original DEM tile that covers the project area using Reformat\Window (example shows the left-hand part of the basin).

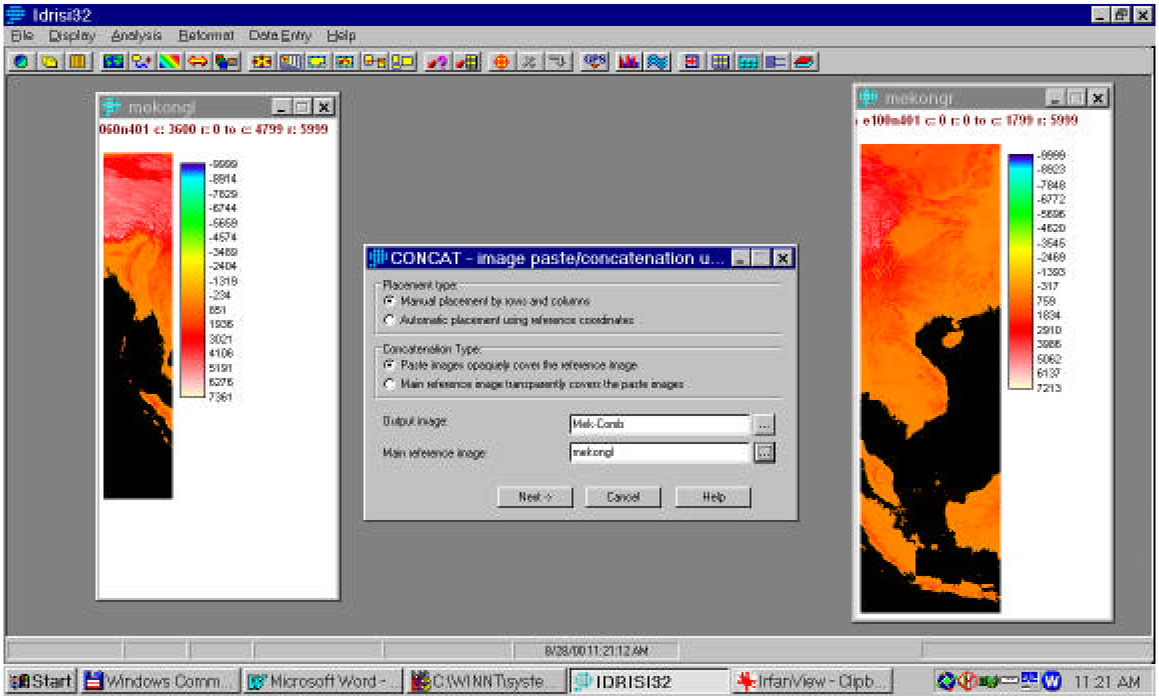

Idrisi32
File Display Analysis Reformat Data Entry Help
e060n401
Band 1 extracted from E060N40
Composer
e060n401
Add Layer
Remove Layer
Layer Properties
Map Properties
Feature Properties
Save Composition
Print Composition
WINDOW - image windowing
Image files
Filename
e060n401
Number of files:
Insert layer group...
remove file...
Minimum X coordinate :
Maximum X coordinate :
Minimum Y coordinate :
Maximum Y coordinate :
90.004
100.004
-10.004
39.996
Output image:
MekongL
Header size (optional) :
0
Window specified by :
Row/column positions
Geographical positions
An existing windowed image
OK
Cancel
Help
8/25/00 3:40:29 PM
Start
Windows Comm...
IDRISI32
IrfanView - Clipb...
Microsoft Word -
3:40 PM

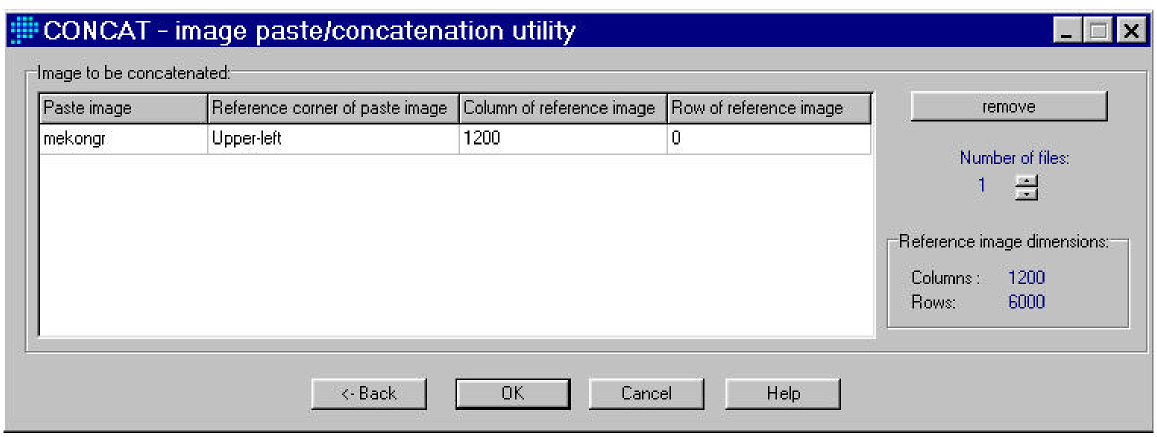

Idrisi32
File Display Analysis Reformat Data Entry Help
e060n401
Band 1 extracted from E060N40
mekongl
060n401 c: 3600 r: 0 to c: 4799 r
Composer
mekongl
Add Layer
Remove Layer
Layer Properties
Map Properties
Feature Properties
Save Composition
Print Composition
8/25/00 3:42:52 PM
Start
Windows Comm...
IDRISI32
IrfanView - Clipb...
Microsoft Word -
3:42 PM

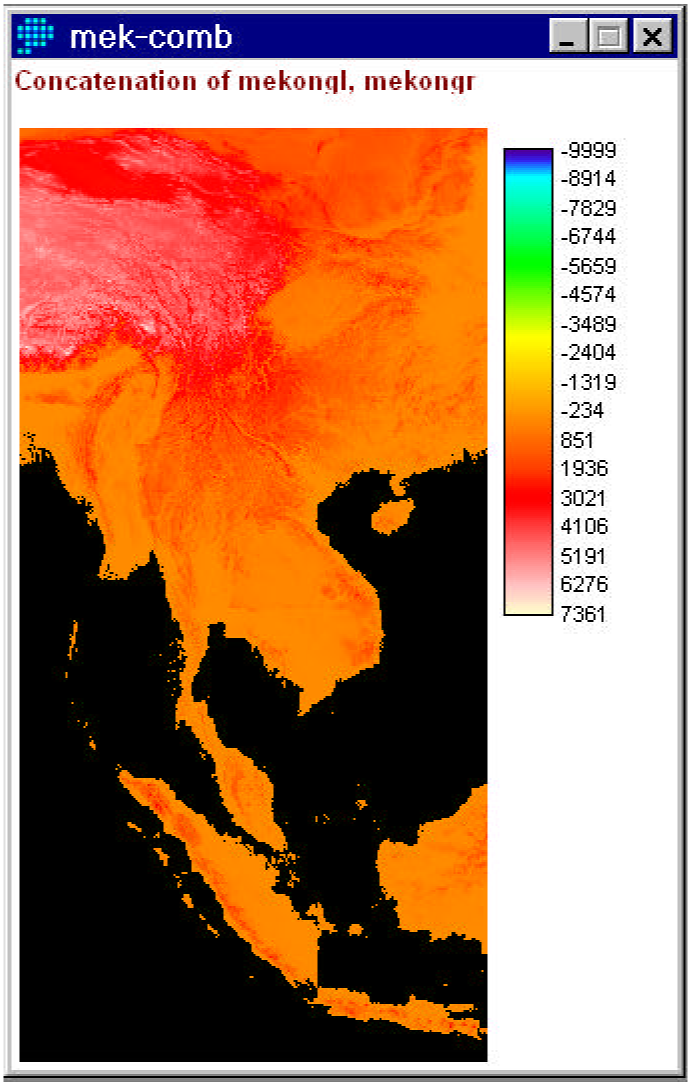
4. Follow steps 2 and 3 again to extract the right-hand side of the basin from the second tile, E100N40.TGZ, so that we have two windows.



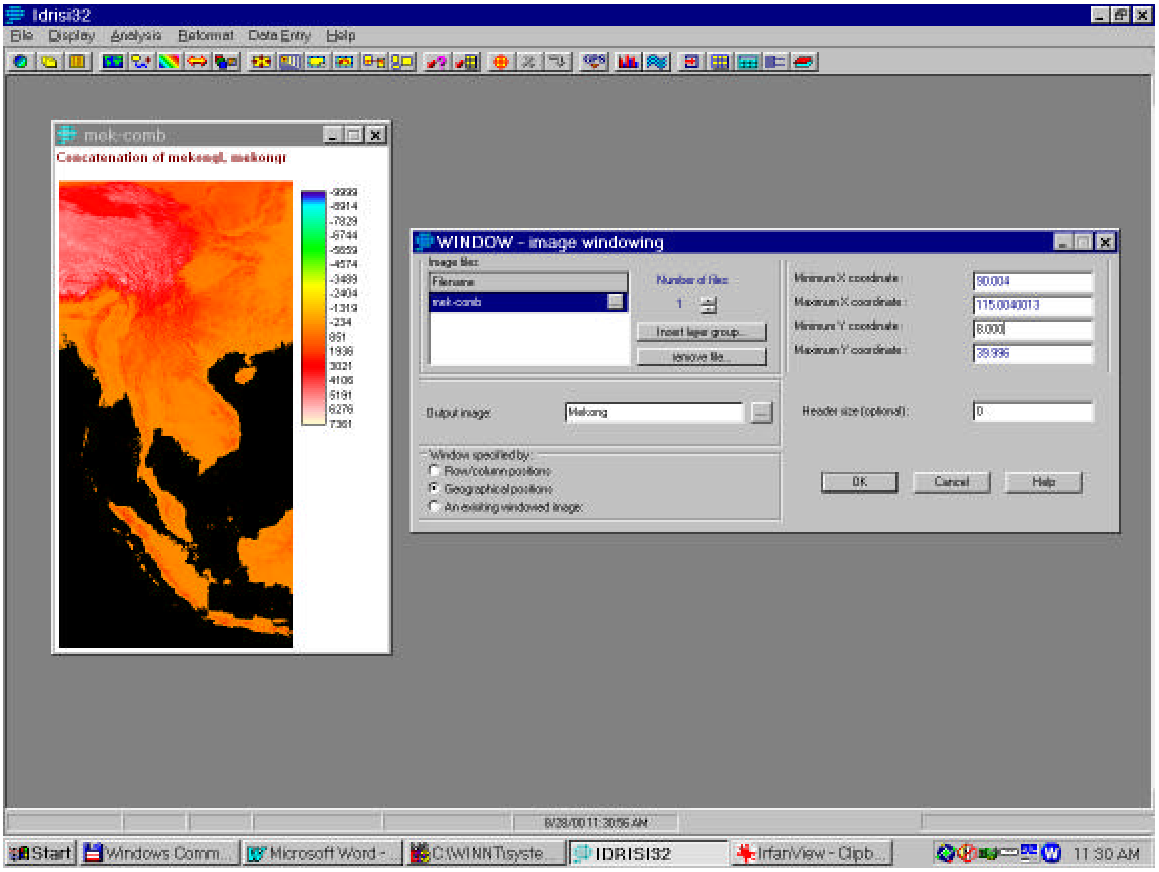
5. Now these two windows are combined using REFORMAT\CONCAT to image MEK-COMB.

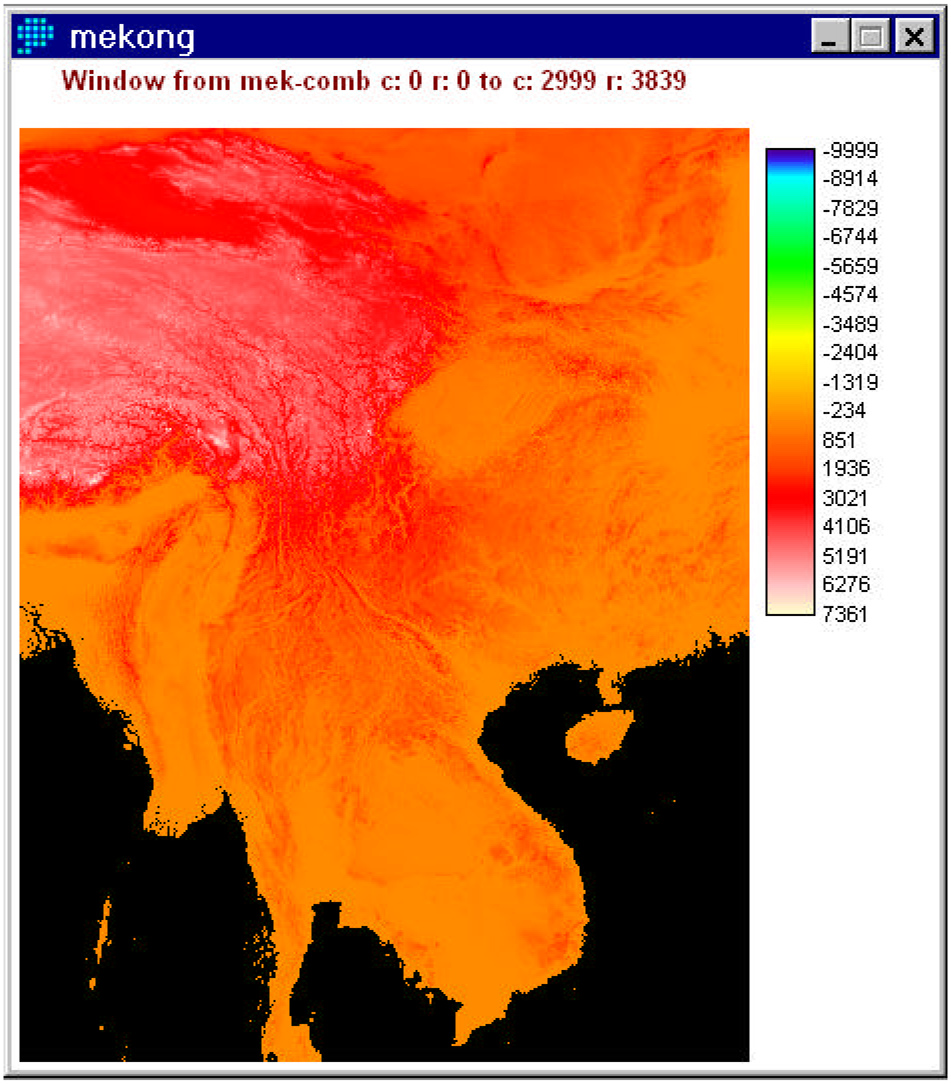




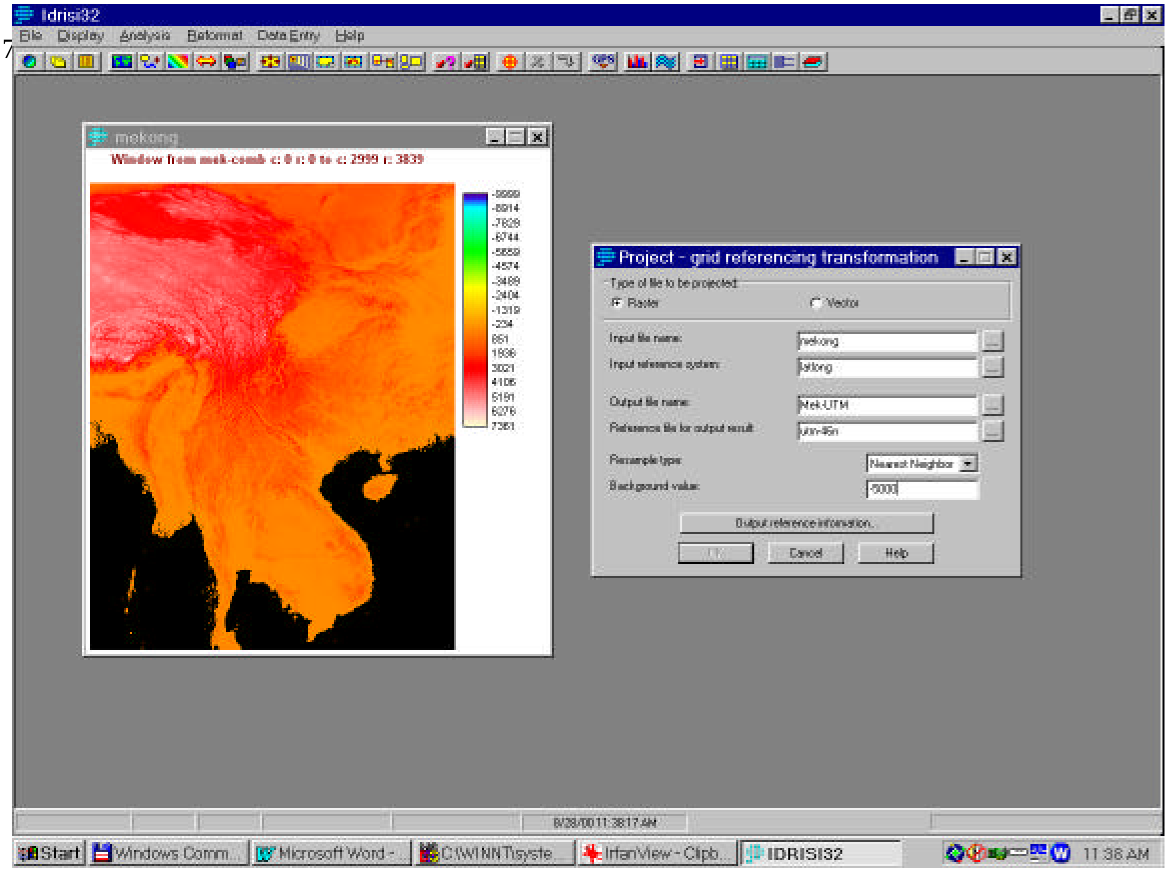

mek-comb
Concatenation of mekongl, mekongr
-9999
-8914
-7829
-6744
-5659
-4574
-3489
-2404
-1319
-234
851
1936
3021
4106
5191
6276
7361

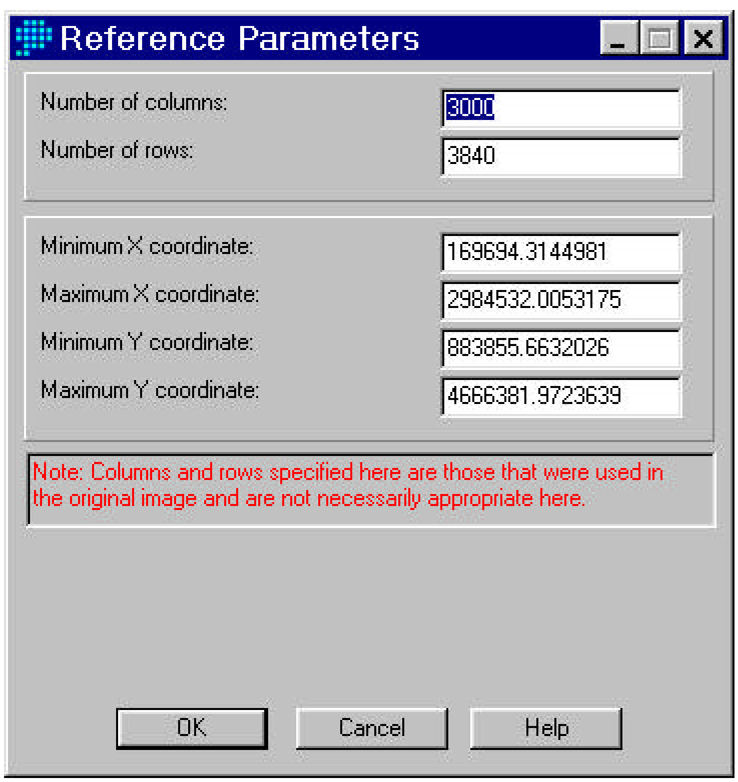
6. Next, cut the concatenated image to the appropriate latitudes using \Reformat\WINDOW to image MEKONG:

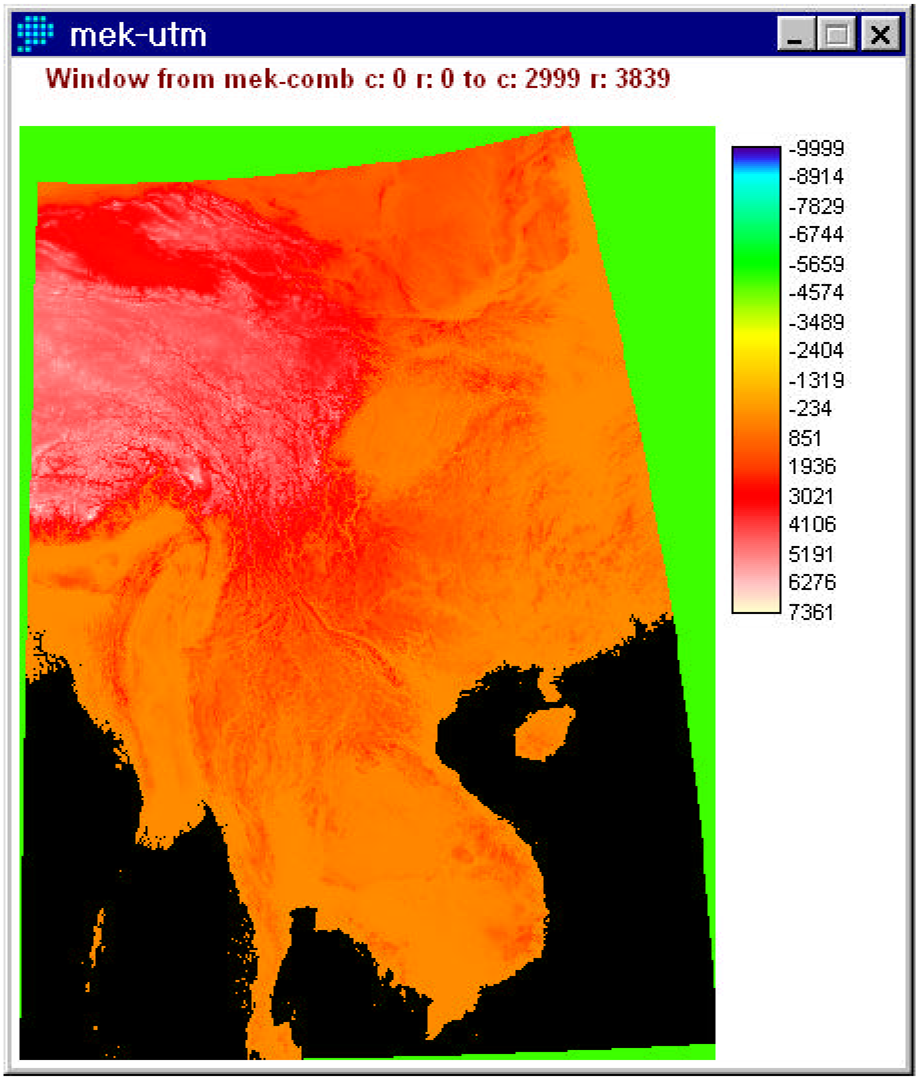




7. Convert from the GTOPO30 lat-long projection to Universal Transverse Mercator (UTM). The Mekong Basin covers three UTM zones, 46N (90–96º), 47N (96–102º) and 48N (102–108ºE). To keep x or easting values positive, we chose to use the 46N zone. Conversion uses \Reformat\PROJECT to give file MEK-UTM. First, we do a conversion of the entire image; later we can window closer to the actual river basin area and can resample to force the resulting UTM image to 1 km x 1 km pixels. The 1 km dimension is needed to ensure compatibility with other, later, images. Note that the background area is set to a negative number to distinguish areas that will be outside the image when converted to UTM. Note also that there are two screens to complete.


Idrisi32
File Display Analysis Reformat Data Entry Help
mekong
Window from mek-comb c: 0 r: 0 to c: 2999 r: 3839
-9999
-8914
-7828
-6744
-5659
-4574
-3489
-2404
-1319
-234
851
1936
3021
4106
5191
6276
7361
Project - grid referencing transformation
Type of file to be projected:
Raster
Vector
Input file name:
mekong
Input reference system:
latlong
Output file name:
Mek-UTM
Reference file for output result:
utm-46n
Resample type:
Nearest Neighbor
Background value:
-5000
Output reference information...
OK
Cancel
Help
Start
Windows Comm...
Microsoft Word -
C:\WINNT\syste...
IrfanView - Clipb...
IDRISI32
11:38 AM


Reference Parameters
Number of columns:
3000
Number of rows:
3840
Minimum X coordinate:
169694.3144981
Maximum X coordinate:
2984532.0053175
Minimum Y coordinate:
883855.6632026
Maximum Y coordinate:
4666381.9723639
Note: Columns and rows specified here are those that were used in the original image and are not necessarily appropriate here.
OK
Cancel
Help



The average pixel size of the new UTM image can be calculated from the data on the previous screen as:

x_length = (2984532 – 169694)/3000 = 938m
y_length = (4666381-883855)/3840 = 985m.

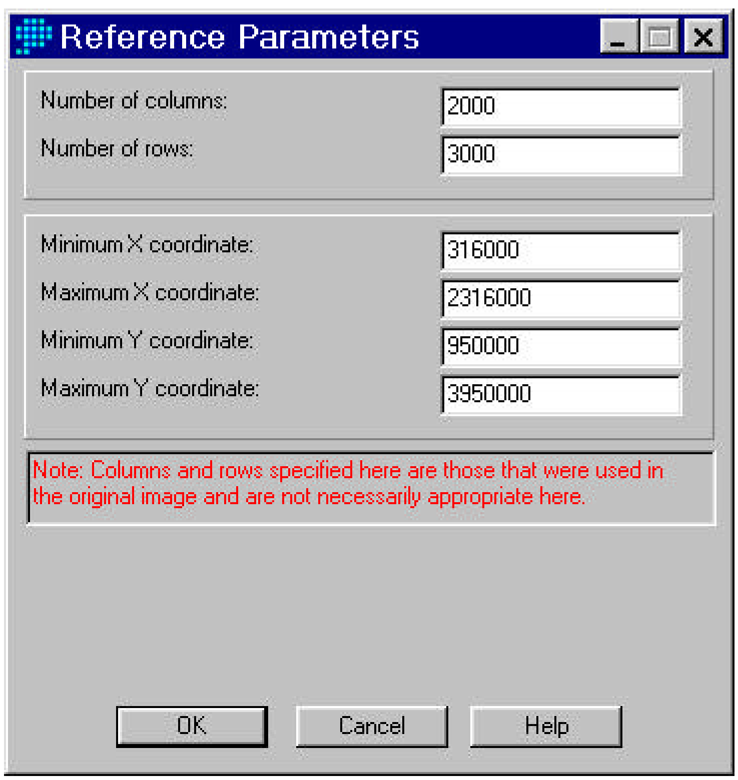
Now, we can window closer to the actual river basin area and can resample to force the resulting UTM image to 1 km x 1 km pixels. The 1 km dimension is needed to ensure compatibility with other, later, images. Select the image MEK-UTM and use the Cursor Enquiry Mool (the arrow and question mark on the toolbar) to find x and y coordinates for a final UTM image that adequately surround the river basin. Then round these to convenient numbers and compute the number of rows and columns that will be needed to cover this area with 1 km x 1 km pixels:

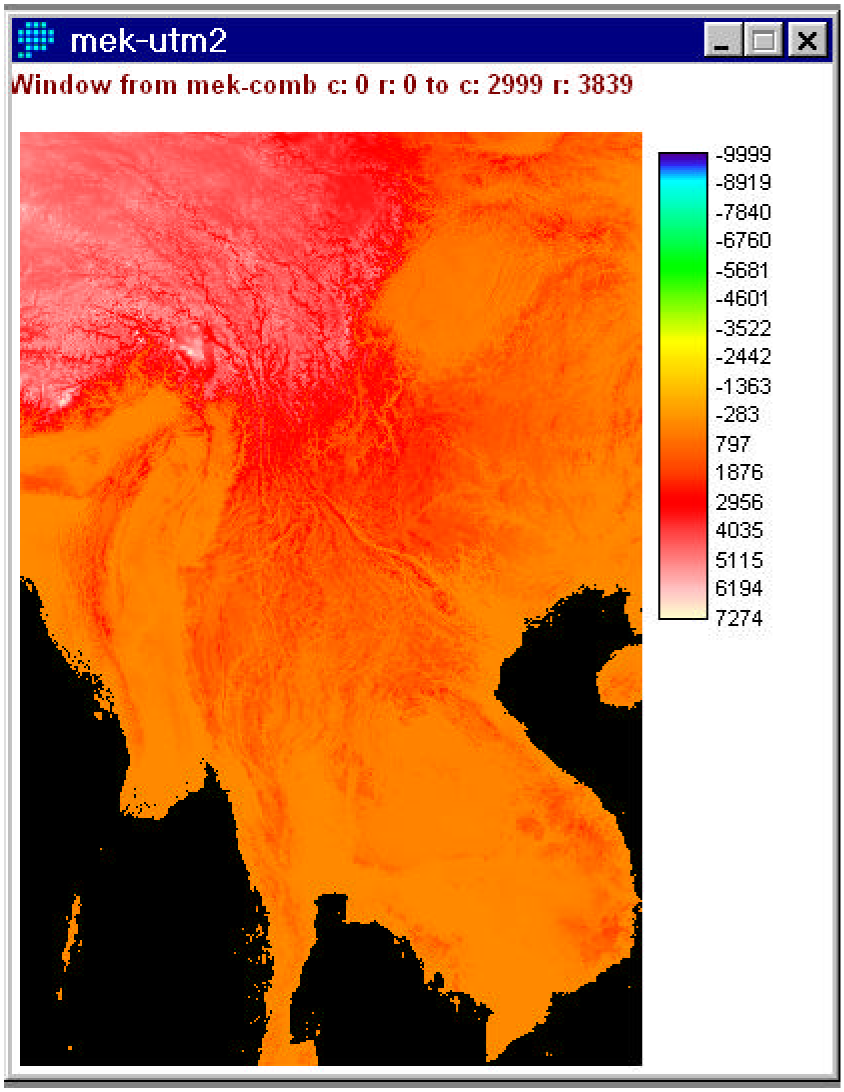
	From MEK-UTM	**Rounded**
min_x	354029.5	316000
max_x	2315813	2316000
min_y	956816.8	950000
max_y	4127563	3950000

number of rows at 1 km resolution = (max_y – min_y)/1000 = 3000

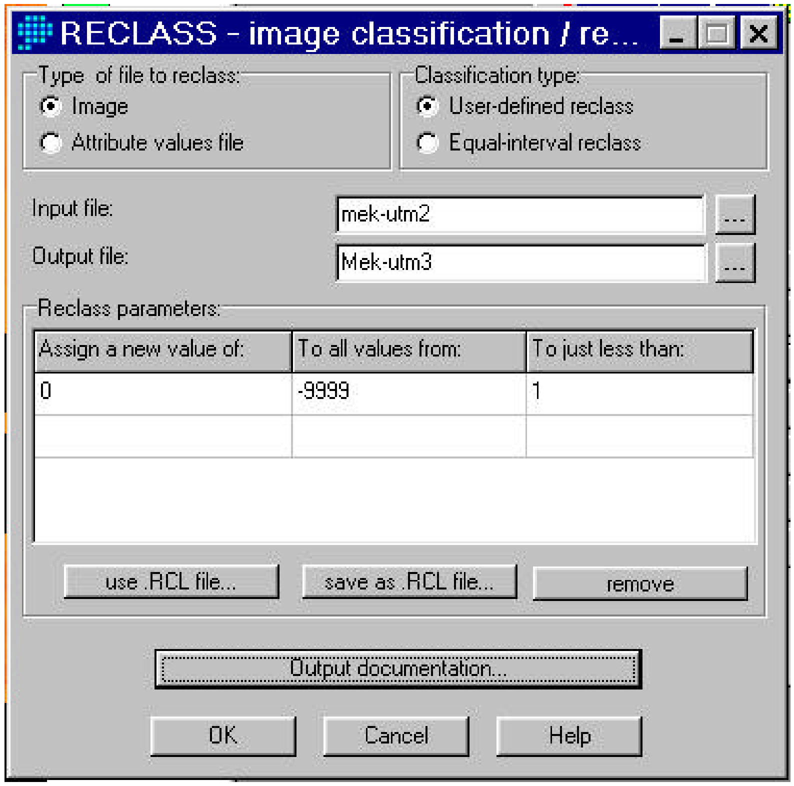
number of columns at 1 km resolution = (max_x – min_x)/1000 = 2000

8. Now go back to the image Mekong and repeat the \Reformat\PROJECT procedure using the derived numbers of rows and columns and max and min x and y values from the table above on the second screen to derive image MEK-UTM2:

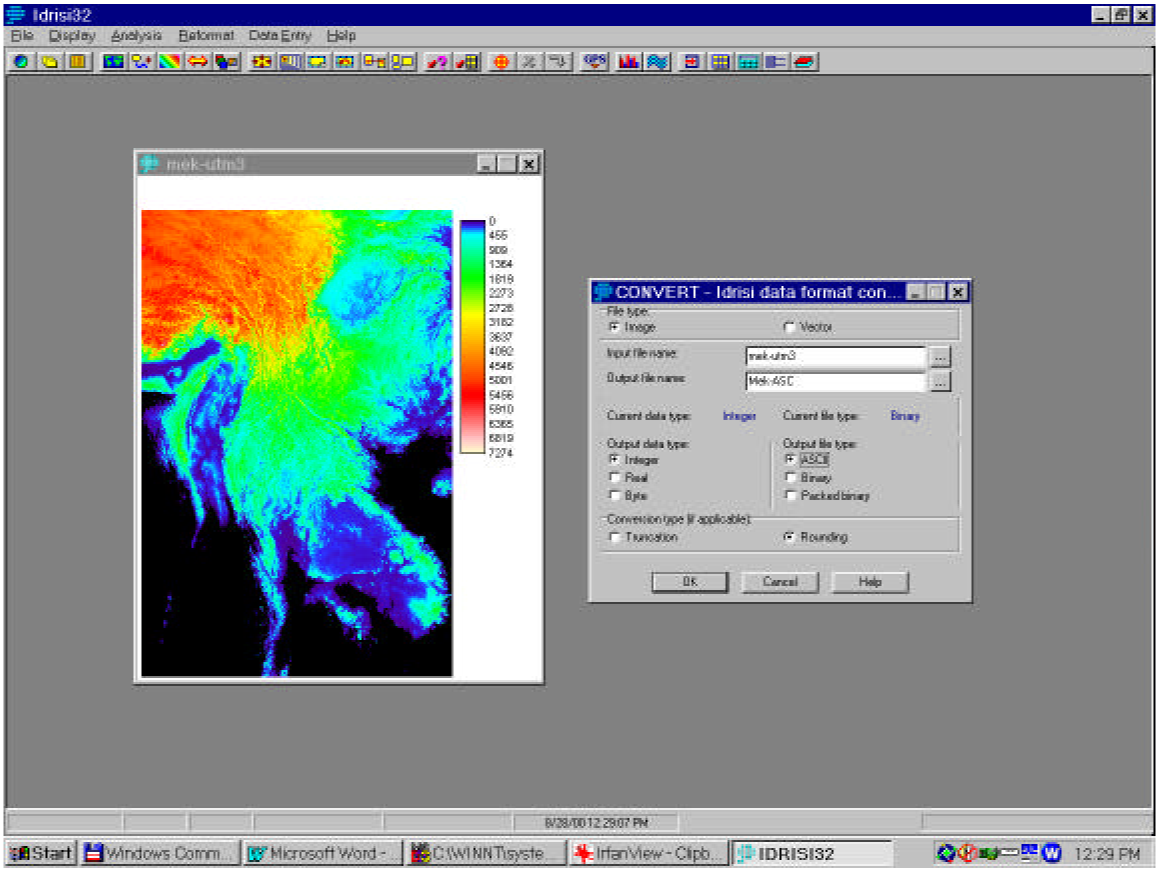



mek-utm2
Window from mek-comb c: 0 r: 0 to c: 2999 r: 3839
-9999
-8919
-7840
-6760
-5681
-4601
-3522
-2442
-1363
-283
797
1876
2956
4035
5115
6194
7274

9. Next, reclassify the –ve values on image MEK-UTM2 to 0 on a new image MEK-UTM3 using \Analysis\Database Query\RECLASS or the RECLASS icon on the toolbar:



10. Convert the DEM from binary to ASCII using \Reformat\CONVERT to image MEK-ASC.



11. Copy Mek-ASC.RDC and Mek-ASC.RST to the directory in which you will do the topographic analysis and rename them to DEDNM.RDC and DEDNM.INP respectively. The DEM is then ready for processing with TOPAZ, the topographic analysis system (Garbrecht and Martz 1997).

Appendix B

TOPOGRAPHIC ANALYSIS

The DEM prepared in Appendix A can be processed with the TOPAZ (Garbrecht and Martz 1997) topographic analysis system to define the river basin, the stream network and the topographic data needed for the SLURP hydrologic model (Kite 2000). The following description of the TOPAZ system is adapted from material on the TOPAZ website (Internet 5).

TOPAZ consists of 6 interdependent programs. Not all programs are needed for each application. A separate program TOPIMAGE has been written to display data produced by TOPAZ in the IDRISI GIS (Eastman 1997) and a further program TOPRIVER has been written to modify a DEM to correct river channels.

Program DEDNM (Digital Elevation Drainage Network Model) performs the basic raster processing and produces fundamental raster data necessary for the operation of all other TOPAZ programs. Program DEDNM performs the following specific functions:

- read and check the DEM input data
- optionally perform smoothing and/or aggregating of the DEM data
- rectify depressions and flat surfaces in the DEM
- identify surface drainage
- define the drainage network
- identify basin and sub-basin boundaries
- assign indices to the channel links and sub-basins
- define channel link length and topology
- calculate sub-basin area
-

Program RASBIN (RASter to BINary network) transforms a raster-based drainage network definition into a binary (2 inflows per junction) drainage network definition. Program RASBIN :

- decomposes complex junction nodes into simple junction nodes;
- assigns channel link and sub-basin indices to the binary network;
- computes the sequence for cascade-type flow routing through the binary network;
- defines channel link length and topology for the binary network;
- calculates sub-basin areas for the binary network.

Program RASPRO (RASter PROperties) derives the following additional spatial landscape information and parameters from the basic rasters produced by program DEDNM:

- location and extent of depressions and flat surfaces in the DEM;
- elevation reclassification into user-specified classes;
- alternative evaluations of raster cell slope and aspect;
- enhancement of the visualization of channel network and drainage divides;

- sub-basin aggregation;
- distance from each cell to the next channel and to the basin outlet;
- elevation drop from each cell to the next channel and to the basin outlet.

Program RASFOR (RASter FORmatting) reads the unformatted raster files produced by programs DEDNM and RASPRO, and reformats them into either ASCII or IDRISI formats.

Program NSSTAT (Network and Sub-basin STATistics) computes the statistics of the channel link and sub-basin properties for both the raster and binary channel network. Program NSSTAT computes mean and standard deviations for the entire network and for each Strahler channel order for:

- number of channel links;
- length of channels and channel links;
- elevation of channels and channel links;
- slope of channels and channel links;
- direct and total drainage areas;
- drainage density;
- channel link sinuosity;
- network composition;
- sub-basin drainage areas;
- channel, right, left and source drainage areas.

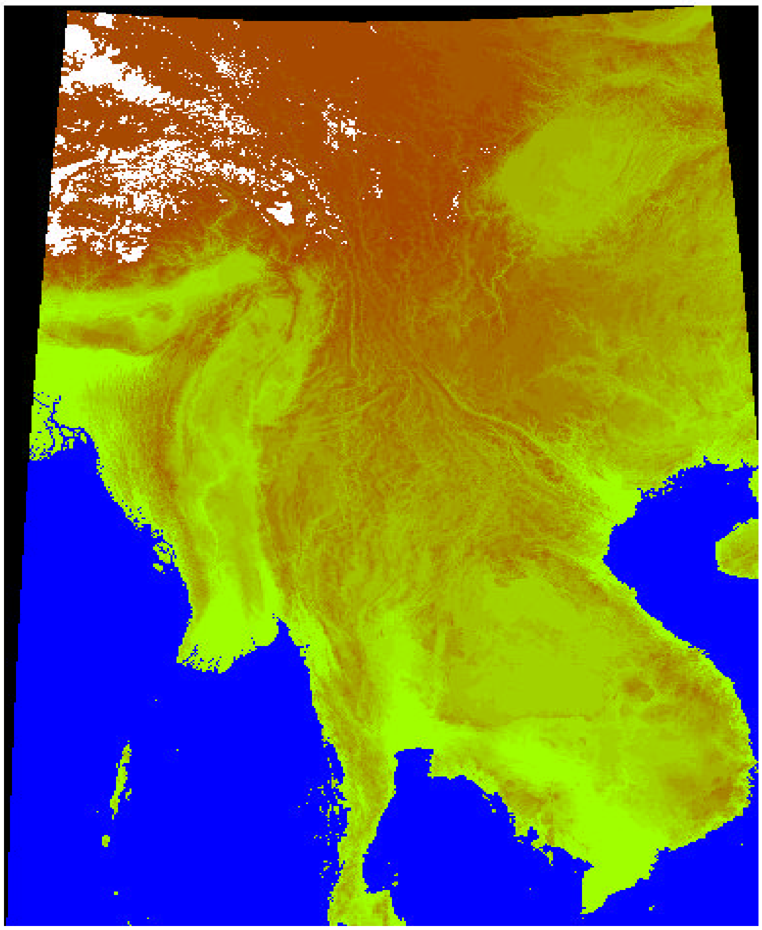
Program PARAM (PARAMeterization) computes the following representative sub-basin properties and parameters from the rasters produced by programs DEDNM and RASPRO:

- length to the center of moment;
- mean flow path length;
- drainage area;
- topography-based slope alternative;
- flow-path-based slope alternative;
- cell-path-based slope alternative.

The TOPAZ programs are interdependent (the output of one program is used as input into other programs) except for program DEDNM that accepts only user-provided data and does not depend on input from any other program. Because of this interdependence, the sequence in which the programs are executed is important for proper TOPAZ operation.

? Program DEDNM is always run first, followed by any of the three programs RASBIN, RASPRO or RASFOR.
? If the user chooses to use program RASPRO, then program RASFOR should be executed after program RASPRO.
? Program NSSTAT can only be used when program RASBIN has been executed.
? Program PARAM depends on data from both programs DEDNM and RASPRO and so cannot be executed until DEDNM and RASPRO have been run.

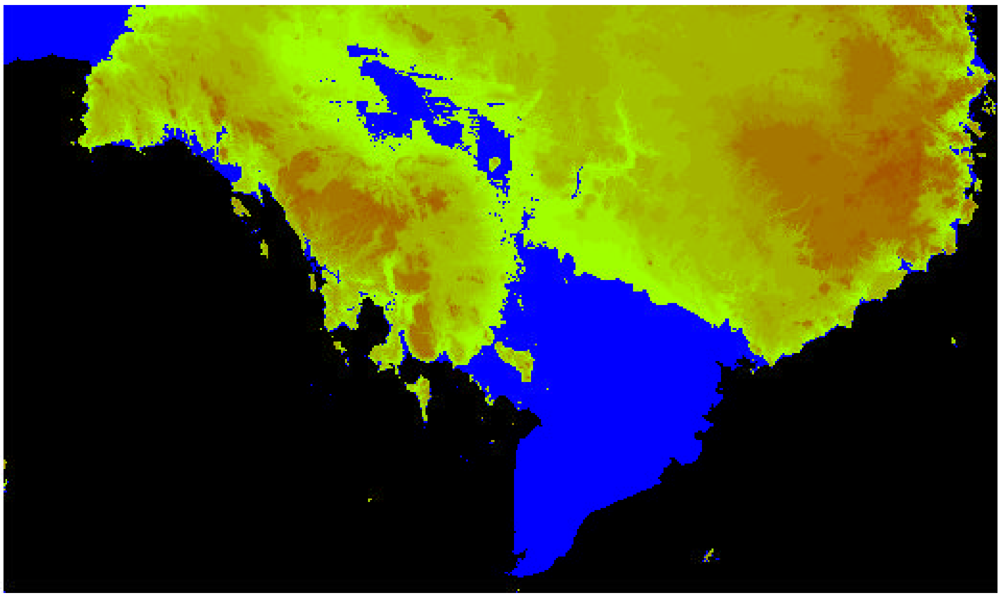
For the type of analysis needed for the hydrological modeling we need only programs DEDNM, RASBIN, RASPRO, PARAM and TOPIMAGE (or RASFOR). The following pages describe the sequence of operations used.



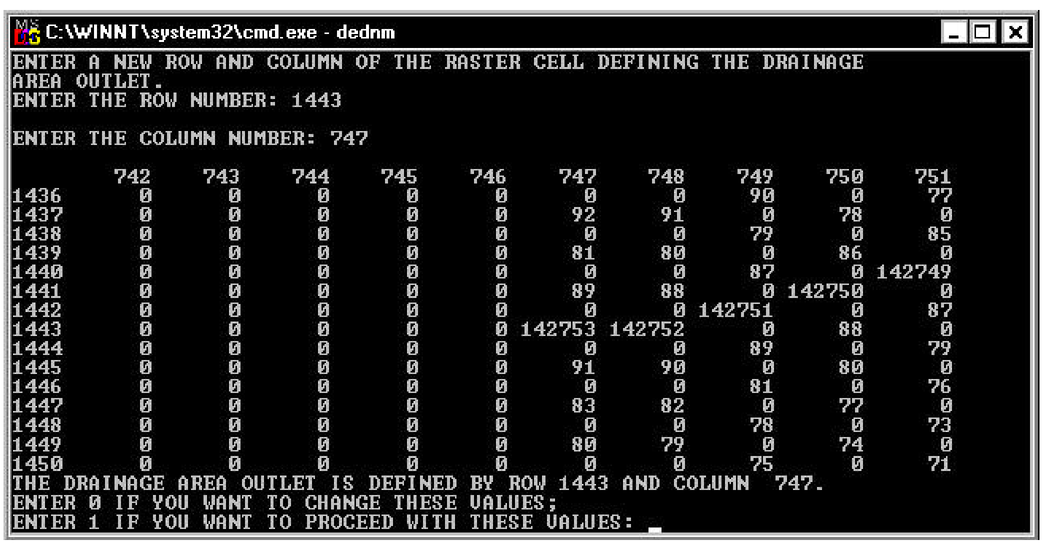
1. First, copy the IDRISI ASCII DEM file '.RST' and the corresponding '.RDC' file to the directory containing the TOPAZ programs and rename them to 'DEDNM.INP' and 'DEDNM.RDC.' Note that the TOPAZ programs can only be run with data files in the same directory as the executables and that all data files must be named and formatted exactly as specified.

2. It is necessary to estimate the row and column numbers of the lowest point on the river before starting TOPAZ. This can be obtained by comparing the DEM in IDRISI with a topographic map showing the river. In this case, our first estimate is that the mouth of the Delta is at column 1,814 and row 2,735. This can be corrected later when running the program DEDNM. Frequently, the lower part of a river may be a Delta with multiple indistinct channels and in such a case it may be better to start the analysis further upstream at a more clear location and then work downstream. The example below shows a window for the Mekong Delta.

3. Prepare input file DNMCNT.INP by modifying an existing file from the samples given on the SLURP CD-ROM or on the TOPAZ website (Internet 5). The UTM zone, number of rows and columns, coordinates of the upper left corner and maximum elevation can be found in the .RDC file corresponding to the ASCII DEM image, DEDNM.INP. The parameters CSA (critical source area—a minimum drainage area) and MSCL (minimum source channel length for 1st order channels) determine the number of sub-basins that DEDNM will define. CSA (in hectares) should be a minimum of 10 cell areas; MSCL (in meters) should be a minimum of one cell length. Run program DEDNM.



4. When running module DEDNM, you can choose the exact river outlet from the DOS display. This display shows the channel route with each cell containing the number of upstream cells (for river cells), or containing a 0 (for non-river cells). At this stage the user can change the row and column for the river outlet. For subsequent runs of DEDNM, the user can enter the corrected outlet row/column values in the file DNMCNT.INP.



```
C:\WINNT\system32\cmd.exe - dednm
ENTER A NEW ROW AND COLUMN OF THE RASTER CELL DEFINING THE DRAINAGE
AREA OUTLET.
ENTER THE ROW NUMBER: 1443

ENTER THE COLUMN NUMBER: 747

         742     743     744     745     746     747     748     749     750     751
1436       0       0       0       0       0       0       0      90       0      77
1437       0       0       0       0       0      92      91       0      78       0
1438       0       0       0       0       0       0       0      79       0      85
1439       0       0       0       0       0      81      80       0      86       0
1440       0       0       0       0       0       0       0      87       0  142749
1441       0       0       0       0       0      89      88       0  142750       0
1442       0       0       0       0       0       0       0  142751       0      87
1443       0       0       0       0       0  142753  142752       0      88       0
1444       0       0       0       0       0       0       0      89       0      79
1445       0       0       0       0       0      91      90       0      80       0
1446       0       0       0       0       0       0       0      81       0      76
1447       0       0       0       0       0      83      82       0      77       0
1448       0       0       0       0       0       0       0      78       0      73
1449       0       0       0       0       0      80      79       0      74       0
1450       0       0       0       0       0       0       0      75       0      71
THE DRAINAGE AREA OUTLET IS DEFINED BY ROW 1443 AND COLUMN  747.
ENTER 0 IF YOU WANT TO CHANGE THESE VALUES;
ENTER 1 IF YOU WANT TO PROCEED WITH THESE VALUES: _
```

For large basins DEDNM may take several hours to run and needs user input at several stages. A version of DEDNM named DEDNM-NQ (for “no questions”) has been prepared, which requires no screen interaction with the user. If you are sure that all inputs to DEDNM are correct then the NQ version can be used as part of a batch file and can be run overnight.

5. When DEDNM has completed successfully, run program RASBIN.

6. Then prepare the input file RASPRO.INP by copying from examples on the SLURP CD-ROM or on the TOPAZ website (Internet 5) and run program RASPRO.

7. Now prepare RASFOR.INP and run program RASFOR. RASFOR is needed to view the output images in a GIS. RASFOR will convert the outputs given in the following table from DEDNM and RASPRO to IDRISI format. Those files given in bold are the ones important for further analyses. Note that the distances contained in file DISOUT.OUT and the changes in elevation in file ELDOUT.OUT are from each cell to the final outlet of the basin. The distances in file DISCHA.OUT and the changes in elevation in file ELDCHA.OUT are from each cell to the outlet of the sub-basin. The dimensions of the elevation data files INELEV.OUT, SMOOTH.OUT, FILDEP.OUT and RELIEF.OUT are m x 10^5 and are converted by TOPIMAGE or RASFOR back to m in the .RST files. The dimensions of the distances in files DISOUT and DISCHA are m.

INELEV.OUT	INITIAL (OPTIONALLY AGGREGATED OR RESAMPLED) DEM
SMOOTH.OUT	INITIAL (OPTIONALLY SMOOTHED) DEM
FILDEP.OUT	INITIAL DEPRESSION ANALYZED AND FILLED DEM
RELIEF.OUT	INITIAL RELIEF MODIFIED DEM
FLOVEC.OUT	FLOW VECTOR RASTER
FLOPAT.OUT	FLOW PATH DEFINITION RASTER
INDTAR.OUT	INDETERMINATE AREA DEFINITION RASTER
UPAREA.OUT	UPSTREAM CATCHMENT AREA RASTER
NTGCOD.OUT	CODES FOR SPATIALLY VARIABLE CSA AND MSCL
NETFUL.OUT	DRAINAGE CHANNELS FOR THE ENTIRE DEM
BOUND.OUT	BASIN AREA DEFINITION
NETW.OUT	DRAINAGE NETWORK RASTER
SUBWTA.OUT	SUB-BASIN AREA RASTER
DEPFLT.OUT	DEPRESSION AND FLAT AREA RASTER
ELVCLA.OUT	EQUAL ELEVATION BAND RASTER
FVASPE.OUT	FLOW VECTOR ASPECT RASTER
TASPEC.OUT	TERRAIN ASPECT RASTER
FVSLOP.OUT	FLOW VECTOR SLOPE RASTER
HSLOPE.OUT	HYDRAULIC SLOPE RASTER
TSLOPE.OUT	TERRAIN SLOPE RASTER
NETWE.OUT	ENHANCED NETWORK RASTER
SUBBDA.OUT	AGGREGATED SUB-BASIN BOUNDARY LINE
SUBWTB.OUT	AGGREGATED SUB-BASIN AREA RASTER
SUBBDB.OUT	SUB-BASIN BOUNDARY LINE
DISOUT.OUT	FLOW PATH DISTANCE TO BASIN OUTLET
DISCHA.OUT	FLOW PATH DISTANCE TO CHANNEL
ELDCHA.OUT	FLOW PATH ELEVATION DROP TO CHANNEL
ELDOUT.OUT	FLOW PATH ELEVATION DROP TO BASIN OUTLET

8. If you use RASFOR, the .IMG and .DOC files produced must be modified before the images can be displayed in IDRISI 32:

- In IDRISI use \File\Metadata\Raster to modify the reference system description in the .RDC file from "utm" to the correct (for this example) "utm-46n," and use the options in \Tools to calculate the correct maximum and minimum values and resolution.

- Convert the IDRISI 2 ASCII image produced by RASFOR to an IDRISI 32 binary image using \File\IDRISI Conversion Tools.

9. Because of the limitations of program RASFOR and to produce outputs for IDRISI 32, a more general program TOPIMAGE was written. TOPIMAGE will convert TOPAZ .OUT files to IDRISI 2 image files, to IDRISI 32 image files and to ASCII 1-D and 2-D files. TOPIMAGE uses the same input file as RASFOR, RASFOR.INP. No changes are needed to the files produced by TOPIMAGE before display in IDRISI 32.

Batch file TOPAZ.BAT will run the sequence DEDNM, RASBIN, RASPRO, PARAM and TOPIMAGE automatically (but note that all .INP files must be prepared before running TOPAZ.BAT) and all programs can also be. run from within the SLURP basin model

10. The resulting stream network can be viewed in IDRISI by first displaying the raster image RELIEF, converting the stream network raster (NETW) to vector using

\Reformat\Raster/vector conversion\POINTVEC

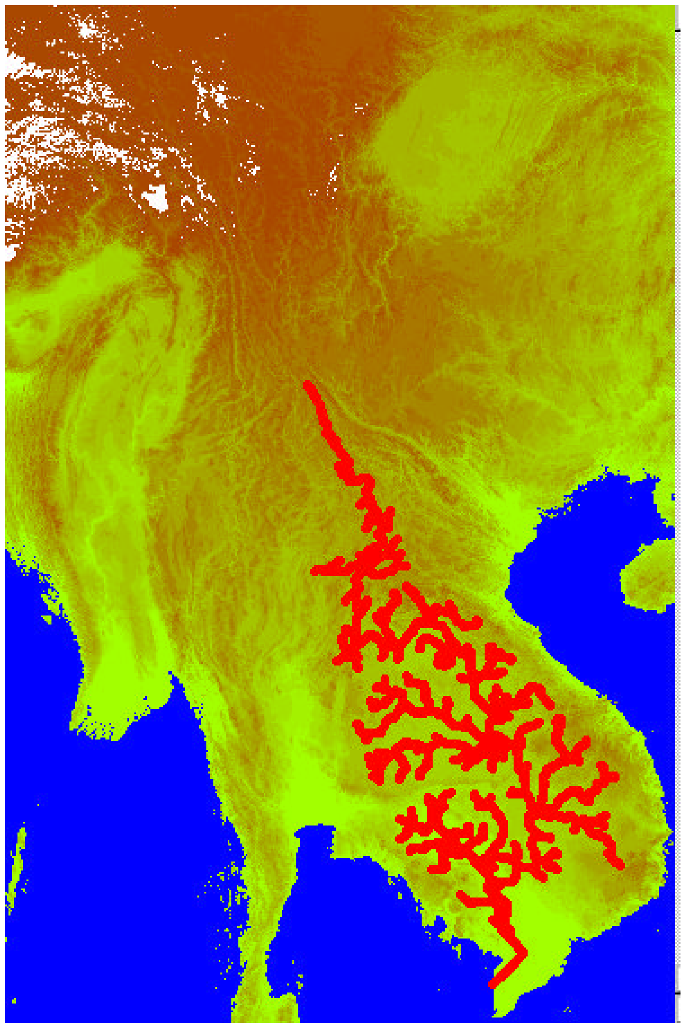
and then overlaying the resulting vector onto RELIEF using

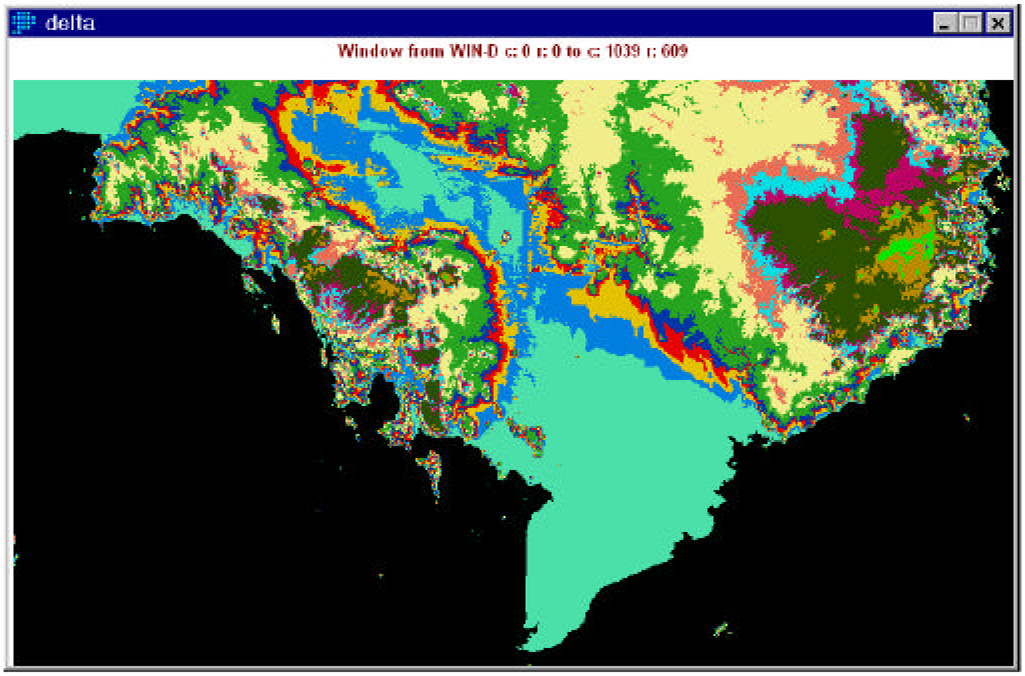
\Composer\Add layer.

Note that when viewing images in IDRISI the row and column numbers start at (0,0) whereas, examining the matrices in most editors will start at (1,1).

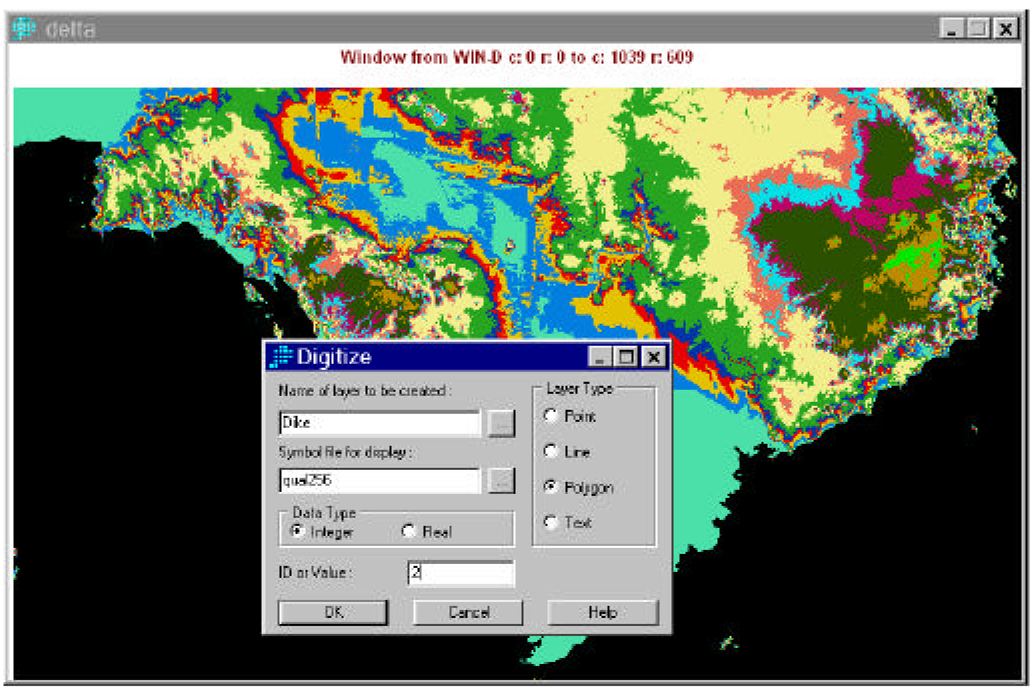
There are obviously two problems with the river network in this example. First, the unnatural shape to the river outlet in the lower right corner of the image, and, second, the fact that the river does not extend as far into the mountains in the top left hand corner as it should do.

The first problem is caused by the lack of precision in the DEM. The whole of the Delta area is registered as 1 m elevation in the DEM and so the topographic analysis software selects an arbitrary route to the sea. This can be corrected by building artificial dikes in the DEM to constrain the river to a more natural course.

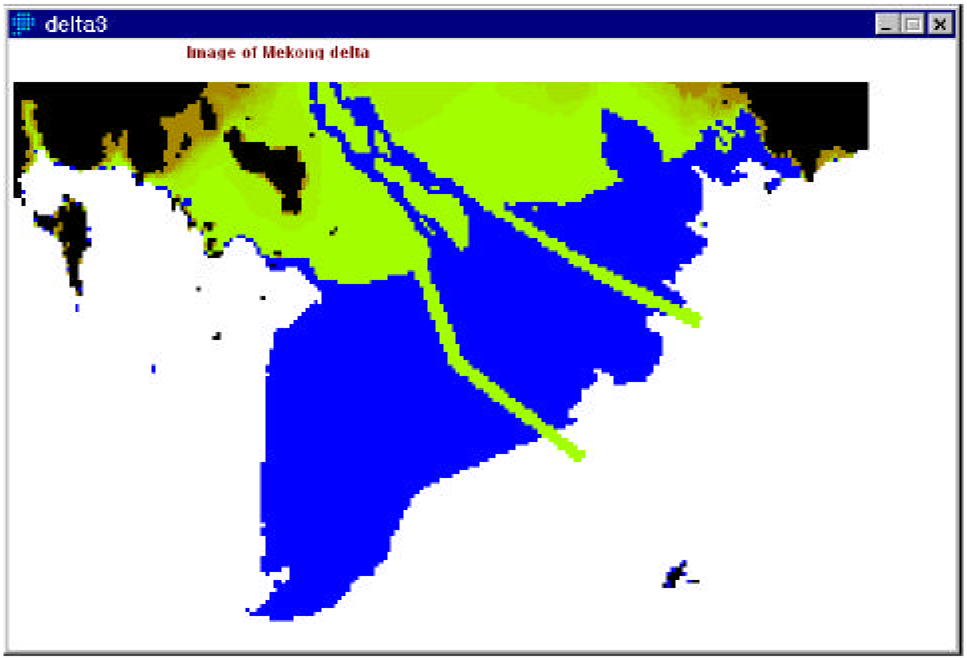




Displaying the Delta area, select On-screen Digitizing (the circle and square icon) specifying polygon and a Feature ID equal to the height of the dike we wish to build (in this case 2 meters is sufficient).



Digitize the dikes following the instructions in the help text.



Next, convert the digitized vector to a raster image using \Reformat\Raster/vector conversion\POLYRAS updating the image DELTA3.

For clarity, the example above has looked only at a window from the full DEM. In practice, it is the full-size DEM which must be changed. This is done as:

11. Resample the full DEM, MEK-DEM using a reclassification scheme which shows full detail for the low elevations (DELTA.RCL).

12. Display the resampled image at Expansion Factor 1 using a palette file which will show up the differences between low elevations (DEM16.SMP).

13. Digitize the dikes as vectors using a Feature ID of 2. The dikes must be made sufficiently wide that they will still be distinguishable after any resampling of the DEM during the topographic analysis procedures.

14. Convert the digitized vector to a raster image using \Reformat\Raster/Vector Conversion\POLYRAS, updating the original full DEM, MEK-DEM.

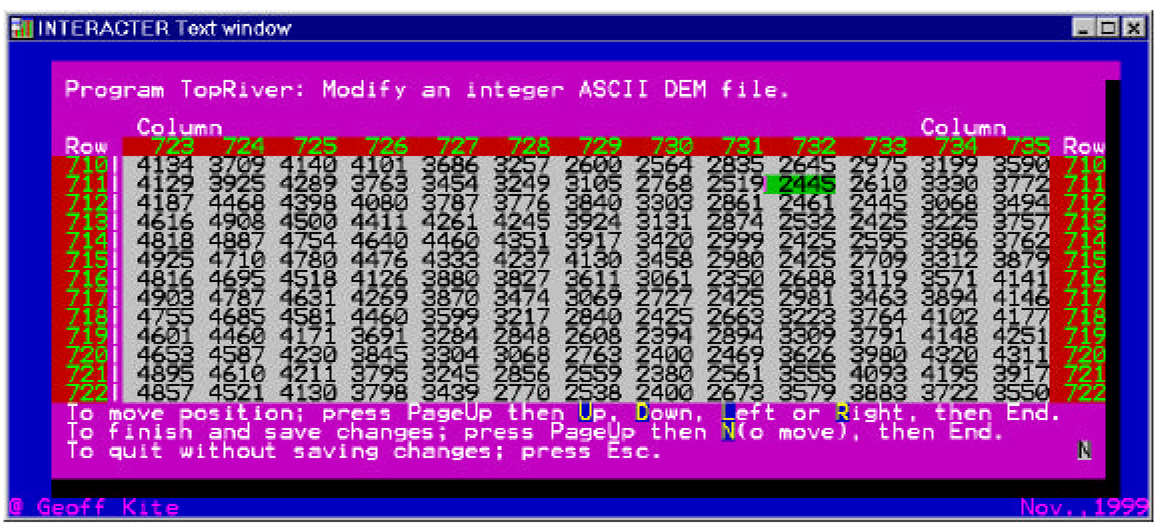
The second problem with the derived stream network is that it does not go far enough into the mountains. This is, again, caused by the resolution of the DEM. The river passes through a series of gorges that are narrower than the 1-km resolution of the DEM and, as a consequence, the river becomes discontinuous. This can be solved in IDRISI by changing the elevations of DEM pixels using:

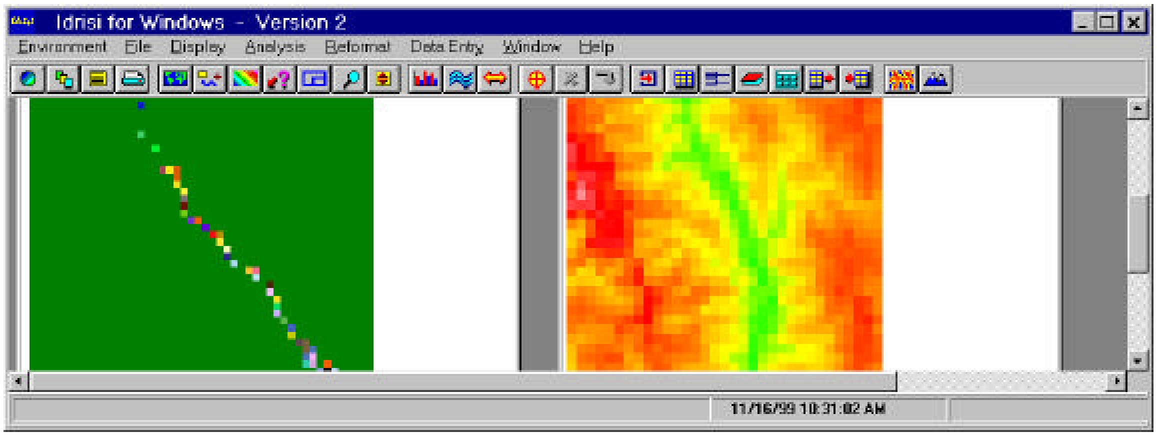
Data Entry\UPDATE

However, this procedure gets extremely tedious if many changes are to be made and so the programs TopRiver and TopGrid were written to make the task easier. Run TopRiver and specify the path to the ASCII DEM file DEDNM.INP, the starting row number and the starting column number on the first program screen. The starting row and column can be decided by displaying the .RST file in IDRISI and moving the cursor to the required starting point. Program TOPRIVER will read the number of rows and columns of data in file DEDNM.INP from the IDRISI file DEDNM.RDC if it exists or, if not, the user can specify these values on the first screen. TopRiver will display a matrix of 13 rows and 13 columns of the DEM centered on the specified row and column. The user can change the value of any cell and can move around in the DEM by keying in U for up, D for down, L for left or R for right in the box in the bottom right of the screen.

TopRiver is best used with IDRISI on the screen displaying the cell elevations as a guide (see below). Because IDRISI can display a maximum of 256 colors, if your DEM contains a range of elevations greater than 256 then the DEM should be resampled to eliminate values less than and greater than those of interest using a recalls file. The example below sets all elevations between –1 and 500 to 500 and all elevations between 750 and 9999 to 750. Every 1 m step in the range 500 to 750 will be displayed (use QUANT256) exactly.

```
500      -1       500
750      750      9999
-9999
```





Once the DEM has been corrected, run TOPAZ.BAT to execute the sequence of TOPAZ programs and obtain the final stream network and basin boundary. Vary the values of CSA and MSCL until the required number of sub-basins is obtained. The values used for the Mekong are listed below. The number of sub-basins determined by TOPAZ can be found in file NETWB.TAB.

No.	Starting column	Starting row	CSA	MSCL	No. of sub-basins
1	2886	1494	150,000	20,000	195
2	2860	1654	150,000	20,000	244
3	2860	1654	1,500,000	20,000	24
4	2860	1654	2,000,000	20,000	12
5	2860	1654	2,500,000	20,000	12

For this study, run 4 with 12 sub-basins was selected. At the final stage, the computed basin area was 803,600 km^2 while the published area is 795,000 km^2.

Display the relief modified DEM, RELIEF.RST. Convert the stream network NETW and the basin boundary BOUND images to point and polygon using:

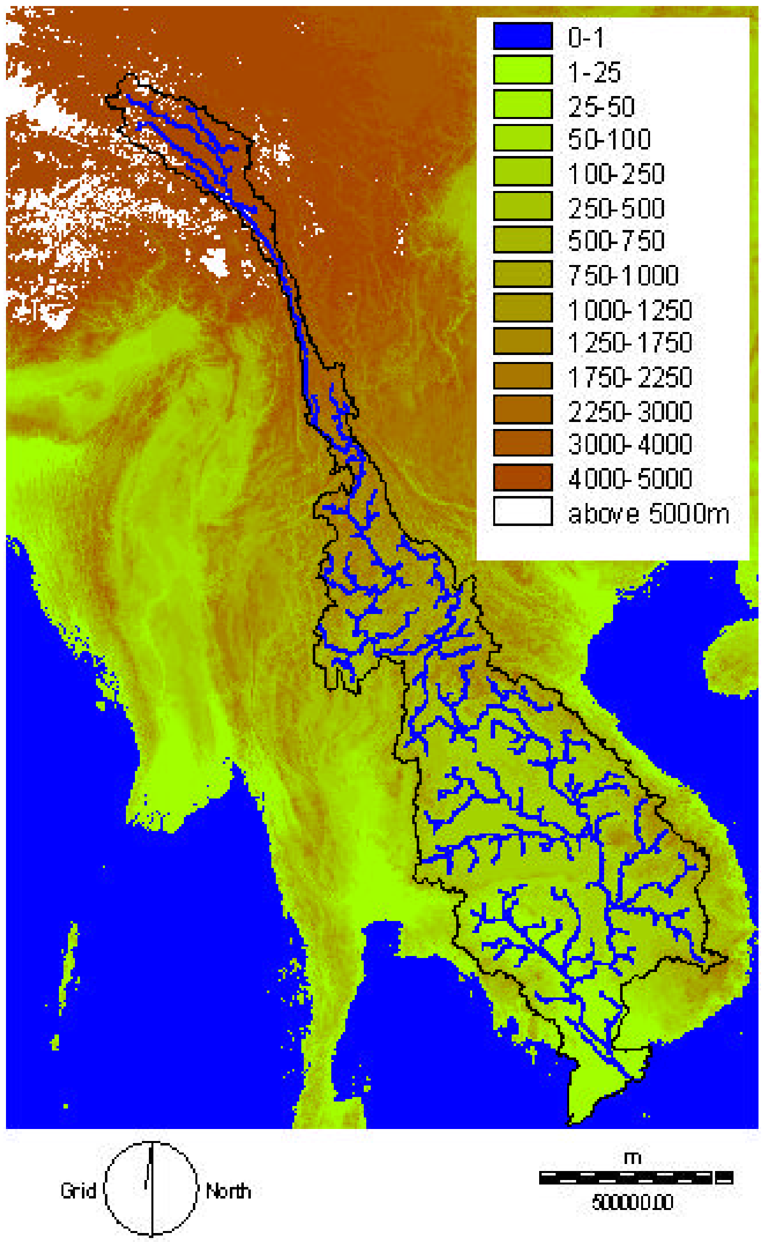
\Reformat\Raster/Vector conversion\POINTVEC, and
\Reformat\Raster/Vector conversion\POLYVEC respectively (exclude the background polygon).

Create symbol files RIVER.SM0 and BOUND.SM2 using

Display\Symbol Workshop.

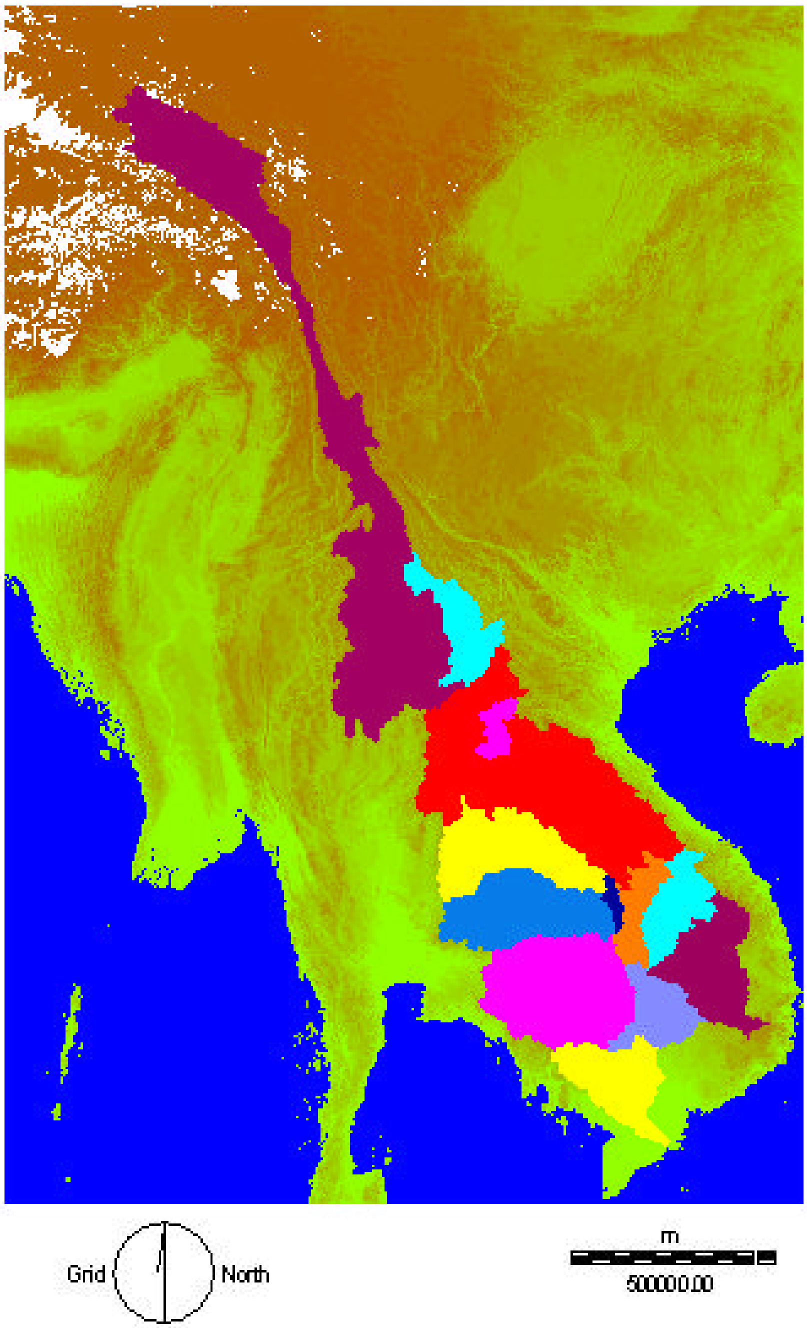
ow display the DEM as the base map and add the stream network and basin boundary as vector layers using \Composer\Add Layer. Finally, the boundary can be smoothed using:

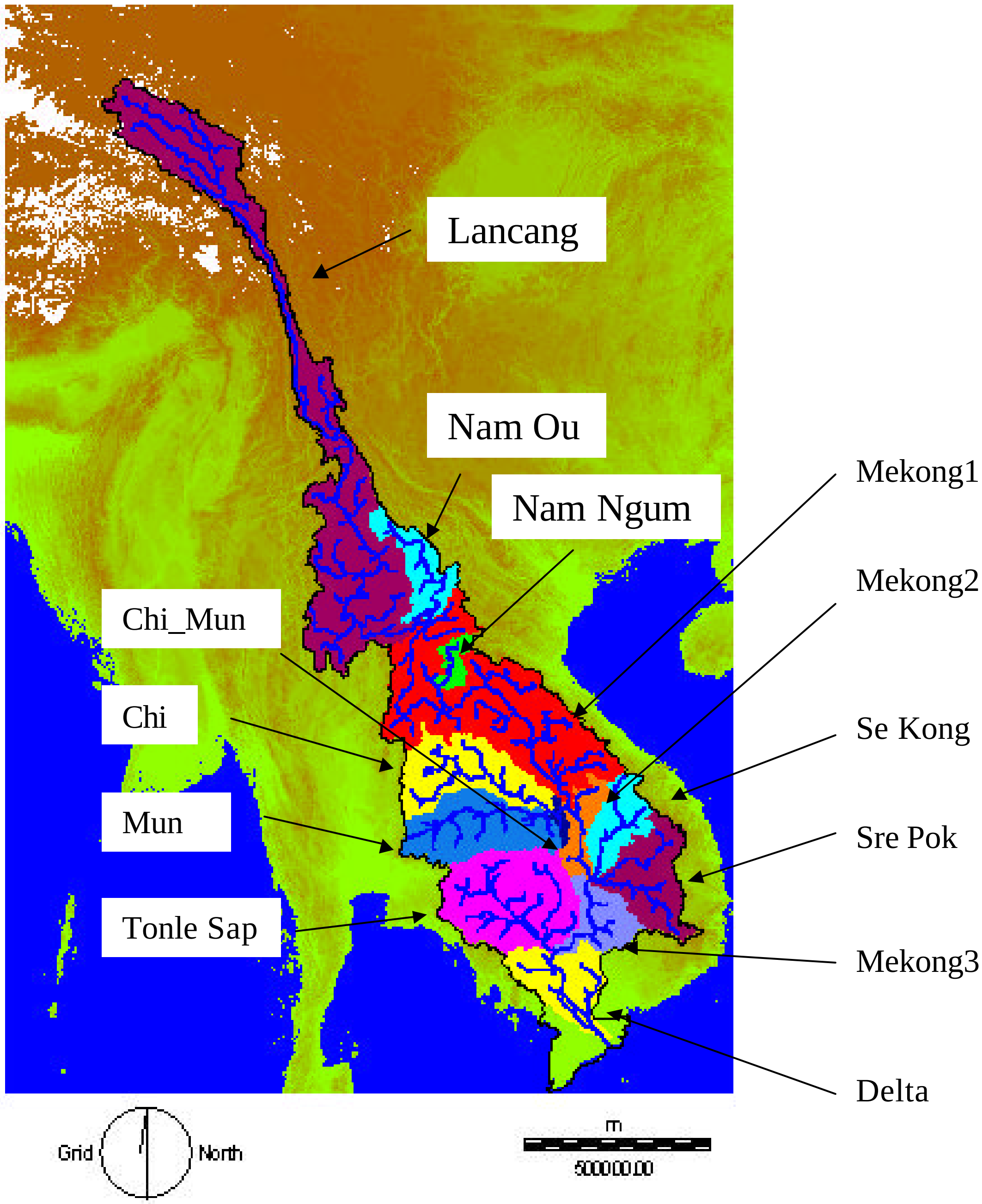
\Reformat\LINRGEN\Low-pass filtering.


0-1
1-25
25-50
50-100
100-250
250-500
500-750
750-1000
1000-1250
1250-1750
1750-2250
2250-3000
3000-4000
4000-5000
above 5000m
Grid
North
m
500000.00

To display the sub-basins on top of the DEM, first reclassify the DEM to 16 classes (say 1-16), then reclassify the sub-basin image to classes –16 to 0 and use

Analysis\Mathematical Operators\OVERLAY\First covers Second except where Zero or, alternatively, convert the sub-basin raster to vector and add it as a layer to the DEM.




Lancang
Nam Ou
Nam Ngum
Mekong1
Mekong2
Chi_Mun
Chi
Se Kong
Mun
Sre Pok
Tonle Sap
Mekong3
Delta
Grid
North
m
500000.00

Specify the sub-basins (ASA) as the first image, the DEM (DEM16) as the second image and output to a temporary image. Reclassify the temporary image to a final image (DEM&ASA) using the palette DEM&ASA.SMP. The scale and north arrow can now be added and, finally, the images containing the river network and sub-basins can be saved as .BMP files for use in other software using Composer\Save composition. In particular, the image containing the sub-basins should be saved as MEKONG.BMP as it will be displayed in the Windows version of SLURP when the MEKONG.CMD file is opened.

Finally, once the land cover image, LCLASS.INP, and the list of climate stations, CLMTSTNS.INP, are completed (see Appendices C and D, respectively), program SLURPAZ can be run. SLURPAZ uses the DEM, land cover and climate station data to prepare all the input files needed to run the SLURP hydrological model. It is best to copy LCLASS.INP and CLMTSTNS.INP to the directory that contains the results of the topographic analysis and run SLURPAZ in this directory as SLURPAZ also uses other files produced by TOPAZ.

List of data files used by SLURPAZ

DNMCNT.INP
LCLASS.INP
CLMTSTNS.INP
ORDPM.INP
OUTCNF.UNF
NETW.TAB
NETWB.TAB
SBCT.TAB
RELIEF.OUT
SUBWTB.OUT
DISCHA.OUT
DISOUT.OUT
ELDCHA.OUT
ELDOUT.OUT

Following a review of the river network contained in the “Lower Mekong Basin Forest & Land Cover 1997” maps (MRC 1999), it was realized that because of errors in the DEM, the junction of the Chi and Mun Rivers and the river network below Nam Ngum Reservoir were wrongly represented in the TOPAZ-derived stream network. These were corrected by changing the elevations of several pixels in the DEM and re-analyzing.

Appendix C

PREPARING A LAND COVER MAP

The SLURP hydrological model uses land cover information to subdivide sub-basins. There are many different global land cover classification schemes available at many different scales. For this study we used the U.S. Geological Survey's (USGS) Earth Resources Observation System (EROS) Data Center 1-km resolution global land cover characteristics database. The following description of the dataset derivation is based on material published on the USGS website (Internet 6).

This land cover dataset is derived as a multitemporal unsupervised classification of normalized difference vegetation index (NDVI) data with post-classification refinement using multi-source earth science data. The NDVI data are derived from the advanced very high resolution radiometer (AVHRR) on board the NOAA series of satellites. Monthly NDVI maximum value composites for April 1992 through March 1993 are used to define seasonal greenness classes. Past investigations have demonstrated that classes developed from multitemporal NDVI data represent characteristic patterns of seasonality and correspond to relative patterns of productivity (Brown et al. 1993).

The monthly NDVI data are recomposited from the published 10-day composites (Internet 7). The use of monthly rather than 10-day composites represents a compromise between temporal frequency and the need for cloud-free images. Masks representing water bodies, snow and ice, and barren or sparsely vegetated areas are developed to eliminate NDVI data from the composites for those areas where the meaning of the NDVI values is ambiguous. The water mask is developed through the interpretation of single-date AVHRR channel 2 (near-infrared) images supplemented with water body information taken from the Digital Chart of the World (Defense Mapping Agency 1992). Snow and ice, barren, and sparsely vegetated masks are produced from a 12-month maximum value NDVI composite threshold values that vary according to continental characteristics.

The initial segmentation of the 12-month NDVI composites into seasonal greenness classes is performed using unsupervised clustering. In this case, the clusters correspond to annual sequences of greenup, peak, and senescence. The clustering is controlled by predetermined parameters for number of iterations and number of resulting clusters.

The resulting seasonal greenness classes are then translated to seasonal land cover regions by post-classification refinement including use of digital elevation, ecoregion data and a collection of other land cover/vegetation reference data using computer-assisted image processing tools and traditional manual image interpretation.

Finally, the postclassified seasonal land cover regions are converted to land cover type using a convergence of evidence approach. All available documentation, including the region attributes, image maps, atlases, other existing land cover/vegetation maps, and any other relevant materials are consulted and compared to the spatial distribution of each region. The seasonal land cover regions are then translated into the Global Ecosystem framework (Olson 1994) and cross-referenced to the land cover classes used in various published schemes including the International GeosphereBiosphere Programme (Belward 1996) and USGS (Anderson et al. 1976). Urban areas, extracted from the Digital Chart of the World (Defense Mapping Agency 1992) are added to these derived data sets.

For this study, the USGS classification was used as this contains an irrigated cropland classification. The USGS classification contains a total of 24 land classes globally but most regions contain much fewer land classes.

To import a land cover image into the IDRISI 32 GIS:

1. Unpack the .gz file using GNU gunzip or Windows Commander or similar (I recommend using the USGS version of the image as this includes irrigated agriculture as a land class while the IGBP does not).

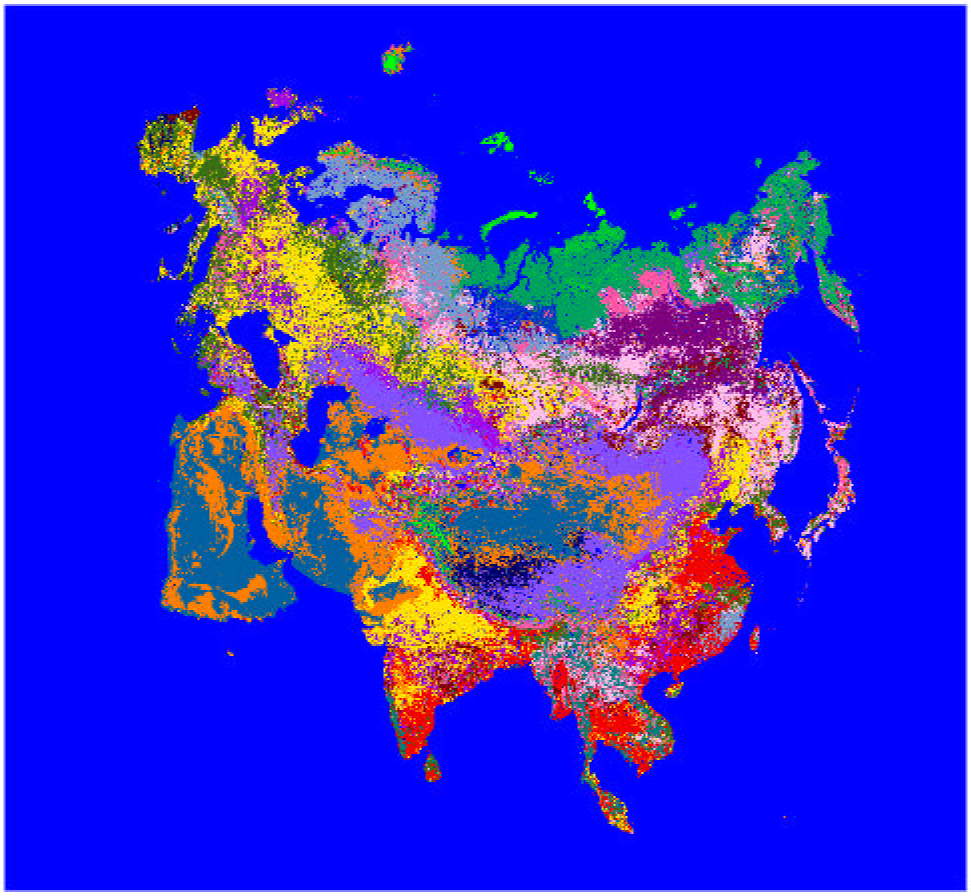
2. Read the geometric characteristics of the image from the .htm or .txt file.

3. In IDRISI, prepare a palette file (say USGS-LC.SMP) covering the 24 land covers contained in the Landdaac USGS images using \Display\Symbol workshop.

4 Prepare a projection reference file (say MekongLC.REF) by copying and renaming an existing .REF file from the \IDRISI32\GEOREF directory and changing the contents. Obtain the datum, Delta WGS84, ellipsoid, major semi-axis and minor semi-axis information for an appropriate geographic area from Appendices 1 and 2 in the IDRISI manual (Eastman 1997) and the origin long and lat., X and Y from the Landdaac .txt file for the appropriate land cover map. Note that longitudes east of Greenwich are +ve numbers followed by E in Landaac text and are simply +ve numbers in IDRISI. Note also that the IDRISI LAZEA.REF file labelled "Lambert Azimuthal Equal Area Projection" has an origin longitude given as –100 which is somewhere in New England, USA.

5. Import the land cover image using \File\Import\General Conversion Tools\BILIDRIS with parameters:

   Number of bands: 1
   No header
   Data type: 8 bit
   Number of columns, number of rows, minimum X, maximum X, minimum Y and maximum Y copied from .the htm or .txt file, e.g.,
   Number of columns per band 13000
   Number of rows per band12000
   Minimum X coordinate -8000000
   Maximum X coordinate 4999000
   Minimum Y coordinate -5499000
   Maximum Y coordinate 6500000
   Reference system: MekongLC
   Reference units: Meters
   Unit distance: 1000



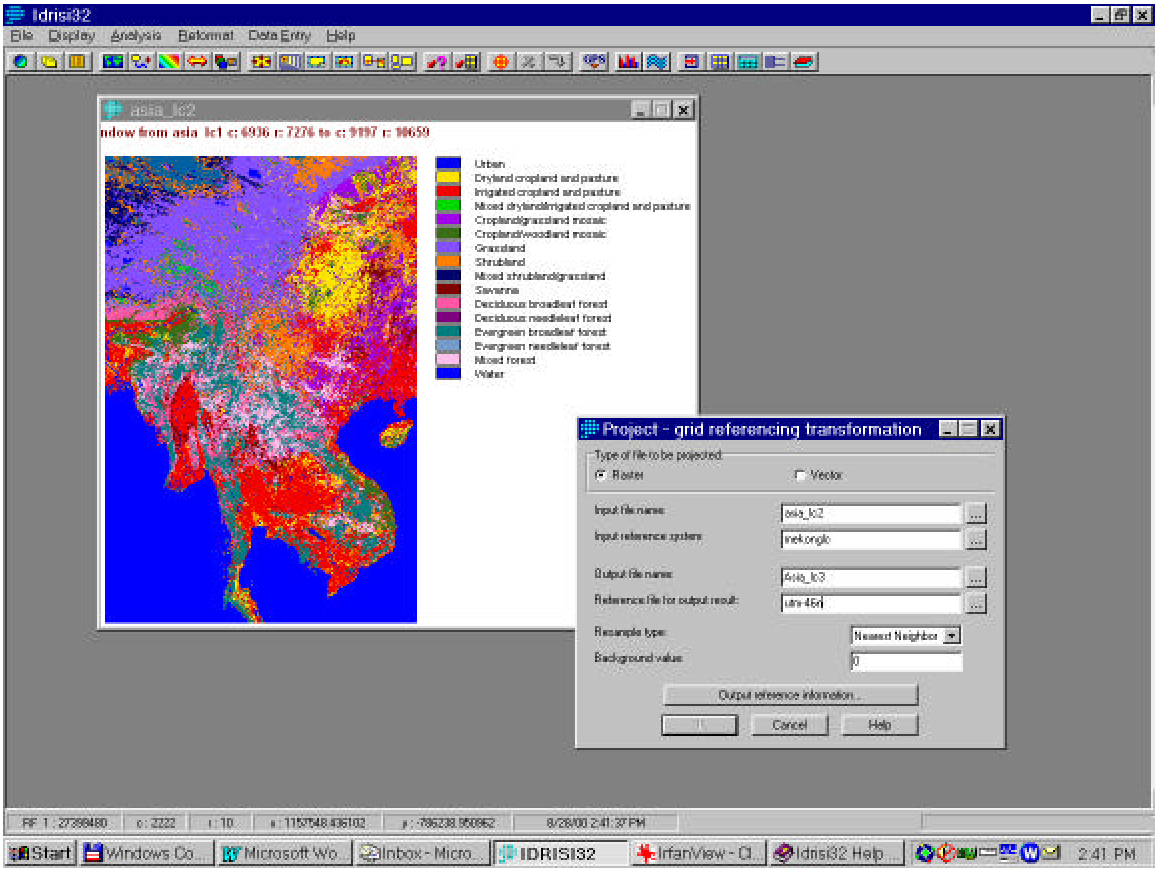
6. Display the imported image using \Display\DISPLAY Launcher with the USGS-LC palette.

7. Extract a window that contains the river basin area and which is larger all round than the DEM of the river basin. Use the “two rectangles” icon on the tool bar. Save this as a new image using Composer\Properties.

8. The windowed image must now be made to correspond to the DEM image prepared in Appendix A by converting from the Lambert Azimuthal Equal Area projection to the UTM-46N projection and by forcing the image have the same number of rows and columns. Use:

   \Reformat\PROJECT

When the Input file is specified as the windowed image, the Input reference file should appear automatically as “MEKONG-LC”. Specify an Output file name and an output file specification as “UTM-46N”.

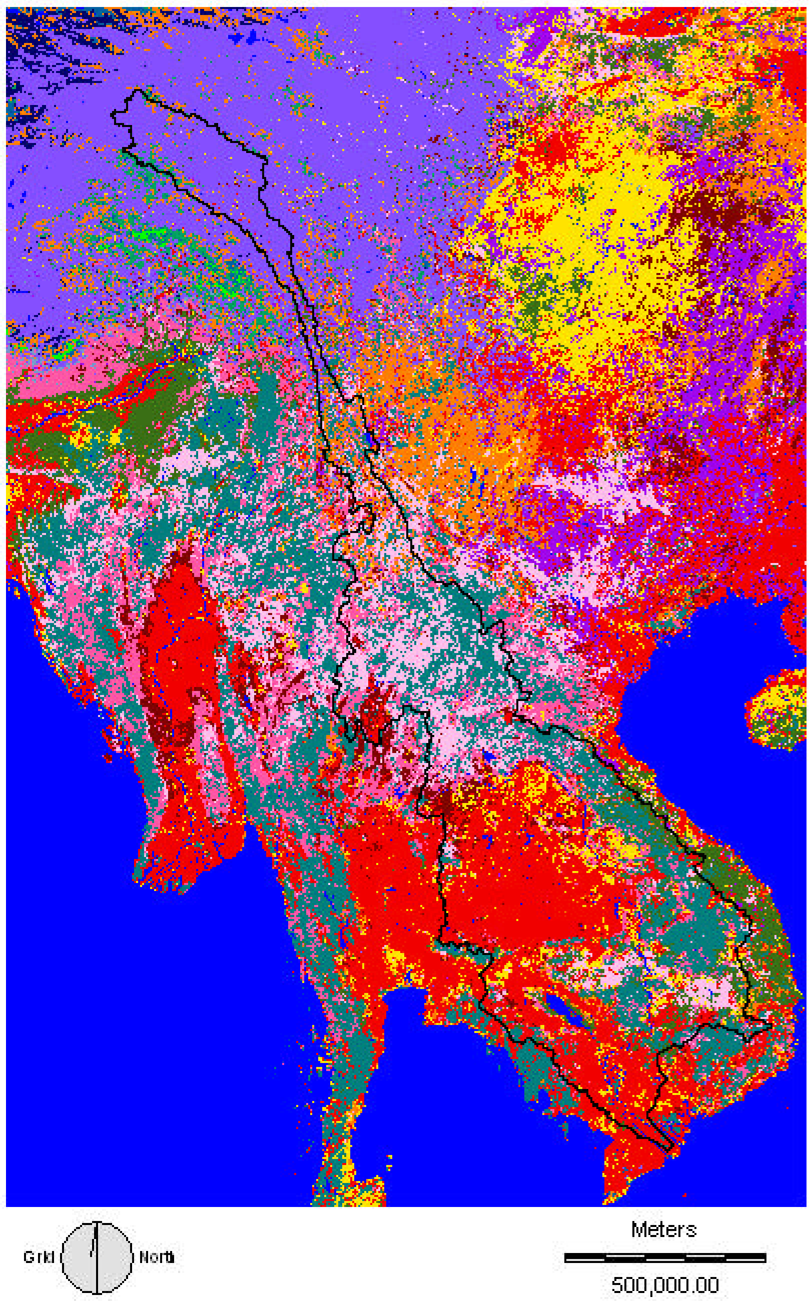


On the next screen, complete the reference parameters using the following data from the DEM .RDC file. In this case:

Columns	2000
Rows	3000
min. X	316000.0
max. X	2316000.0
min. Y	950000.0
max. Y	3950000.0

The basin boundary can be added as a layer.

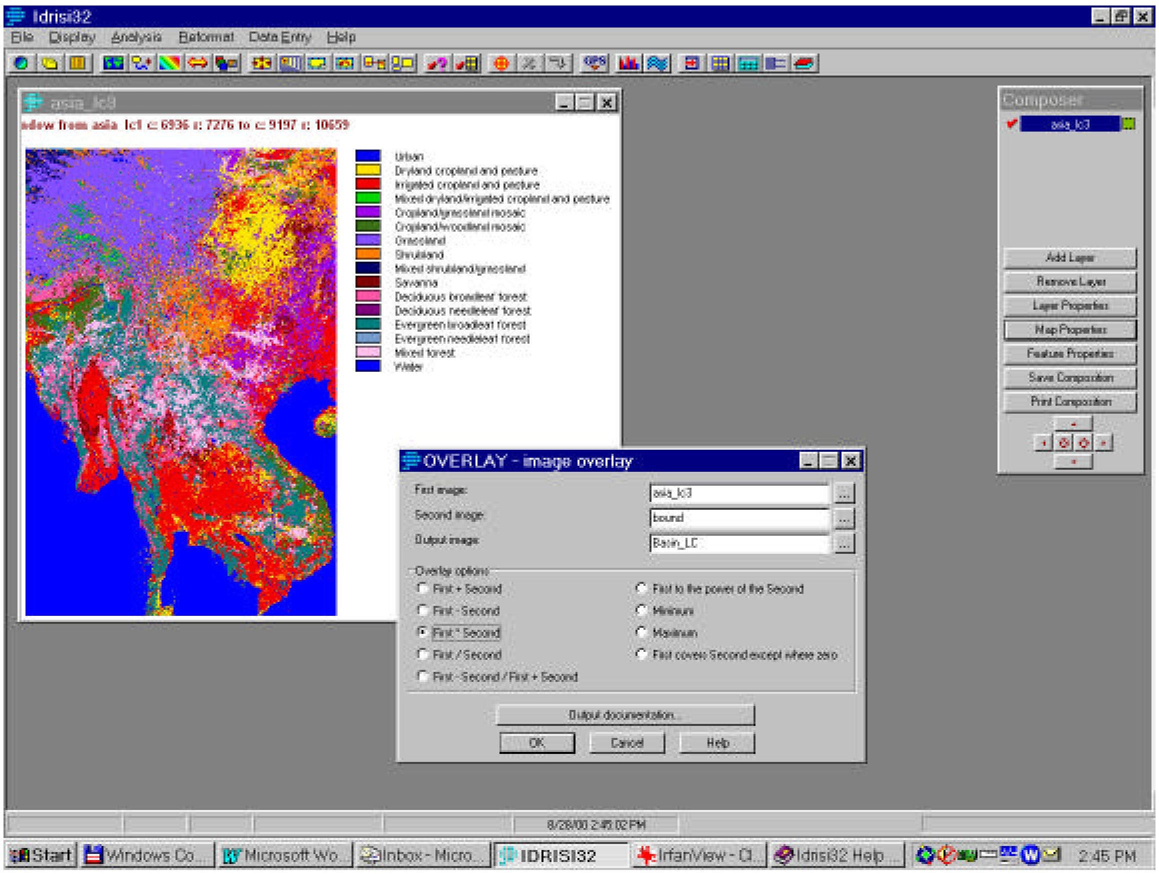
Landdaac USGS land cover classification

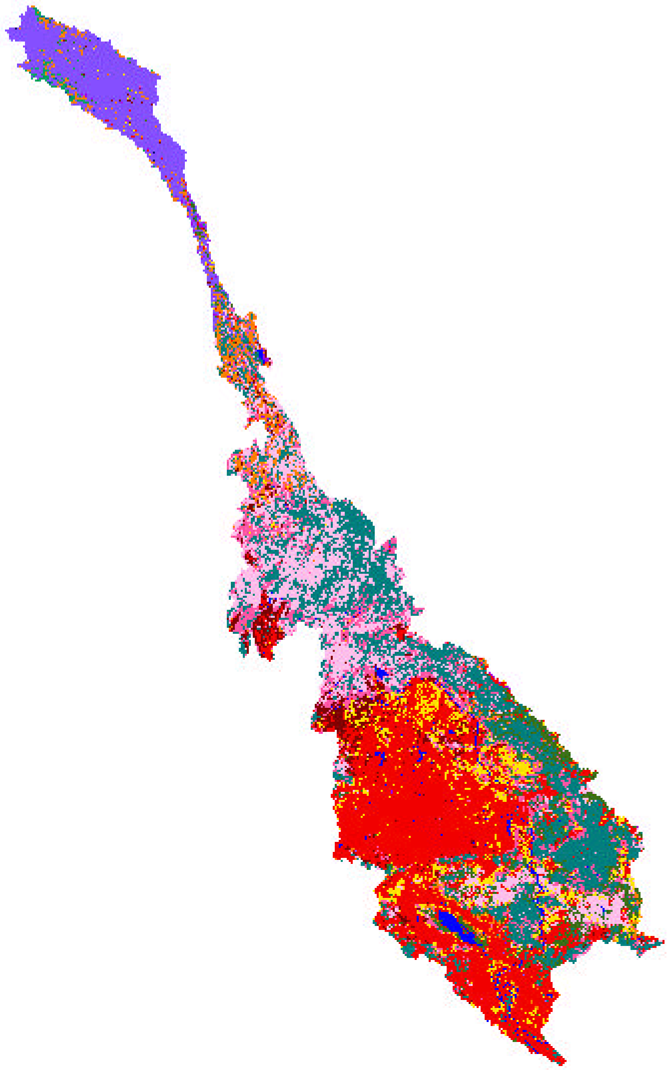


The original Landdaac USGS global classification contains 24 land classes, many of which are not needed in our analysis. To reduce the number of land classes used:

1. Prepare a land cover image of the basin alone using:

\Analysis\Database Query\Overlay with the basin outline as the overlay. This image has the value 1 inside the basin and 0 outside the basin. Multiplying the land class cover and the boundary image will leave a land class image of the basin alone.





2. Do a histogram of the land classes within the basin using:

   Analysis\Database query\HISTO

for image Basin_LC. Adjusting the percentages of land cover within the image to give percentages within the basin shows:

No.	Name	Percent
1	Urban and Built-Up Land	0.1
2	Dryland Cropland and Pasture	5.4
3	Irrigated Cropland and Pasture	28.7
4	Mixed Dryland/Irrigated Cropland and Pasture	0.0
5	Cropland/Grassland Mosaic	0.3
6	Cropland/Woodland Mosaic	4.7
7	Grassland	8.9
8	Shrubland	3.7
9	Mixed Shrubland/Grassland	0.0
10	Savanna	3.8
11	Deciduous Broadleaf Forest	9.1
12	Deciduous Needleleaf Forest	0.0
13	Evergreen Broadleaf Forest	19.8
14	Evergreen Needleleaf Forest	0.0
15	Mixed Forest	13.7
16	Water Bodies	1.4
17	Herbaceous Wetland	0.0
18	Wooded Wetland	0.0
19	Barren or Sparsely Vegetated	0.0
20	Herbaceous Tundra	0.0
21	Wooded Tundra	0.4
22	Mixed Tundra	0.0
23	Bare Ground Tundra	0.0
24	Snow or Ice	0.0

3. These land classes can now be reduced to a smaller number using RECLASS (from the tool bar) as follows:

- combine classes 2,4,5 and 6 into B
- combine 8,9,10 and 19 into E
- combine 11 and 12 into F
- combine 13 and 14 into G
- combine 16, 17 and 18 into I
- combine 20-24 into J

No.	*Name*	*Percent*
A	Urban	0.1
B	Crop/grassland	0.4
C	Crop/pasture	28.7
D	Semi-desert	8.9
E	Shrubland	7.5
F	Deciduous Forest	9.1
G	Evergreen Forest	19.8
H	Mixed Forest	13.7
I	Water Bodies	1.4
J	Tundra	0.4

At this stage the final land cover image can be displayed. A title, north arrow, scale and legend can be added by selecting

Composer\Map Properties

and selecting the appropriate components. For a legend to be added, the legend categories must be added to the .RDC file using

\File\Metadata

Finally, to convert the land cover image into a form useable in SLURPAZ, use:

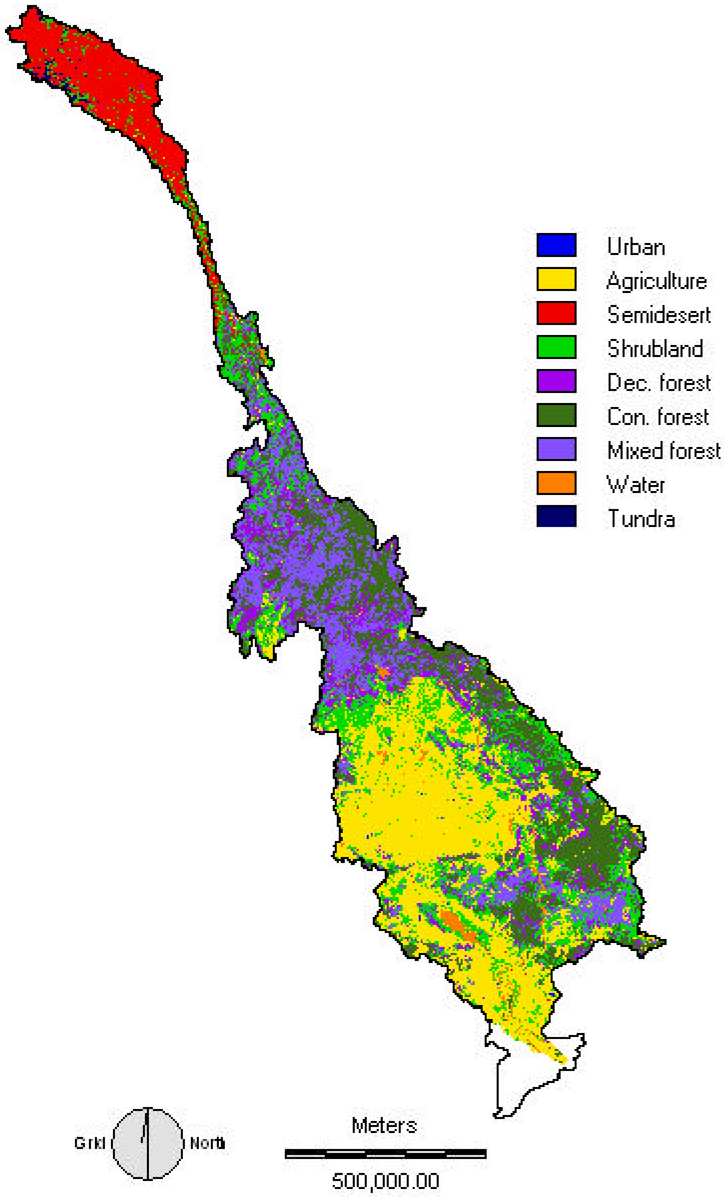
Reformat\CONVERT

to go from byte binary to integer ASCII and rename the .RST file to LCLASS.INP. Note that land cover 0 should always mean only 'outside the basin'. Do not have a real land cover numbered 0 as this will be ignored by SLURPAZ.

The land cover classification derived from the USGS NOAA satellite image in the first phase of this study was revised after reviewing the "Lower Mekong Basin Forest & Land Cover 1997" maps (MRC 1999) as follows:

Phase 1 Land Covers	Revised Land Covers
Urban	Urban
Crop/grass	Agriculture
Crop/pasture	Agriculture
Semi-desert	Semi-desert
Shrubland	Shrubland
Deciduous forest	Deciduous forest
Evergreen forest	Evergreen forest
Mixed forest	Mixed forest
Water	Water
Tundra	Tundra

After changing the land covers, it was necessary to rerun program SLURPAZ with the new land cover image in order to compute the new percentages of each land cover in each sub-basin. These were then incorporated into the command file for the SLURP hydrological model. Similar changes were needed to files .SB, .GRA and .PM.



Classifying land cover images

In some cases, published land cover maps will not be adequate and it will be necessary to derive land cover information. The following pages describe a procedure that has been successfully used in the past.

Three sets of data are used to prepare the land cover map. First, a series of monthly NDVI or near infra-red images from the NOAA AVHRR (Internet 7) satellite sensor over a full year is 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 non-irrigated 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.

The satellite images should be *georeferenced* to the DEM. First, a correspondence file (.COR) is created in IDRISI using the basin DEM image with one of the NOAA images (the table below shows an example of a COR file). This is created by visually selecting the same points from the DEM and from the NOAA image. The more points selected over the widest area possible on the images, the more precise the georeferencing will be.

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

The next step is to **RESAMPLE** all the NOAA images using the created .COR file in order to georeference all the images. An IDRISI batch file (.IML) can be used (the table below shows an example).

RESAMPLE	x	i	950201b2	c50201b2	ndvi-dem	utm-35n	m	1	0	470000	750000	4138000	4350000	280	212	1	1
RESAMPLE	x	i	950301b2	c50301b2	ndvi-dem	utm-35n	m	1	0	470000	750000	4138000	4350000	280	212	1	1
RESAMPLE	x	i	950401b2	c50401b2	ndvi-dem	utm-35n	m	1	0	470000	750000	4138000	4350000	280	212	1	1
RESAMPLE	x	i	950501b2	c50501b2	ndvi-dem	utm-35n	m	1	0	470000	750000	4138000	4350000	280	212	1	1
RESAMPLE	x	i	950701b2	c50701b2	ndvi-dem	utm-35n	m	1	0	470000	750000	4138000	4350000	280	212	1	1
RESAMPLE	x	i	950801b2	c50801b2	ndvi-dem	utm-35n	m	1	0	470000	750000	4138000	4350000	280	212	1	1
RESAMPLE	x	i	950901b2	c50901b2	ndvi-dem	utm-35n	m	1	0	470000	750000	4138000	4350000	280	212	1	1
RESAMPLE	x	i	951001b2	c51001b2	ndvi-dem	utm-35n	m	1	0	470000	750000	4138000	4350000	280	212	1	1
RESAMPLE	x	i	ndvi-g-m	ndvi-cor	ndvi-dem	utm-35n	m	1	0	470000	750000	4138000	4350000	280	212	1	1

Next, **OVERLAY** the 9 NOAA images with the DEM outline of the basin. Again, an IDRISI batch file can be used as:

overlay	x	7	2bounds3	C50201b2	O50201b2
overlay	x	7	2bounds3	C50301b2	O50301b2
overlay	x	7	2bounds3	C50401b2	O50401b2
overlay	x	7	2bounds3	C50501b2	O50501b2
overlay	x	7	2bounds3	C50701b2	O50701b2
overlay	x	7	2bounds3	C50801b2	O50801b2
overlay	x	7	2bounds3	C50901b2	O50901b2
overlay	x	7	2bounds3	C51001b2	O51001b2
overlay	x	7	2bounds3	ndvi-cor	Ondvicor

Once the series of NDVI images are correctly aligned they may be analysed using principle components to determine the significant groupings of components. This is done in IDRISI using:

\Analysis\Change\Time Series\TSA.

Next a 3-band composite is produced using the image from the first principal component, a NOAA image showing large spatial changes (usually a summer image) and the DEM. Carry out an unsupervised classification on the resulting image using:

\Analysis\Image processing\Hard classifier\Cluster

Check the result in the field and change as necessary. Finally, in IDRISI use \Reformat\CONVERT to convert your final land cover image to an integer ASCII file named LCLASS.INP and copy this to the directory containing the DEM.

Appendix D

PREPARING CLIMATE DATA

The SLURP and airports and the following section will not be needed.

However, in many countries, climate data are 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) (Internet 8) (also available from IWMI [Internet 9] and GSOD (Global Summary of the Day) (Internet 3), 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. GSOD contains 13 parameters for over 8000 stations for the period 1994 to date, is updated on the web every month and is held in imperial units. GDS has neither radiation nor humidity data and GSOD does not have radiation data.

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

For the Mekong Basin model we used NCDC/GSOD data. A series of programs, listed in the following table, were written to help extract the climate data for the stations and years required.

Program	Input file(s)	Purpose	Output file(s)
GSOD-0.EXE	STNLIST.TXT	Creates a list of available stations within a specified lat/long box. and the corresponding IDRISI 32 point vector files.	CLMTSTNS.INP CLMTSTNS.VCT CLMTSTNS.VDC
GSOD-1.EXE	month-yy.TXT where month is the full month name and yy is a 2-digit year.	Converts the downloaded and unzipped GSOD climate files from UNIX to DOS format and changes names to include 4-digit years.	Gyyymm.TXT where yyyy is year and mm is month.
GSOD-2.EXE	CLMTSTNS.INP Gyyyymm.TXT	Extracts individual station data for the stations listed in CLMTSTNS.INP from the monthly Gyyyymm.TXT files. Computes average temperatures and sunshine hours.	station.PCP station.TAV station.TDP station.SUN where station is the station number. MISSDATA.TXT
GSOD-3.EXE	CLMTSTNS.INP station.*	Checks that data files station.* are the correct length and fills in missing values	station.*
INP2VXP.EXE	CLMTSTNS.INP	Creates IDRISI .VXP file from the modified CLMTSTNS.INP for display in IDRISI 32. Also works with STRMSTNS.INP and DAMS.INP to produce vector files.	CLMTSTNS.VXP
MAP.EXE	station.PCP	Computes long-term mean precipitation from a daily precipitation file for use in the Morton CRAE evapotranspiration method.	
MERGE.EXE	CLMTSTNS.INP CLMTSTNS.VXP	Produces a text file that can be used in a spreadsheet to trim the list of stations	CLMTSTNS.MER

The procedure used to extract climate data from the Internet can be summarised as first, download the files for the dates required; second, select which climate stations to use, and, third, extract the climate data for the required stations:

1. Download and unzip the .tar files from the Internet site (~65MB each) for the years required using Windows Commander or similar, e.g.,

all-1994.tar
all-1995.tar

2. For each of the annual files, extract the individual month files that are of interest (~5.5MB each) using Windows Commander or similar, e.g.,

september-97.txt.Z
october-97.txt.Z

3. Unzip the .Z files using WinZip or similar to the data files, e.g.,

september-97.txt
october-97.txt

This can be carried out using WinZip in a batch file such as cli-unzp.bat as provided on the SLURP CD-ROM.

4. Copy the programs GSOD-0.EXE, GSOD-1.EXE, GSOD-2.EXE, MAP.EXE, CRLF.EXE and the data file STNLIST.TXT from CD-ROM directory \CLIMATE\RUN_FILE and INP2VEC.EXE from \SLURP\RUN_FILE to your working directory.

5. Run program GSOD-0.EXE specifying the path to the directory containing the .Z climate files and the latitude/longitude coordinates of the top-left and bottom-right corners of a box containing the area of interest, e.g.,

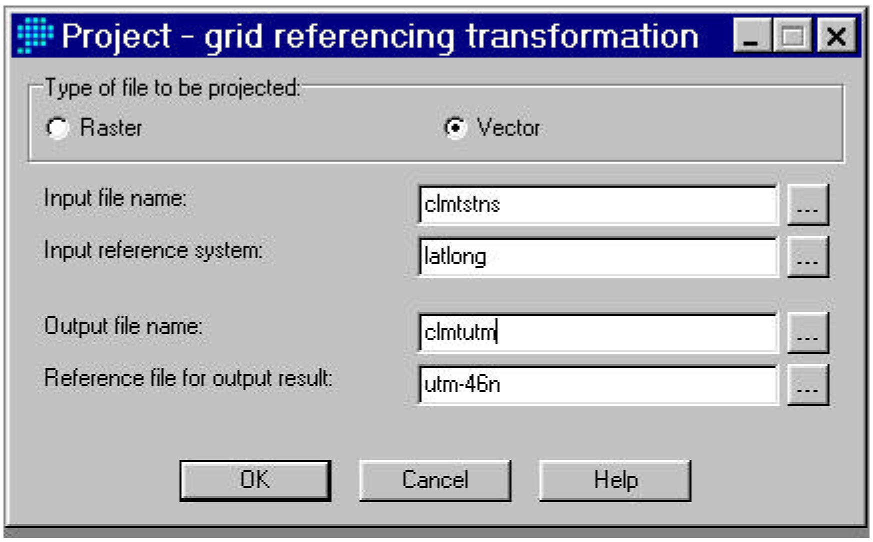
GSOD-0 c:\Mekong\Climate 40.0 90.0 8.0 115.0

This program reads file STNLIST.TXT and creates four files containing data on stations found within the specified lat/long box:

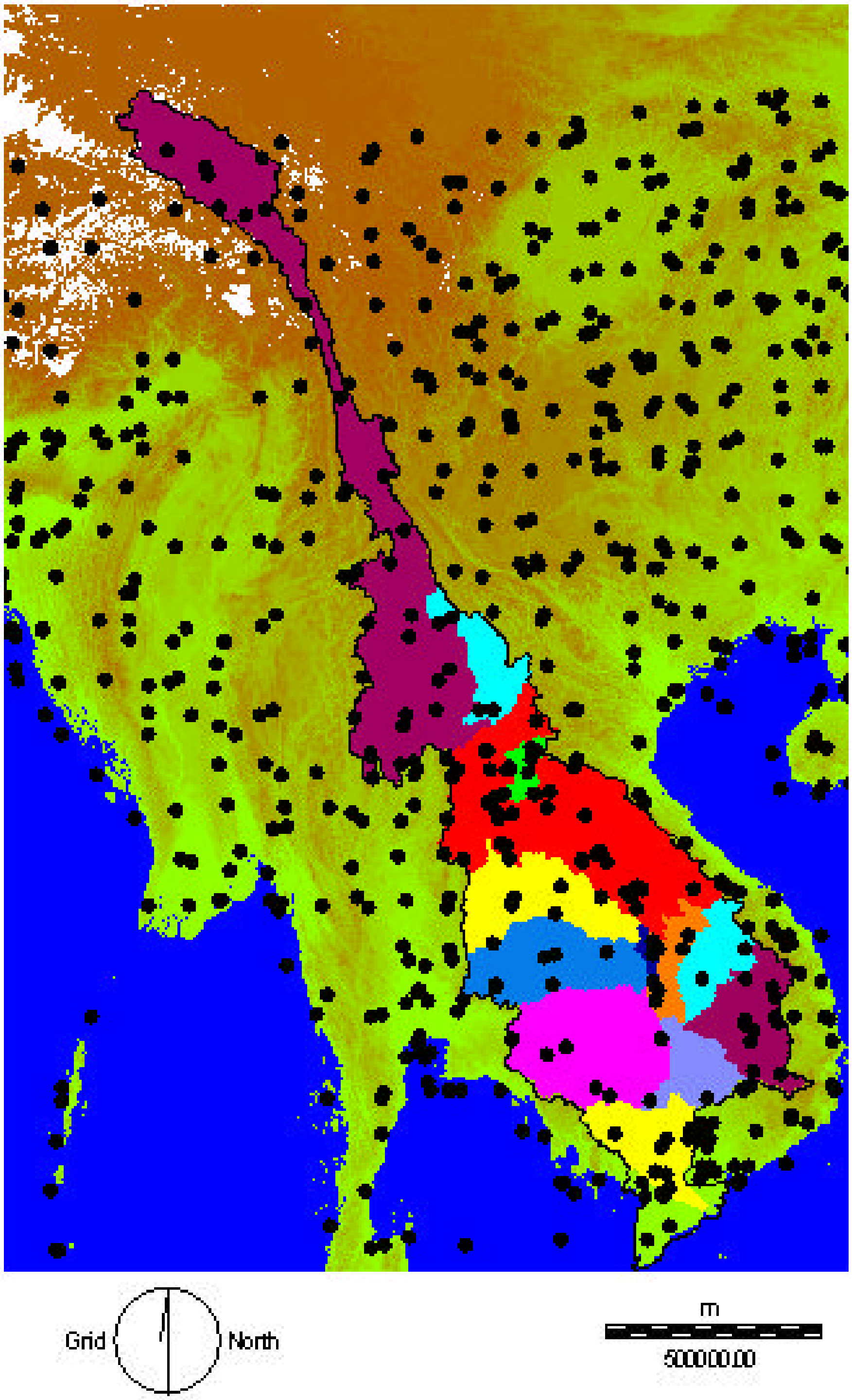
a. CLMTSTNS.INP which contains the number, name, country, latitude, longitude and height. This file will be used in later programs to extract the climate data.
b. CLMTSTNS.VCT and CLMTSTNS.VDC, a pair of IDRISI 32 vector files containing the latitude and longitude of the stations.
c. CLMTSTNS.VAL, an IDRISI values file containing the station numbers.

Note that the version of file STNLIST.TXT on the CD-ROM has been corrected for format errors. If you download a new version of STNLIST.TXT from the GSOD website, you must be aware of possible format errors.

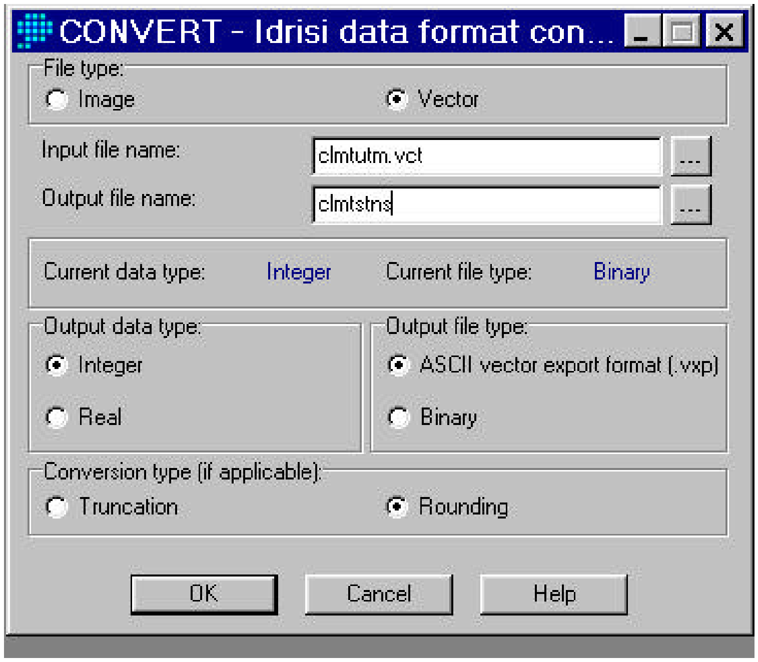
6. In IDRISI 32, convert from the lat/long projection used by the GSOD database to the UTM projection used for modeling work using \Reformat\Project and selecting the appropriate output projection; in this case UTM-46N:



7. The resulting climate stations point file should then be viewed in IDRISI by first displaying the sub-basin image and then adding the CLMTUTM layer with the CLMTSTNS symbol file. Using the "Cursor or Enquiry mode" (looks like an arrow and question mark) and the "Feature Properties" (looks like an arrow and a table) icons on the toolbar and with the CLMTUTM layer highlighted in Composer, click on the stations you want to keep (5 or 6 per sub-basin is enough) and note down the corresponding station identity numbers.


Grid
North
m
500000.00

8. In IDRISI, produce an ASCII output file, CLMTSTNS.VXP, using \Reformat\Convert

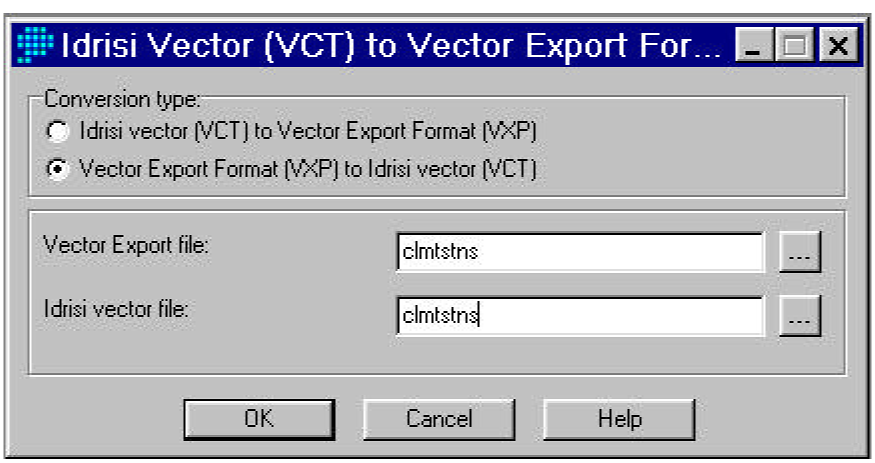


Modify CLMTSTNS.VXP in an editor by deleting all the records for the stations you wish to remove from the list, retaining only those stations you wish to keep. Change the "Number of Features" figure in the 7^{th} line of CLMTSTNS.VXP to the revised number of climate stations.

At the same time, change the file CLMTSTNS.INP in a text editor in the same way, deleting the records of the stations not required.

9. Then use:

File\Import\Software Specific Format\Vector Export Format



to convert the revised CLMTSTNS.VXP back to IDRISI 32 CLMTSTNS.VCT and .VDC vector files ready for display.

For the Mekong Basin, this resulting figure (below) shows that, out of the 901 climate stations identified in the NCDC/GSOD list, only 17 were found to have enough data to be useable. This would be an adequate number if they were distributed evenly across the basin. However, they are not; the figure shows that the top of the basin, in China, has enough stations as does the Thai part of the basin. The rest of the basin has no climate data for the GSOD period of 1994-1998. Before using these data stations, we checked the other major source of Internet data, GDS using the IWMI Atlas Synthesizer software (Internet 9). The procedure used is given in Lacroix et al. (1999). No new stations were found with significant numbers of data but the GSOD station records could be extended back to 1977 if required.

The image showing the climate stations should be saved as CLMTSTNS.BMP as it will be displayed in the Windows version of SLURP when the sub-basin climate data is computed.

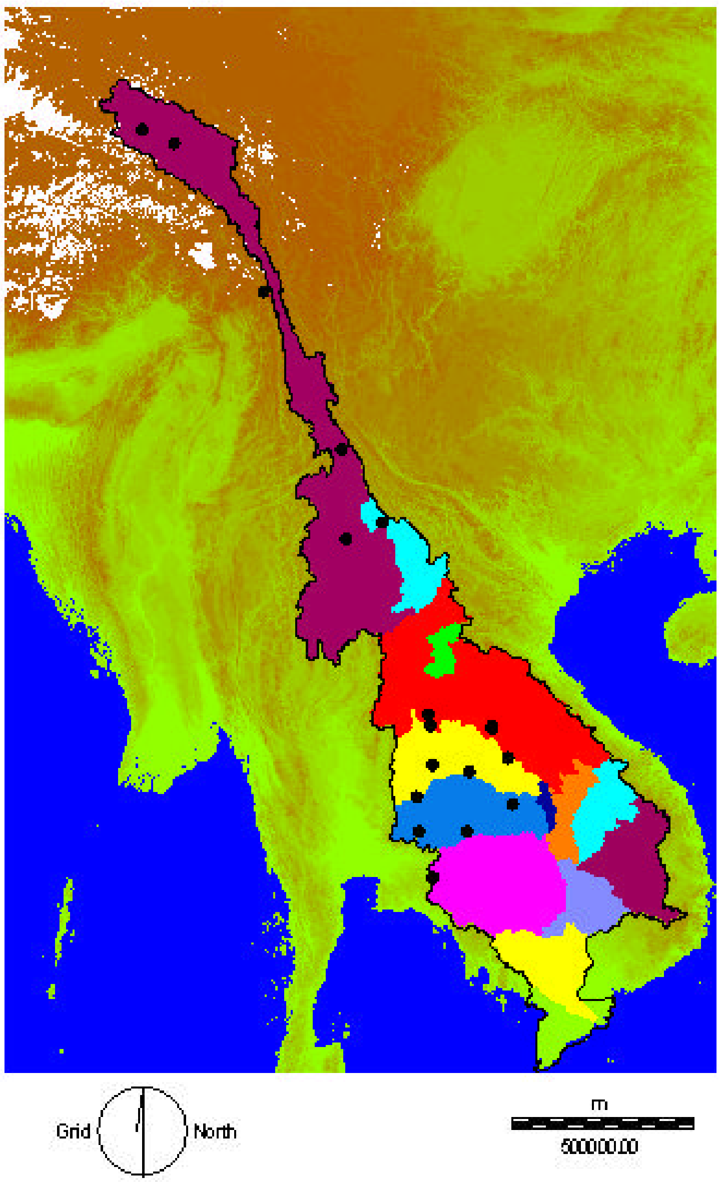


Table showing number, name, country, latitude, longitude, easting, northing and height for selected climate stations in the Mekong Basin.

56018000	ZADOI	CI	32.54	N	95.18	E	704717.4	3602389	4068
56125000	NANGQEN	CI	32.15	N	96.13	E	795226.6	3561356	4145
56347000	ZEN-YAN (?)	CI	29.12	N	98.48	E	1033565	3233722	0
56856000	JING-DONG	CI	24.26	N	100.51	E	1263766	2703658	1676
48923600	NAM LIEU	LA	20.34	N	100.35	E	1268794	2266312	579
56959000	JINGHONG	CI	22.01	N	100.48	E	1273629	2452933	553
48300500	CHIANG KHONG	TH	20.11	N	100.25	E	1259418	2240235	353
56977000	JIANGCHENG	CI	22.37	N	101.49	E	1376346	2498616	1121
48928500	NAM BAC	LA	20.38	N	102.27	E	1470571	2281041	351
48930100	LUANG^PRABANG	LA	19.54	N	102.1	E	1457790	2186169	298
48941000	PHONHONG	LA	18.28	N	102.24	E	1480052	2046103	179
48944500	GROVE JONES-2	LA	18.03	N	104.19	E	1690568	2029812	159
48948500	BANG DONG HEN	LA	16.42	N	105.18	E	1808751	1855139	143
48948800	KENG KOK	LA	16.27	N	105.11	E	1802155	1837765	171
48850100	KHE SANH	VN	16.38	N	106.43	E	1945376	1859362	420
48850500	KHE SANH	VN	16.38	N	106.43	E	1945376	1859362	420
48354000	UDON THANI(CI	TH	17.23	N	102.48	E	1511678	1929951	182
48354500	UDORN AB (USA	TH	17.23	N	102.48	E	1511678	1929951	178
48381200	KHON KAEN	TH	16.28	N	102.47	E	1515715	1823592	202
48381800	NAM PHUNG DAM	TH	16.58	N	103.59	E	1635168	1863272	320
48947100	SAVANNAKHET	LA	16.33	N	104.45	E	1729971	1840322	155
48403000	CHAIYAPHUM	TH	15.48	N	102.02	E	1470986	1731938	183
48431000	KORAT/NAKHON	TH	14.58	N	102.05	E	1478396	1631441	188
48431600	KORAT AB (USA	TH	14.56	N	102.05	E	1478486	1629205	225
48416000	THA TUM	TH	15.19	N	103.41	E	1623535	1706296	129
48432000	SURIN	TH	14.53	N	103.3	E	1615002	1631683	147
48407000	UBON/RATCHATH	TH	15.15	N	104.52	E	1744921	1707942	127
48955800	BAN KHENG NHA	LA	15.19	N	105.59	E	1861853	1718998	186
48952000	SARAVANE	LA	15.41	N	106.25	E	1932788	1748259	168
48959500	MUANG KHONG	LA	14.07	N	105.51	E	1860171	1591981	76
48462000	ARANYAPRATHET	TH	13.42	N	102.35	E	1516252	1502952	49
48966000	SIEMREAP	KP	13.22	N	103.51	E	1644503	1485667	15
48968000	KRAKOR	KP	12.31	N	104.11	E	1715008	1386178	5
48972000	STUNG TRENG	KP	13.31	N	105.58	E	1872428	1506508	56
48957000	ATTOPEU	LA	14.48	N	106.5	E	1966783	1644595	105
48863700	DAK PEK	VN	15.05	N	107.45	E	2067633	1715964	731
48855500	THUONG DOC	VN	15.51	N	107.57	E	2077313	1769188	19
48861500	BEN HET	VN	14.41	N	107.4	E	2066861	1642811	680
48858000	BECAME STN 48	VN	14	N	108.01	E	2137646	1600473	742
48858100	PLEIKU/CU-HAN	VN	14	N	108.01	E	2137646	1600473	742
48874600	PLEI DJE RENG	VN	13.58	N	107.39	E	2071613	1548319	291
48876600	BAN DON	VN	12.53	N	107.47	E	2087490	1429321	244
48875000	BANMETHUOT	VN	12.41	N	108.05	E	2153249	1419330	537
48995000	KOMPONG-CHAM	KP	12	N	105.27	E	1845182	1356835	16
48885500	BU DOP	VN	12.01	N	106.49	E	1981077	1364428	153
48876800	BU PRANG	VN	12.15	N	107.23	E	2062998	1384601	0
48991000	PHNOM-PENH/PO	KP	11.33	N	104.51	E	1763894	1277655	10
48991100	PHNOM-PENH	KP	11.33	N	104.51	E	1763894	1277655	10
48992100	PHNOM-PENH/CA	KP	11.33	N	104.51	E	1763894	1277655	10
48900800	BEN SOI	VN	11.17	N	105.59	E	1884995	1264602	13
48891500	TAY NINH WEST	VN	11.19	N	106.04	E	1935189	1269082	8
48909700	CAI CAI	VN	10.54	N	105.33	E	1858903	1192167	1
48910000	VINH LONG	VN	10.15	N	105.57	E	1887521	1149135	3
48910100	VINH LONG	VN	10.15	N	105.57	E	1887521	1149135	3

10. Now that the list of stations CLMTSTNS.TXT, has been reduced to only those stations needed, the actual extraction of the climate data can begin.

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, 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. Note that, because of the long file names used, this program (and the others used in this section) must be compiled and linked in Windows using a batch file such as CL-WIN.BAT.

11. Run program GSOD-2.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 will create data files of average temperature, .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). In the absence of radiation or sunshine hour data, the ratio of actual to maximum possible sunshine hours (.sun) is derived from the precipitation data (.pcp). 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 precipitation between 0 and 25 mm, the hours of sunshine are computed proportionately.

12. Run program GSOD-3.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 will fill in any missing values and ensure that all data files are the correct length. It is possible that no data will be found by GSOD-3 for some of the stations in CLMTSTNS.INP. The records for those stations with no data should be removed from CLMTSTNS.INP at this stage. In this case, the stations that were less significant were deleted keeping about 5 prominent stations for each ASA region.

This .INP file will used in the SLURPAZ program to create a .WTS file for use in the SLURP model to convert point data to sub-basin averages (see main report and Appendix B).

13. If you are using the Morton evapotranspiration method, then run the program MAP.EXE 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. Now, the DEM, land cover and climate station list are all ready for input to SLURPAZ. Copy CLMTSTNS.INP to the directory containing the DEM and land cover files and run SLURPAZ. SLURPAZ will compute a .WTS file and a .CMD file, which can be used in the option on the SLURP main menu to convert the climate station data to sub-basin-average climate data.

Including local climate data

The first phase of the modeling used only climate data from the Internet. In the second phase, the Mekong River Commission provided precipitation and pan evaporation data at a large number of sites.

Using a different directory to the Internet climate data (to avoid confusion with file names) these data were reviewed as follows:

1. Using a text editor a station list CLMTSTNS.INP was prepared for the local stations. This should be the same format as was used for the file CLMTSTNS.INP for Internet stations, e.g.,

```
48352000 1504692 1962131     175 0.0
48354000 1511678 1929951     182 0.0
48356000 1684985 1923481     172 0.0
```

2. Run program INP2VXP.EXE to convert the file CLMTSTNS.INP to the IDRISI 32 ASCII vector file CLMTSTNS.VXP as:

INP2VXP path F P

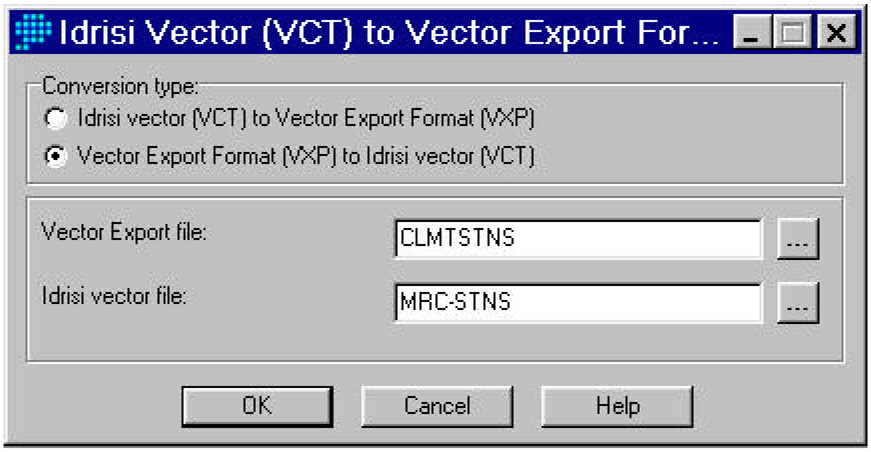
where path is the path to the directory containing the file CLMTSTNS.INP, F is the file type, C for climate and S for streamflow (use C) and P is the projection of the data, U for UTM and L for lat/long (use L). The resulting CLMTSTNS.VXP file will look like this:

```
Vector Layer Name  : CLMTSTNS
Vector Layer Type  : Point
Reference System   : utm-
Reference Units    : m
Unit Distance      : 1
ID/Value Type      : Integer
Number of Features :    18

Feature Number     :          1
ID or Value        :    48352000
Coordinates (X,Y)  : 1504692.000000 1962131.000000

Feature Number     :          2
ID or Value        :    48354000
Coordinates (X,Y)  : 1511678.000000 1929951.000000
```

If the climate data are in UTM projection, it will be necessary to edit CLMTSTNS.VXP in a text editor to add the UTM zone number to the third line of the file. In this case, we changed “utm-“ to “utm-46n”.

3. Next, in IDRISI 32, import the ASCII vector file CLMTSTNS.VXP to binary vector files d to the corresponding IDRISI 32 vector files MRC-STNS.VCT and .VDC using:

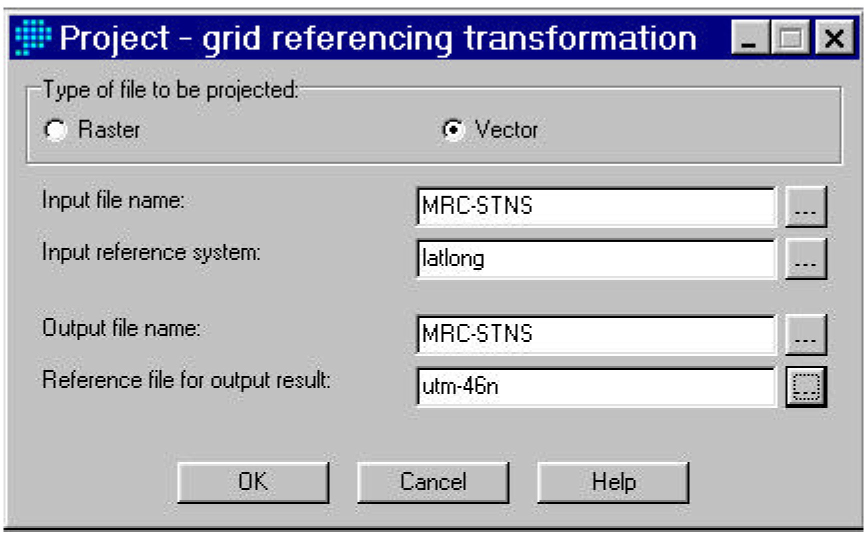
\File\Import\Software Specific Formats\Vector Export Format



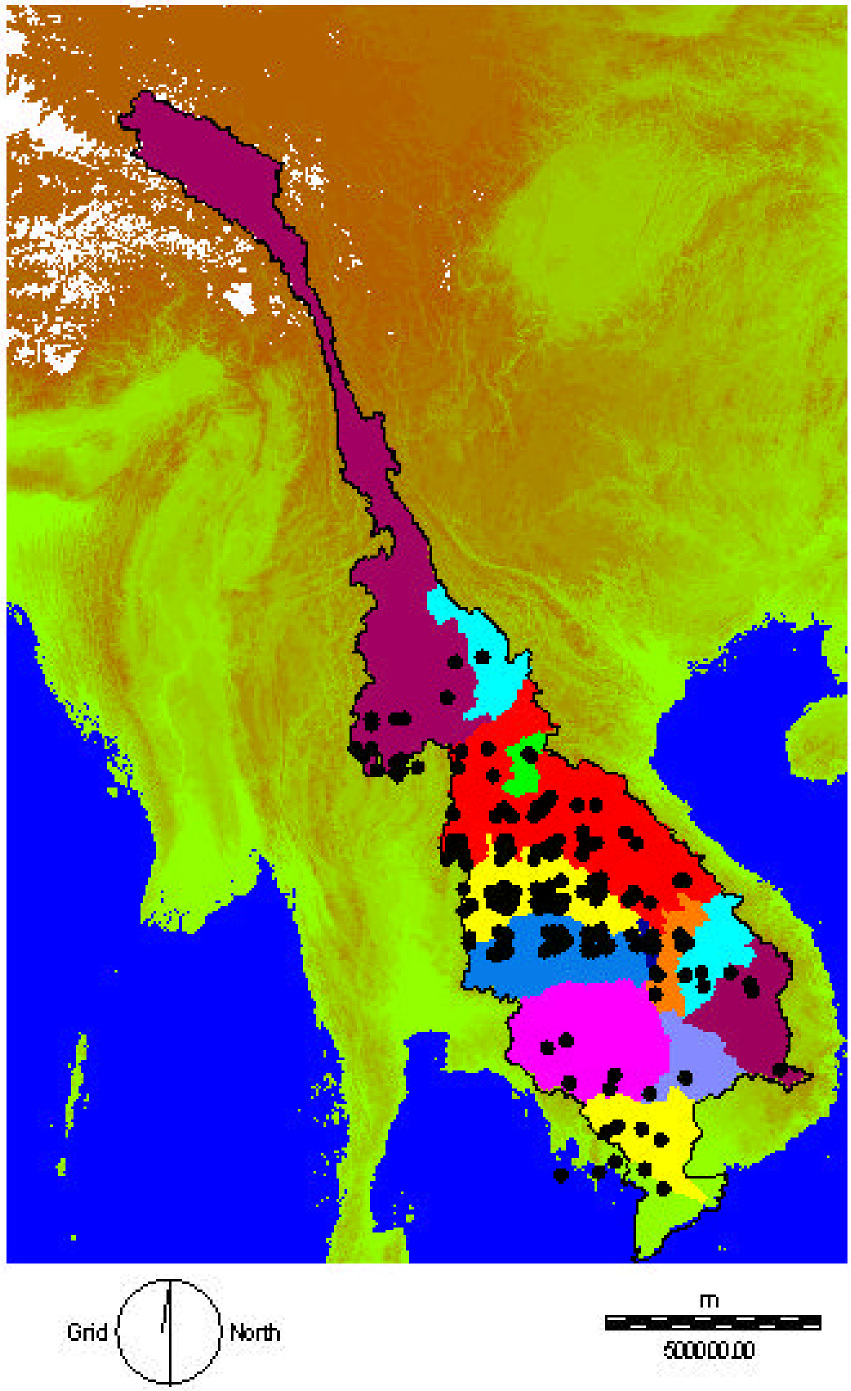
4. Then transform the IDRISI 32 vector files from the lat/long projection to a UTM 46N reference system using:

\Reformat\Project\Vector

setting the input reference system to Latlong and the output reference file to UTM-46N.



The following image shows the locations of the stations obtained from the Mekong River Commission. In this case, the climate data obtained from the Mekong River Commission were not used as no data were available for the 1994-1998 modeling period.



Appendix E

PREPARING SOIL DATA

Although SLURP does not use soil data directly, soil information may be used to derive some of the model parameters such as wilting point and field capacity through the use of pedotransfer functions (Droogers and Kite 1999).

For the Mekong Basin, the FAO Digital Soil Map of the World (FAO 1998) was used. The legend of the original soil map of the World comprises an estimated 4,930 different map units, which consist of soil units or associations of soil units. When a map unit is not homogeneous, it is composed of a dominant soil and component soils. The latter are associated soils, covering at least 20 percent of the area; and inclusions, important soils which cover less than 20 percent of the area.

The legend comprises 106 soil units (from Af to Zt), grouped in 26 major soil groupings. An alphabetical list of soil unit symbols and their names is available on the FAO CD-ROM.

Textural classes reflect the relative proportions of clay (fraction less than 0.002 mm), silt (0.002 - 0.05 mm) and sand (0.05 - 2 mm) in the soil. Three textural classes are recognized: coarse (1): sands, loamy sands and sandy loams with less than 18 percent clay and more than 65 percent sand; medium (2): sandy loams, loams, sandy clay loams, silt loams, silt, silty clay loams and clay loams with less than 35 percent clay and less than 65 percent sand; the sand fraction may be as high as 82 percent if a minimum of 18 percent clay is present; and fine (3): clay, silty clays, sandy clays, clay loams, with more than 35 percent clay. The textural class given in the mapping unit refers to the upper 30 cm of the dominant soil. Where two or three texture classes are indicated, each is taken to apply to 50 or 33 percent, respectively, of the dominant soil unit.

The procedure for using the FAO Soil Map is as follows:

1. Copy the IDRISI 2 .IMG and .DOC image files for the appropriate area from the IDRISI directory on the FAO CD-ROM. There are two errors that need to be fixed in the .RDC files. In a text editor, change the reference system from “lat/long” to “latlong” and change the unit distance from “0.08333” to “1.0”. Convert the IDRISI 2 files to the corresponding .RST and .RDC files using:

    \Files\IDRISI Conversion Tools

    in IDRISI 32.

2. Extract a window that contains the river basin area and which is larger all round than the DEM of the river basin. Use the “Zoom Window” icon (a dotted rectangle) on the tool bar. Save this as a new image using Composer\Save Composition.

3. The windowed image must now be made to correspond to the DEM image prepared in Appendix A first by converting from the lat/long projection to the UTM-46N projection and second by making the image the same number of rows and columns. Use:

\Reformat\PROJECT

When the Input file is specified as the windowed image, the Input reference file should appear automatically as “latlong”. Specify an Output file name and an output file specification as “UTM-46N”.

On the next screen, complete the reference parameters using the following data from the DEM .RDC file. In this case:

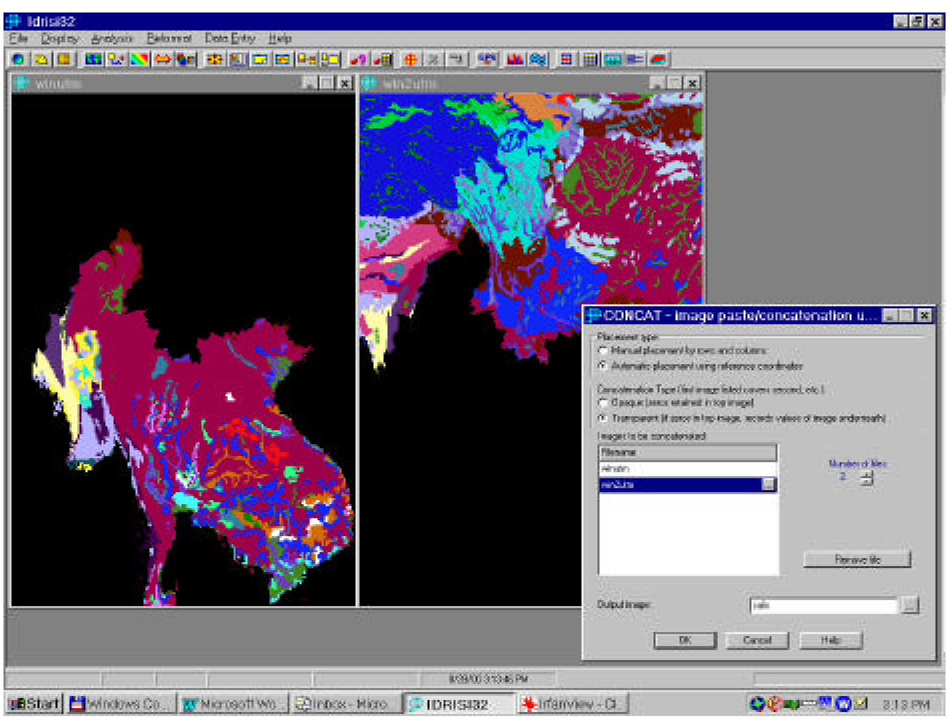
Columns	2000
Rows	3000
min. X	316000
max. X	2316000
min. Y	950000
max. Y	3950000

In the case of the Mekong Basin, two soil maps are needed SEAEAST and FESSOIL. Once each has been converted to UTM-46N, the images can be combined using:

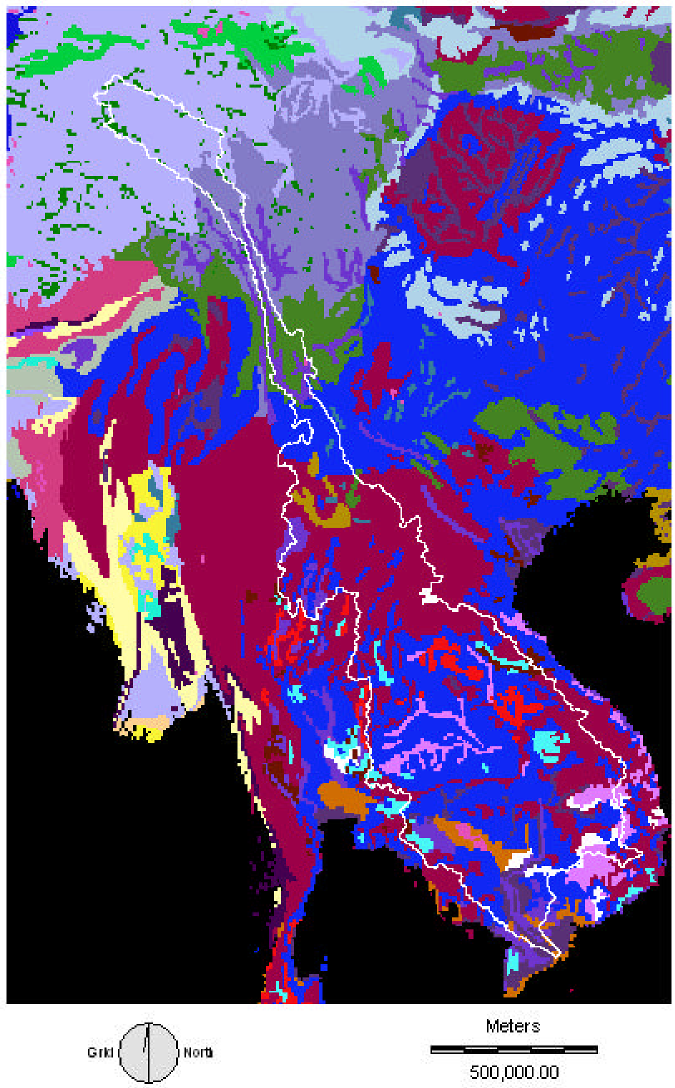
\Reformat\CONCAT

specifying the two part images, automatic placement and that the first image transparently covers the other images.

The basin boundary can then be added as a layer to the concatenated image.



FAO Digital Soil Map of the World



Appendix F

PREPARING STREAMFLOW AND DAMS DATA

The SLURP model does not need streamflow data as inputs. Streamflow data may be used to validate the performance of the model or to calibrate the parameters of the model. The Internet site of the Global Runoff Data Center (GRDC) (Internet 11) based in Koblenz, Germany, and supported by the World Meteorological Organization, contains references to streamflow data. Unfortunately, data are only available from GRDC with the approval of the contributing government, which rather negates the point of collecting global data.

Monthly streamflow data are also available on the public domain CD-ROM issued by the International Satellite Land Surface Climatology Project (ISLSCP 1995) and on the public domain CD-ROM issued by the Oak Ridge National Laboratory (ORNL 1999; Internet 12). For the Mekong Basin, the following data are available from these datasets:

from ISLSCP

Station 2469260 Mekong at Pakse, LA lat. 1512N lon. 10580E

from ORNL DAAC

Station no. 43100, Chi at Yasothon, Thailand, lat 15.78, long 104.14
Station no. 10667, Mun at Ubon at Rachathani, Thailand, lat 15.22, long 104.86
Station no. 18900, Mekong at Chiang Saen, Thailand, lat 20.27, long 100.09
Station no. 391000, Mekong at Mukdahan, Thailand, lat 16.33, long 104.89

The files on the ISLSCP CD-ROM are in UNIX form and program CRLF should be run to add carriage return/line feeds to the UNIX files. The ISLSCP streamflow are also in hydrological year form (i.e., the year labeled 1980 is actually October–December 1979 and January–September 1980). There are many missing data and these are not indicated by the hydrological standard of –9999.

The files on the ORNL CD are in UNIX form and use the character "|" as a separator between fields. To extract data from the ORNL CD, proceed as follows:

1. Change | character in file Glob_RivDis.dat to a space using an editor such as TexPad

2. Run program CRLF to add a carriage return/line feeds to the UNIX file Glob_RivDis.dat

3. Find the sequence numbers of the stations you want by searching the file Glob_RivDis.stn

4. Run program GET_FLOW.EXE to extract the data for the stations needed

5. Fill in missing values and change those missing values indicated by the station number to –9999.9.

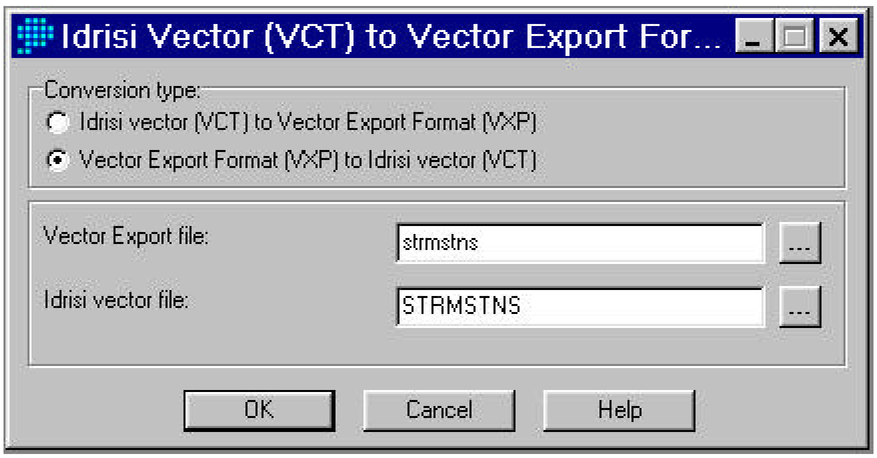
The station locations can now be plotted on a map of the basin as follows:

6. Prepare an ASCII text file listing the station numbers, longitude and latitude, one per record; name this file STRMSTNS.INP.

7. Copy program INP2VXP.EXE from directory \SLURP\RUN_FILE on the SLURP CD-ROM to your working directory and convert the .INP file to an IDRISI vector file named STRMSTNS.VXP. Note that in this case the .INP file contains longitude and latitude whereas for the climate stations (see Appendix E), CLMTSTNS.INP contains eastings and northings.

8. Import this file into IDRISI 32 using:

\File\Import\Software-Specific Formats\Vector Export Format



In a text editor, make sure that file STRMSTNS.VDC contains the same coordinates as in a previously-prepared lat/long image such as those for MEKONG.RDC shown below:

min. X	90.004
max. X	115.004
min. Y	8.004
max. Y	39.996

9. Change the projection of STRMSTNS.VCT from lat/long to UTM using

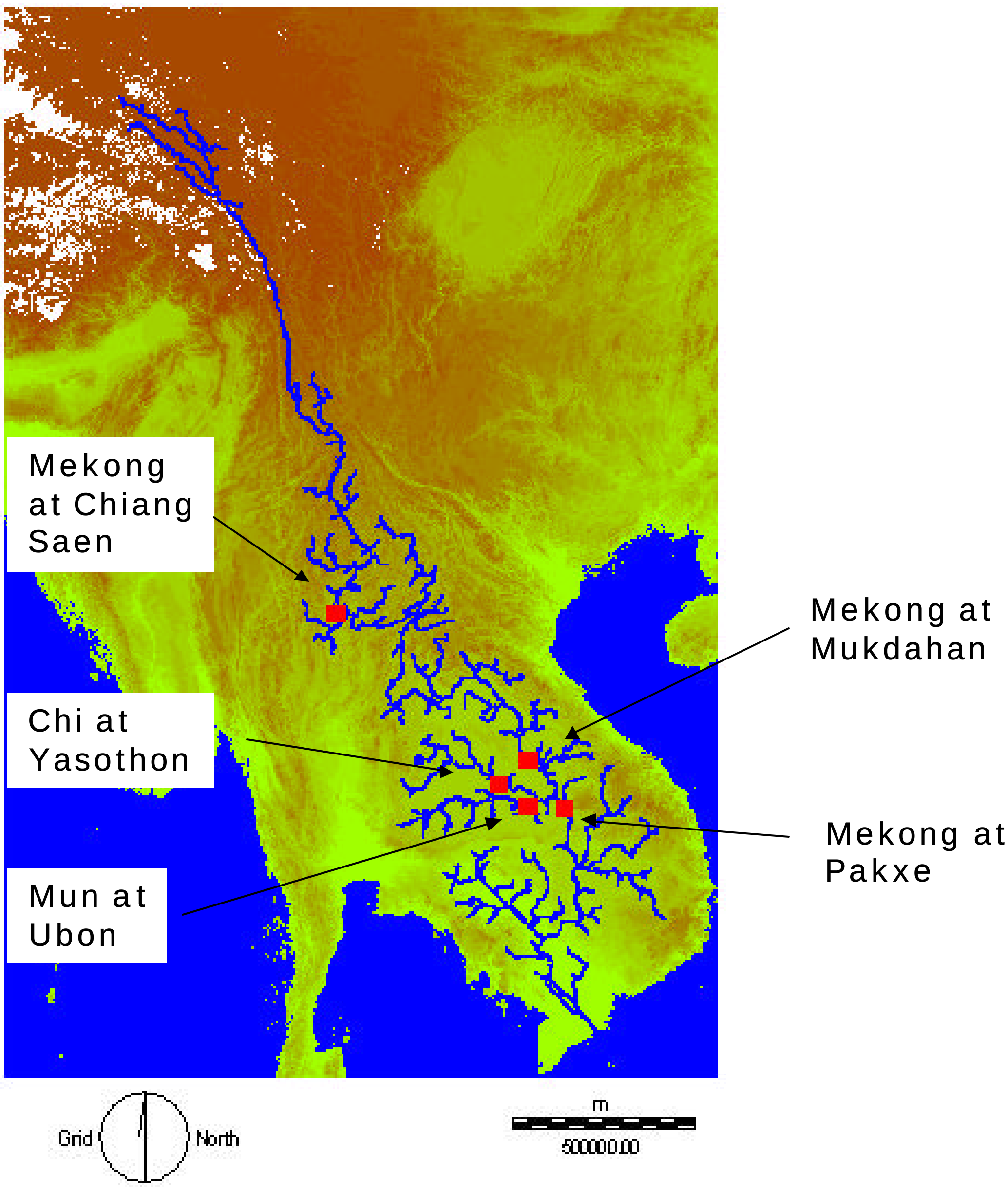
\Reformat\PROJECT\Vector

and specify the coordinates of the UTM .VCT file the same as for the DEM:

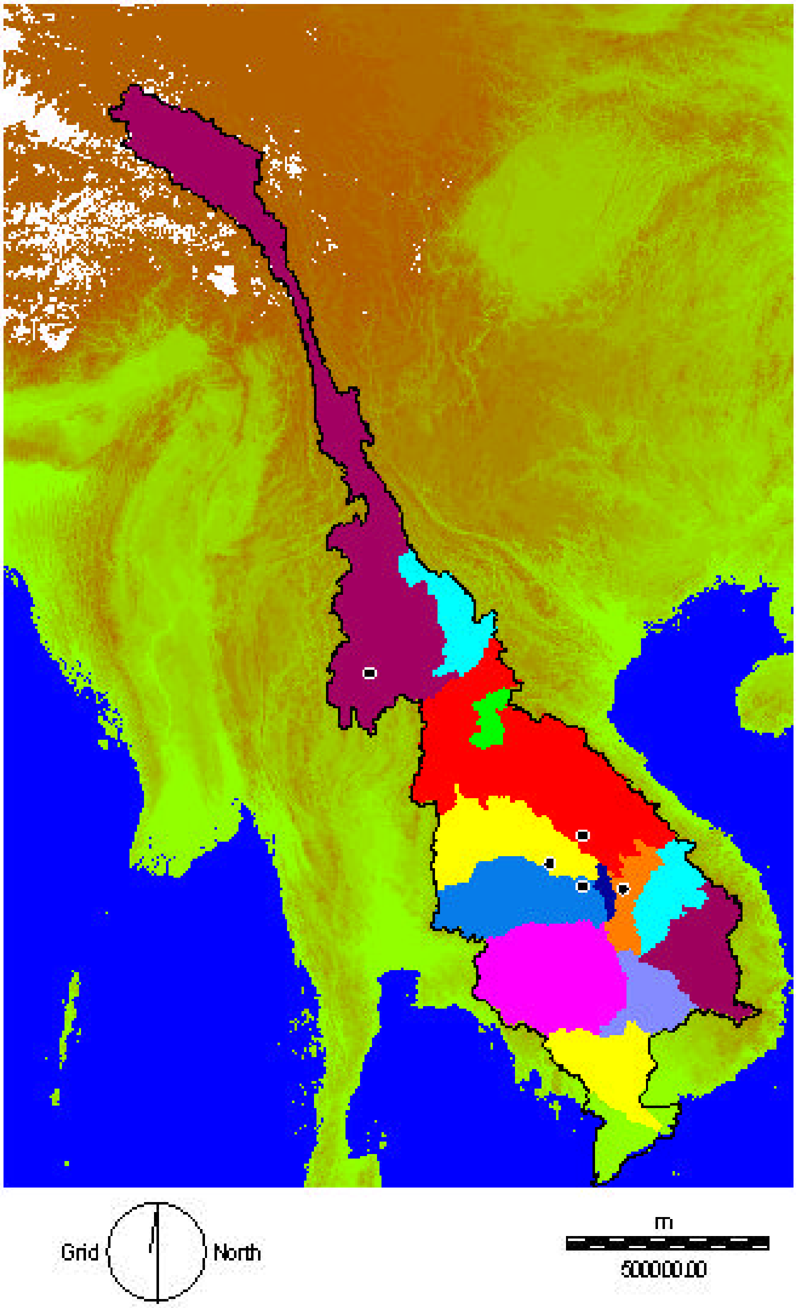
ref. system UTM-46N

ref. units	meters
unit dist	1.0000000
min. X	316000
max. X	2316000
min. Y	950000
max. Y	3950000

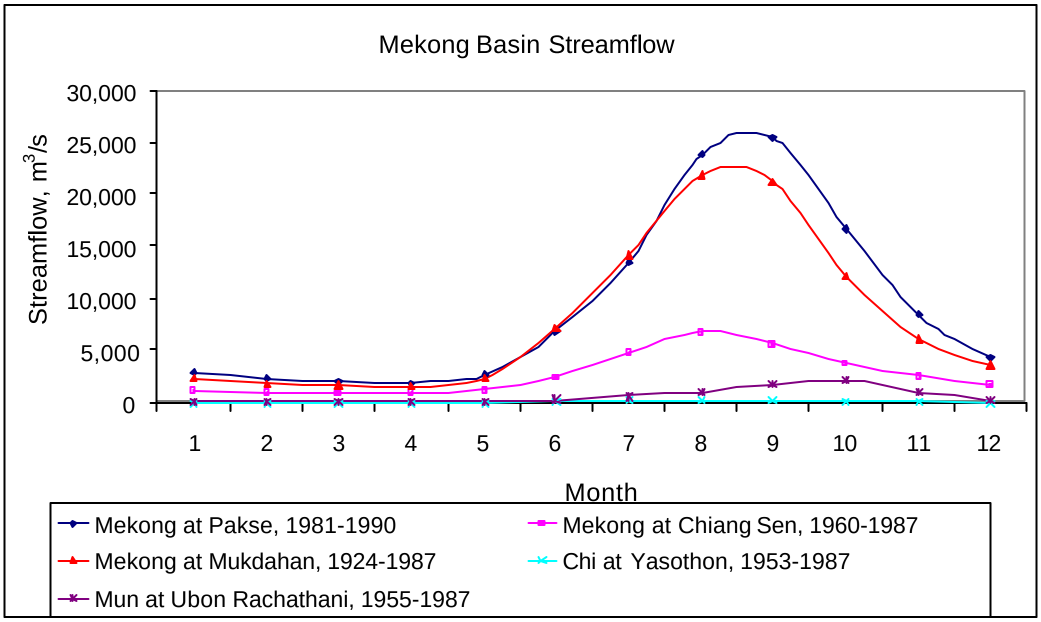
The locations of the streamflow stations can now be displayed in IDRISI using MEK-PIC.RST as the base map with DEM16 palette and adding layers NETW-244.VCT with symbol file RIVER and STRMUTM.VCT with symbol file STRMSTNS.



10. By displaying the station locations on top of the image of sub-basins, we can determine the closest sub-basin for each streamflow station.



11.   Run program HYDROGRF.EXE to compute the long-term mean monthly flows for each station (file “monthly.flo”) and plot these in a spreadsheet.



The series of flow data listed below were obtained from the Mekong River Commission as *.FLO files. These were renamed to *.MFL to avoid confusion with the SLURP format .FLO files. The *.MFL files were converted to SLURP format .FLO files using program Conv_MRC.exe except for file 014901.MRC (Kratie flows), which is in a different format and was converted to 014901.MRC using program KRATIE.EXE.

File	Period of record		River and location
010501.mfl	5/1960	6/97	Mekong, Chiang Saen
011201.mfl	1/39	12/97	Mekong, Luang Prabang
011901.mfl	1/13	12/96	Mekong, Vientiane
011904.mfl	4/68	12/94	Mekong, Pa Mong
013101.mfl	4/24	11/95	Mekong, Nakhon Phanom
013102.mfl	4/24	11/96	Mekong, Thakhek
013402.mfl	1/23	12/95	Mekong, Mukdahan
013802.mfl	1/23	12/95	?
013901.mfl	1/23	12/98	Mekong, Pakse
014501.mfl	1/50	12/93	Mekong, Stung Treng
014901.mrc	1/24	12/98	Mekong, Kratie
019801.mfl	1/60	12/74	Mekong, Phnom Penh
019802.mfl	1/64	3/74	Mekong, Kompong Cham
020102.mfl	11/60	5/73	Tonle Sap, Prek Kdam
033401.mfl	1/64	12/74	Bassac, Phnom Penh
100102.mfl	4/87	12/96	Nam Ou, Muong Ngoy
350101.mfl	3/60	12/96	Se Bang Hieng, Ban Keng Done
370104.mfl	1/51	12/95	Nam Chi, Yasothon
380103.mfl	7/44	12/93	Nam Mun, Ubon
430105.mfl	1/89	12/96	Se Kong, Attopeu (Muong May)

The Kratie 014901.MRC flows are only for a limited period and were replaced by a new flow file 014901.FLO computed from Pakse flows (013901.FLO) using the Institute of Hydrology (1988) equations. A comparison is shown in file EXTEND.XLS. There is no agreement between the observed Kratie flows from MRC (014901.MFL and .MRC) and the extended data created using the Institute of Hydrology (1988) equations with Pakse data (014901.FLO).

The following table shows the relationship between the recorded flow records and the SLURP sub-basins. The recorded station flows at sub-basin outlets have been adjusted to recorded sub-basin flows by multiplying by the area adjustment factor in the last column, e.g., 013901.FLO data were multiplied by 1.04 to derive Mekong2.flo data used in the SLURP model for calibration.

MRC flow and level stations and relationship to SLURP sub-basins d:\mekong-2\slurp\mrc_slurp.xls

River	Location	Number	First year	Last year	Data	Latitude degrees	Longitude Degrees	Elevation mamsl	Upstream area km**2	SLURP sub-basin name	Upstream area km**2	Multiply MRC by
Mekong	Chiang Saen	010501	1960	1997	Q	20.16	100.08	357	189,000	Lancang	228,000	1.21
Mekong	Pakse	013901	1923	1998	Q	15.12	105.80	86	545,000	Mekong2	569,410	1.04
Mekong	Kratie	014901	1924	1970	Q	12.47	106.01	-1	646,000	Mekong3	675,160	1.05
Mekong	Kratie	014901	1934	1998	H							
Mekong	Kampong Cham	019802	1960	1996	H	12.00	105.45	16				
Tonle Sap	Kampong Luong	020106	1924	1965	H							
Tonle Sap	Kampong Chhang	020103	1924	1998	H	12.25	104.67	6				
Tonle Sap	Prek Kdam	020102	1960	1973	Q	11.81	104.80	0.08	84,400			
Tonle Sap	Prek Kdam	020102	1960	1998	H							
Tonle Sap	Phnom Penh	020101	1966	1998	H	11.57	104.93	0				
Mun	Ubon Ratchatani	380103	1944	1993	Q	15.22	104.86	105	104,000	Chi_Mun	122,390	1.18
Se Kong	Attapeu	430105	1989	1996	Q	14.80	106.84		10,500	SeKong	28,910	2.75
Sre Pok										SrePok	48,840	

Effects of Dams

The table below lists the information we have been able to obtain on major dams on the Mekong River and its tributaries using data from Rothert (1995); ICOLD (1988); Plinston and Daming (1999), MRC(1994), Kreuze (1998) and Oud and Muir(1999). Note that a lot of information is unavailable and some of the data (particularly reservoir areas) are of doubtful accuracy.

In 1998, approximately five percent of the annual flow of the Mekong was regulated by dams (Institute of Hydrology 1988). According to Jacobs (1998) there is only one dam on the mainstem of the river, the Manwan in China.

Plinston and Daming (1999) list the dams planned and built in the Lancang cascade in China. The Mannwan was completed in 1993, the Dachaoshan will be completed in 2000, the Xiaowan in 2012 and five other dams are planned. It is estimated that the Manwan alone affects 2 percent of the seasonal flows and does not affect inter-annual flows. The addition of Dachaoshan will mean that 4 percent of the seasonal flows will be affected. When the much larger Xiaowan dam comes on-line there will be sufficient storage to control 92 percent of the seasonal flows but the inter-annual flows will remain unaffected. Only when the Nuozhadu dam is completed in 2017 will there be sufficient storage volume to completely control seasonal flows and, at this stage, 23 percent of the interannual variation could also be controlled.

In northeast Thailand, there are large irrigation projects on the Chi River at Nam Pong/Nong Wai and at Lam Pao. Lam Pao was constructed with US funding in the early 1970s (Jacobs 1998). The Institute of Hydrology (1988) estimates that the mean annual flow of the Chi has been reduced by 28 percent since construction began in 1965. There is also a large dam and reservoir at Shirinthom on the Mun River but no information is available. By the time the flows from the Chi and the Mun are combined and routed to the Mekong, no effects of the irrigation can be detected.

Laos has constructed several dams on tributaries to the Mekong such as Nam Theun, Nam Ngum, Nam Leuk, Houay Ho, Xe Kaman and Xe Pian-Xe Namnoi but, again, little information is available on the regulatory effects of these structures.

According to Kreuze (1998), the reservoirs built up to 1995 have a combined storage capacity of 10.2 billion cubic metres, which is about 2.5 percent of the average wet season flow in the Mekong at Kratie and compares to the average Tonle Sap capacity of 56 billion cubic metres.

Dams on the Mekong and its tributaries affect not only the river flows but also the sediment load, which is important for riparian agriculture and fisheries. Plinston and Daming (1999) note that although China supplies only 16 percent of the long-term average annual flow in the Mekong (as measured at its outlet to the South China Sea), over 50 percent of the estimated 150-170 million tons per year of sediment load carried in the lower Mekong comes from China. Dams and reservoirs will trap sediment. It is expected, for example, that the dead storage of the Manwan reservoir (662 million cubic metres) will be filled within 15-20 years. However, since the sediment-free river below the reservoirs will scour the bed and erode more sediment, it is not clear that the planned dams and reservoirs will significantly affect sediment loads in the Lower Mekong.

INDEX NO. & Attribute	NAME OF DAM	LONGITUDE and LATITUDE Degrees	YEAR FINISHED	RIVER	CITY, COUNTRY	RESERVOIR CAPACITY mcm	RESERVOIR AREA km^2	SPILLWAY CAPACITY m^3/s, and BASIN AREA, km^2	DAM HEIGHT, m
29	Gonguoqiao	99.1136 25.9367	not built	Lancang (Mekong)	China	510	3.42	97,200	130
30	Xiaowan	100.1492 24.7448	not built	Lancang (Mekong)	China	14,550	23.58	113,300	300
31	Manwan	100.4619 24.5690	1996	Lancang (Mekong)	China	920	3.11	114,500	126
32	Dachaoshan	100.3446 24.0610	2000	Lancang (Mekong)	China	960	6.52	121,000	110
33	Nuozhadu	100.4814 22.6150	not built	Lancang (Mekong)	China	22,700	23.98	144,700	254
34	Jinghong	100.7745 22.0484	not built	Lancang (Mekong)	China	1,040	3.99	149,100	118
35	Ganlanba	100.969 921.8921	not built	Lancang (Mekong)	China		0.11	151,800	
36	Mengsong	101.1067 21.6772	not built	Lancang (Mekong)	China		0.58	160,000	
1 B	Prek Thnot	104.5654 11.4506		Prek Thnot	Phnom Penh Cambodia	223	28	740	29
2 N		107.7669 12.8657							
28 2	Pak Mun	105.0911 14.8483	1990	Mun	Thailand	225		117,000 18,500	42
4 M		105.8272 15.3930							
5 F	Lamphraphl oeng	102.2181 14.8421	1967	Mun	Thailand	152	13.1	807 450	49
6 G	Lamtakhog	101.8256 14.9113	1969	Mun	Thailand	310	37	1,430 1,530	40
7 J	Nam Pung	104.4323 17.0259	1965	Nam Pung	Thailand	165	12	297 300	40
8 I	Nam Oun	103.9776 17.3094	1973	Khong/T	Thailand	520	85	1,100 350	30
9	Lam Pao	103.4822	1969	Chi		1,430	240	5,900	33

H		16.7479			Thailand			1,400	
10 L	Ubol Ratana	102.6952 16.7511	1966	Nam Pong	Thailand	2,263	410	12,000 3,500	35
11 K	Chulabhorn	102.0001 16.3714	1972	Nam Phrom	Thailand	188	12	545 1,000	70
13 O	Mae Tam		1984	Yom	Thailand	0.88	.14		20
11 Q	Mae Kuang		1991	Ping Mae Kuang	Thailand	263	11.563	12	73
14 18	Huai Mae Hang	102.7284 17.7459	1986	Ping HuiMae Hang	Thailand	0.54	.09		16
15 17	Huai Sam Phat	102.9493 17.5247	1990	Chi/T	Thailand	15	4.56	94	16
16 16	Ban Lin Chang		1984	Phet/T	Thailand	0.307	.076	3	16
17 15	Huai Chan La		1989	Mun	Thailand	16.9	3.4	54 47	20
18 14	Huai Sai		1994	Khong/T	Thailand			5	16
19 13	Huai Hong Hang		1980	Ping	Thailand	0.51			18
20 12	Huai Pom		1983	Yom	Thailand	0.72	.14		15
21 11	Lamnangron g		1982	Mun	Thailand	150	24.48	450	23
22 10	Nam Lae		1979	Nan	Thailand	0.18	.01		15
23 7	Huai Kum	101.8890 16.0648	1982	Nam Phrom	Thailand	22.8	2.4	262 1,280	36
24 3	Ban Charat	103.3910 15.0252	1993	Mun	Thailand	15	1.85	69	26
25 4	Huai Pong Chant	102.6842 14.9589	1988	Ping	Thailand	0.61		4	19
26 5	Huai Bon	102.5738 14.8262	1985	Ping Huai Bon	Thailand	1.5	.196		23
27 6	Huai Cho		1985	Khong/T	Thailand	0.3	.06		17

64	NT Hinboun	104.3976 18.4769	1998		Laos	20			
65	Houay Ho	106.5101 16.3473	1997		Laos	523			
66	Nam Leuk		1998		Laos	88			
37	Se Katam 1		1998		Laos				
38	Nam Mang	102.5007 18.2488	1999		Laos	128			
39	Se Katam 2		1998		Laos				
40	Nam Ou	102.6674 21.0733	2010		Laos	66,100			
41	Nam Suong 2	102.6674 20.2285	2012		Laos	2,000			
42	Nam Tha 1	100.9578 20.2285	2001		Laos	2,000			
43	Nam Beng 1	101.2256 20.0224			Laos	430			
44	Nam Khan	102.2554 19.7339	2005		Laos	480			
46	Nam Ting	102.5438 19.4248			Laos				
47	Nam Lik 2	102.1318 18.9096			Laos	740			
12 D	Nam Ngum 1	102.4694 18.4599	1972	Nam Ngum	Vientiane Laos	4,700	370	4,400	75
48	Nam Ngum 2	102.7498 18.7654	2001		Vientiane Laos	2,500			
49	Nam Ngum 3	102.8322 19.1569	2003		Vientiane Laos	1,700			
45	Nam Ngum 4	102.8733 19.4454	2020		Vientiane Laos	800			
50	Nam Ngiep 1	103.5531 18.7654	2002		Laos	2,900			
51	Nam Theun 1	104.1916 18.6624	2002			400			
63	Nam Theun	104.7889	1999			2,607			

	2	18.3327			Laos				
52	Sekong 5	106.1469 16.7108	2010			2,000			
54	Houay Lamphan	105.8815 16.3054	2000			200			
59	Pak Beng	101.5448 19.9420		Mekong	Laos	45	110	29,650 218,000	
60	Luang Prabang	102.7127 20.4993		Mekong	Laos		110	46,700 230,000	
61	Sayaburi	101.9897 19.8863		Mekong	Laos		30	39,450 272,000	
62	Pa Mong	101.8229 18.1030		Mekong	Laos		120	51,800 295,500	
63	Pak Lay	101.6004 18.6046		Mekong	Laos		110	38,400 283,000	
64	Chiang Khan	101.3224 18.1588		Mekong	Laos		90	33,880 292,000	
65	Low Pa Mong	102.9908 18.1030		Mekong	Laos	102	560	51,800 299,000	
66	Ban Koum	104.2698 17.9359		Mekong	Laos	126	130	53,000 419,000	
67	Don Sahong	104.6591 16.8770		Mekong	Cambodia			553,000	
68	Strung Treng	105.2153 16.0411		Mekong	Cambodia		640	79,100 635,000	
69	Tonle Sap	104.3255 12.6411		Tonle Sap	Cambodia			71,000	
70	Sambor	105.7714 15.2052		Mekong	Cambodia	130	880	161,000 646,000	
71	Senamnoy M				Laos	225			
72	Senamnoy D				Laos	20			
	Se Done				Laos	1734			
	Setuman 1				Laos	833			
	Mengsong				China	60			

The dams completed at this time (2000) and the dams planned can be located on the river network in the IDRISI GIS using the following procedure:

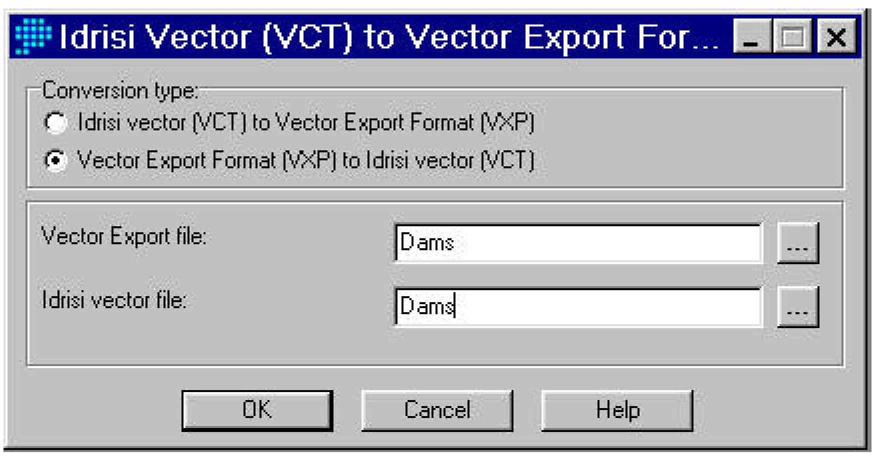
1. Identify the approximate locations (in latitude/longitude) of the dams from the sources identified above and extract the coordinates of the dam locations displaying the digital map of the Mekong River derived in Appendix A.

2. Prepare a text file DAMS.INP in a text editor using the same format as CLMTSTNS.INP (see Appendix D) and STRNMSTNS.INP (see earlier in this Appendix).

3. Copy program INP2VXP.EXE from directory \SLURP\RUN_FILE on the SLURP CD-ROM and run it to create file DAMS.VXP.

4. Import the .VXP file into IDRISI 32 using:

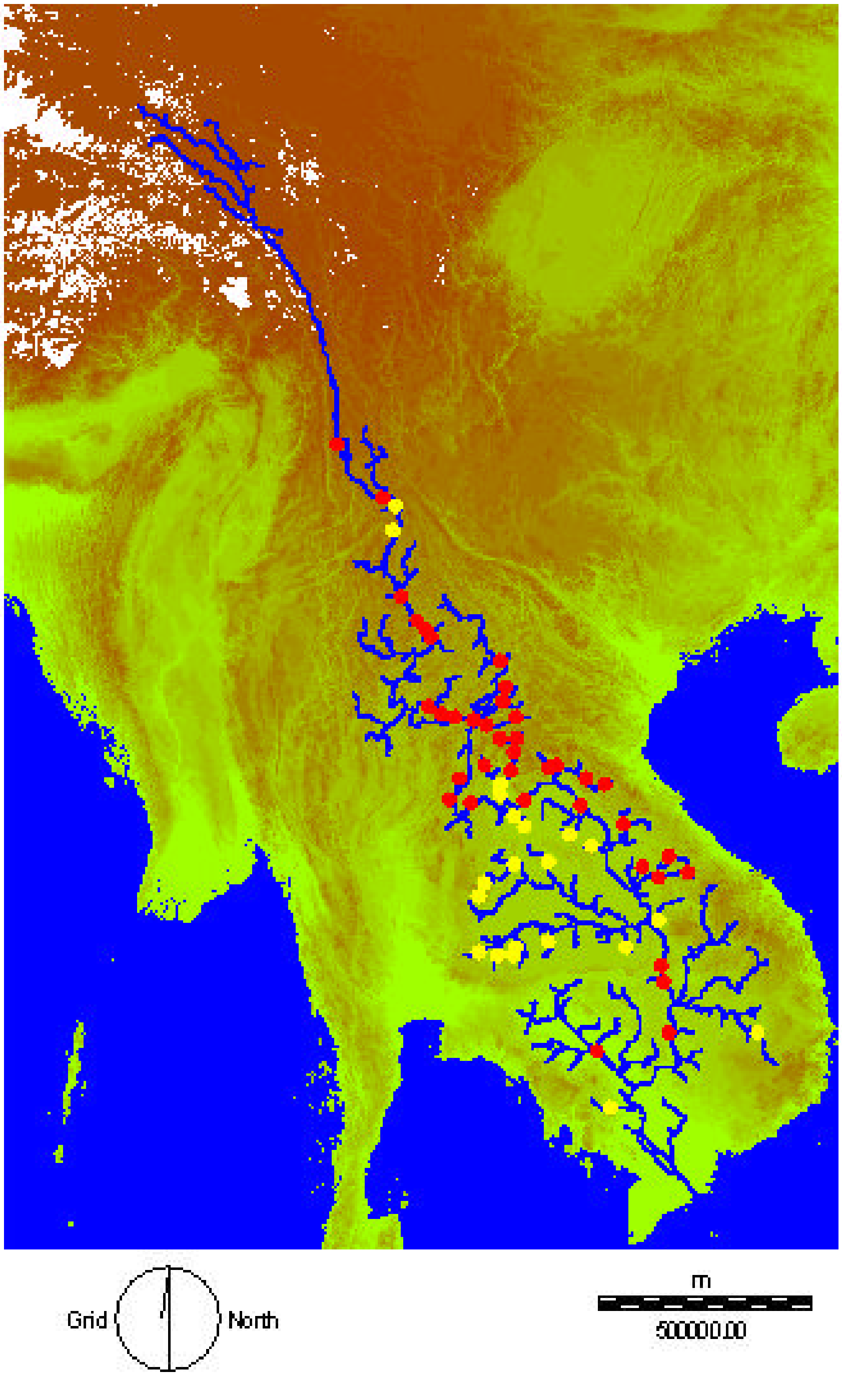
\File\Import\Software-Specific Formats\Vector Export Format



5. Convert the IDRISI 32 file from Latlong projection to UTM 46n using:

\Reformat\PROJECT

and display this as a vector layer on top of the digital elevation model. In practice, two .INP files were used, one for dams already built and the other for dams planned.



Mekong dams:

Built (as of 2000)

Planned

The existing dams can be grouped into the sub-basins used by the hydrological model as follows:

Mekong sub-basin	Index numbers of dams in the table above
Chi	9, 10, 11, 23
Mun	5, 6, 24 , 25, 26
Chi-Mun	28
Mekong 1	7, 8, 14, 15, 38
Mekong 2	4
Sre Pok	2
Delta	1
Nam Ngum	12

At the present stage in modeling the Mekong Basin the following simplifications were made:

1. The reservoirs on the Chi River were included in the model. To model a reservoir we need the stage-discharge, stage-area and stage-storage relationships together with the operating rules. None of these were available for any of the reservoirs and so we lumped the 4 reservoirs together and made some simple assumptions. The area and volume of the imaginary combined reservoir are related to the reservoir level by:

$$Area\ ?\ 24.5 ? Level\ ?\ 5.92 ?^{1.0}$$

$$Volume\ ?\ 126.3 ? Level\ ?\ 2.08 ?^{1.0}$$

The range of level is from 10 to 33 m and the starting level of the combined reservoir is assumed to be 21.5 m. The regulated outflows from the combined reservoir was assumed to approximate the mean annual hydrograph for the years following reservoir construction.

2. Similarly, for the Mun River, we lumped the effects of the 5 dams into one reservoir for which we made simple assumptions. The area and volume of the imaginary combined reservoir are related to the reservoir level by:

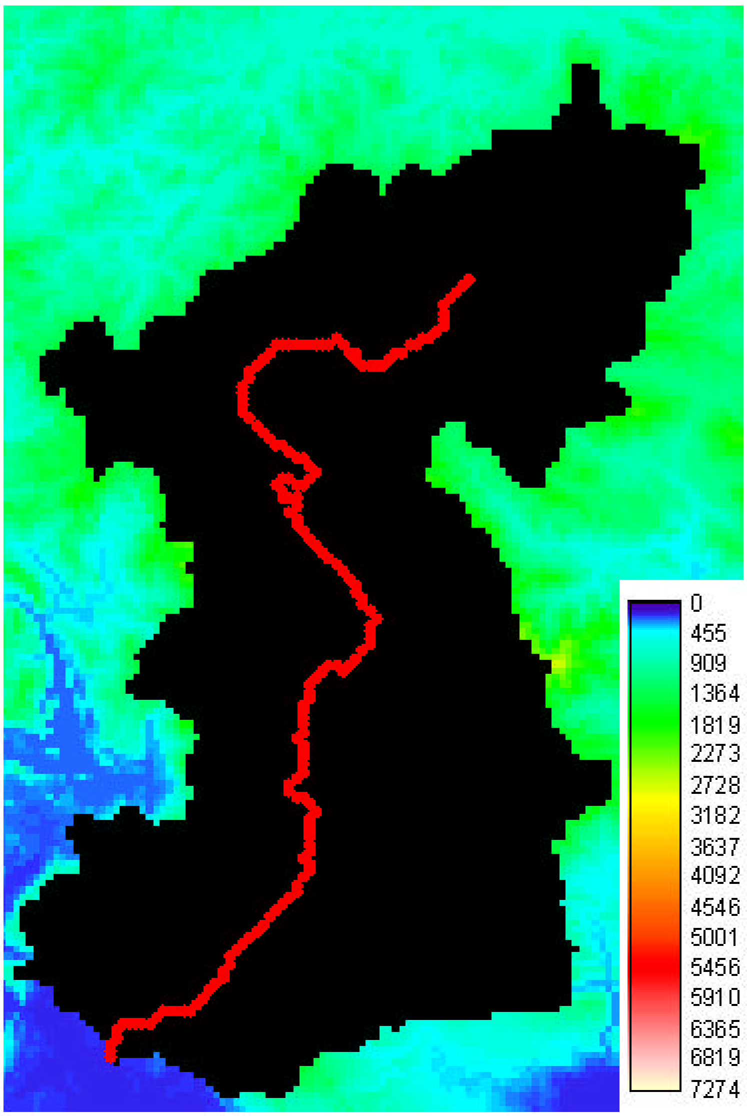
$$Area\ ?\ 1.33 ? Level\ ?\ 1.0 ?^{1.0}$$

$$Volume\ ?\ 8.233 ? Level\ ?\ 0.283 ?^{1.0}$$

The range of level is from 10 to 40 m and the starting level of the combined reservoir is assumed to be 25 m. The regulated outflows from the combined reservoir was assumed to approximate the mean annual hydrograph for the years following reservoir construction.

3. The model was changed to include the Nam Ngum River as a separate sub-basin by re-running TOPAZ specifying a new starting point at the outlet of the Nam Ngum reservoir. The area, volume and simple operating rules were obtained from Oud and Muir (1999). The Nam Ngum was modeled in this way as an example of how individual reservoirs may be added to the model.

The figure below shows the Nam Ngum sub-basin (in black) with the river (in red).



The data contained in the output files from SLURPAZ are then used to modify the existing MEKONG.CMD, MEKONG.WTS and MEKONG.MOR files. The table below shows how the land cover areas in the existing Mekong1 sub-basin were modified to include the Nam Ngum.

Inclusion of Nam Ngum subbasin into Mekong1 subbasin

Land cover	Original Mekong1		Nam Ngum		Revised Mekong1	
	%	km**2	%	km**2	%	km**2
urban	0.0	0	0.0	0	0.0	0
agriculture	17.3	28,926	5.4	485	18.0	28,441
semi-desert	0.1	167	0.0	0	0.1	167
shrubland	24.3	40,630	7.7	692	25.2	39,938
deciduous forest	15.4	25,749	20.6	1,850	15.1	23,899
coniferous forest	26.0	43,472	30.1	2,704	25.8	40,769
mixed forest	15.6	26,083	31.5	2,829	14.7	23,254
water	1.3	2,174	4.7	422	1.1	1,751
tundra	0.0	0	0.0	0	0.0	0
Total area	100	167,201	100	8,982	100	158,219

Appendix G

PREPARING LAI AND NDVI DATA

Leaf Area Index

Leaf Area Index (LAI) is a measure of the density of vegetation expressed as the ratio of the area of vegetation divided by the area of ground beneath the vegetation and varies from 0 to over 5. The SLURP hydrological model uses LAI to control interception (how much of the precipitation is intercepted by vegetation) and to divide evapotranspiration between evaporation from soil and leaf surface and transpiration from vegetation. Running et al. (1986) identified LAI as the single most important variable for quantifying energy and mass exchange by plant canopies over landscapes.

Leaf area index has traditionally been calculated using species-specific allometric equations relating stem diameter and foliage biomass. These equations are generally of the form:

$$\ln(y) = a + b ? \ln(x)$$

Where, y is the foliage biomass and x is the diameter breast height. Biomass is converted to leaf area using surface area to mass conversion factors (e.g., from Gholz et al. 1976). LAI is then calculated by summing individual leaf areas and dividing by ground surface area (Running et al. 1986).

Direct estimates of LAI are often very laborious (e.g., Gower and Norman 1991). They also can be imprecise. Differences in light conditions cause large variations even within a single species and leaf area biomass changes with age. Separate regression equations to account for different light conditions and age are possible but also tedious. There are inconsistencies in the reporting of data. Most reported LAI of broadleaf species represent only a single surface of the leaf but, as exchange can occur on more than one leaf surface, total surface area is the most desirable context in which to express LAI (Gholz et al. 1976).

These problems become even more cumbersome when investigations take place at the landscape or regional scale. With increasing demand for an understanding of regional and global scale exchanges between the land and atmosphere, a more efficient method of determining evapotranspiration and interception should be found. Running et al. (1986) suggest the only feasible method to estimate LAI at the regional scale is from satellite.

Normalized Difference Vegetation Index

Research (e.g., Nemani and Running 1989) has established significant correlations between LAI, as an index of canopy properties, and reflectance measured by satellites. Chlorophyll pigments in green leaves absorb radiation in the red wavelengths and so reflectances are inversely proportional to the quantity of chlorophyll present in the canopy vegetation. On the other hand, near infrared radiation is scattered by internal leaf structure and is then either reflected or transmitted. The spectral reflectance of vegetation is more than three times greater in the infrared than in the visible. The difference between the values of the infrared and the red is an indicator of the amount of green vegetation.

Suitable spectral bands of reflectance data are measured by sensors on the NOAA series of meteorological satellites and on the Landsat and SPOT satellites. The Advanced Very High Resolution Radiometer (AVHRR) sensor on the NOAA satellites measures reflectances in the visible and infrared channels at a resolution of 1.1 km with a twice daily repeat cycle. A particular advantage of using AVHRR for regional analysis is that it integrates over a large area such that variations caused by canopy closure, understory vegetation and background reflectance at local scales may be eliminated in favour of large scale variations caused by regional climatic patterns (Running et al. 1986).

The most commonly used indicator of vegetation activity is the normalized difference vegetation index (NDVI), which is generally computed from the AVHRR sensor as:

$$NDVI = \frac{(IR - R)}{(IR + R)}$$

where IR is the pixel value from band 2 (infrared: 0.73 - 1.0µm) and R is the pixel value from band 1 (visible; 0.58 - 0.68 µm). Using a normalized index partially compensates for changing illumination conditions, surface slope and viewing aspect. However, Spanner et al. (1990) note the importance of using LAC (local area coverage) data and of using data with reasonably consistent solar zenith angle. Kineman and Hastings (1992) point out the need to be aware of the calibration drift of the AVHRR sensor. Caused by ageing and orbital changes, this drift produces an NDVI, which increases with time about 3 percent per year in low vegetation areas for NOAA - 9 and decreases each year for NOAA - 11. Eastman and Fulk (1993) have used standardised components analysis to uncover the magnitude of the sensor drift.

NDVI is strongly related to the amount of chlorophyll in the vegetation cover and to the amount of absorbed photosynthetically active radiation (APAR) absorbed by the plant canopy. As such, the NDVI could be used directly in a hydrological model as an indicator of canopy evaporation and of transpiration but, to correspond to the more detailed ecosystem models available (e.g., Running et al. 1989), it is more usually converted to LAI. The relationships between LAI and NDVI vary according to seasonal changes based on phenological changes in LAI, proportions of surface cover types contributing to overall reflectance and effects resulting from large variations in solar zenith angle (Spanner et al. 1990).

For the Mekong Basin, a series of monthly NDVI images were downloaded from the website for the NOAA AVHRR satellite sensor (Internet 7) for the first 10-day period of each month from February to December 1995 (there is no January image). Note that as of August 2000, production of the Global AVHRR composites has been temporarily suspended while funding and new processing techniques are under consideration.

The image analysis method used is as follows

1. On the website (Internet 7) specify the date and coordinates required and click the left mouse button over the site “Retrieve data”. The program will respond with the size, number of lines (rows) and samples (columns) and the actual coordinates of the image available. Position the mouse over the phrase “Retrieve the data” and press the right mouse button and select “Save Target As” to start the download process. The

compression method selected does not seem to matter; the image is downloaded in uncompressed format anyway. The problem now is that the NDVI images are specified as 1 km resolution and are also specified in latitude-longitude coordinates. The two are incompatible as is apparent from the image below. The requested and actual coordinates were:

Requested Coordinates:

Northernmost Latitude: 40.000000

Westernmost Longitude: 90.000000

Southernmost Latitude: 8.000000

Easternmost Longitude: 110.000000

Actual Coordinates:

Northernmost Latitude: 40.010837, line 4225

Westernmost Longitude: 89.473410, sample 28417

Southernmost Latitude: 7.788129, line 7808

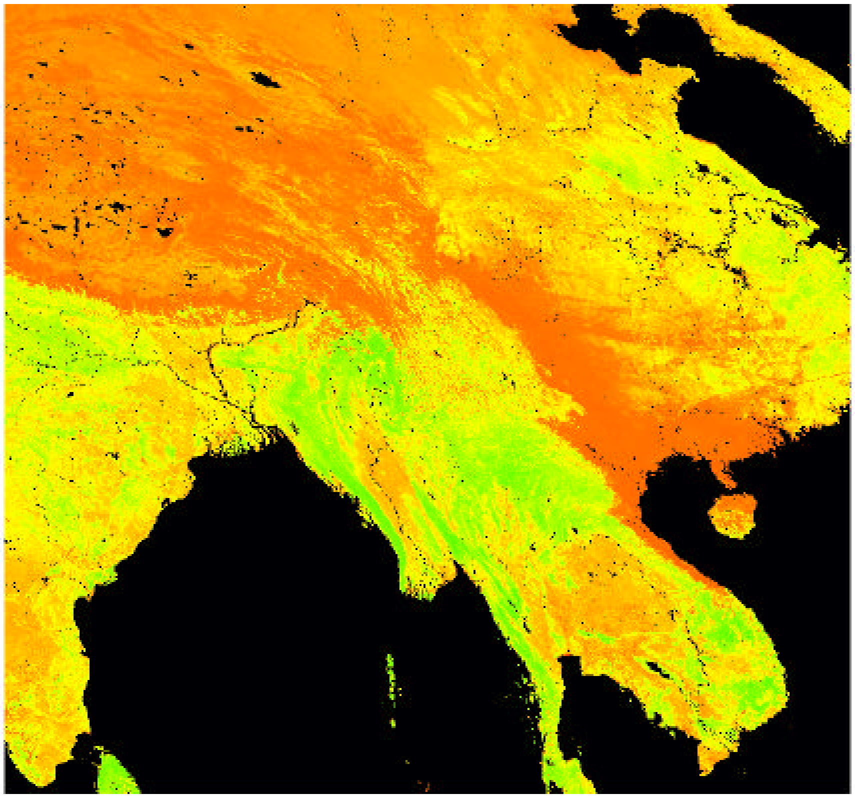
Easternmost Longitude: 110.822528, sample 32256

In fact, the image is not a latitude and longitude rectangle. These are the coordinates of the top-left and bottom-right corners of the image but the lines of latitude and longitude are not parallel to the sides of the image. This means that, although we can display the image in IDRISI, we cannot use \Reformat\PROJECT to change the image to a UTM projection as was done with the DEM, the land cover and the soil map. Instead we have to do a geometric correction using the UTM projected DEM as the base map.

2. To view the image, first rename the downloaded image to <name>.RST and, in IDRISI 32, prepare a <name>.RDC file using

\File\Metadata

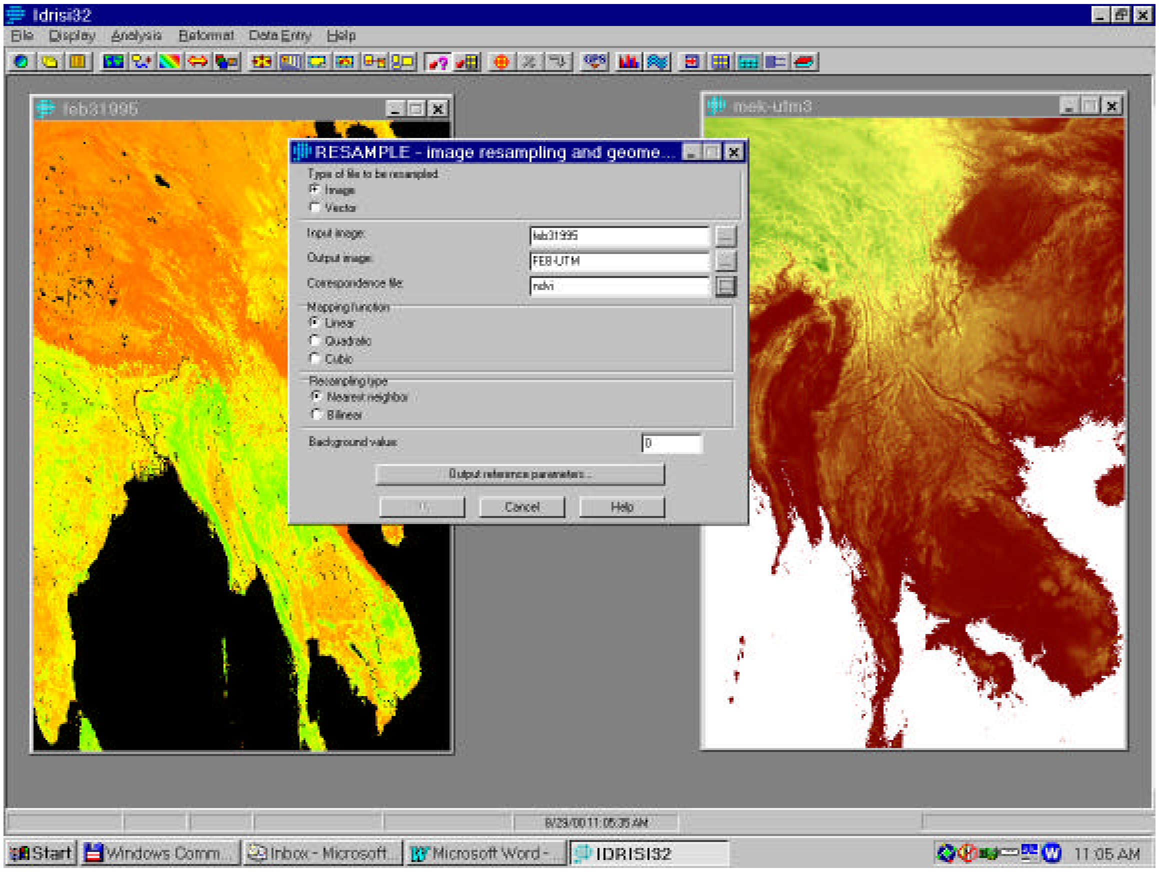
Set ‘Raster files’ and click on \File\New. Fill in the fields specifying a byte binary image with latlong projection and using the actual coordinates given above. Use \Tools to compute the resolution and the maximum and minimum values and save the file to <name>.RDC. Display using the IDRIS256 palette.

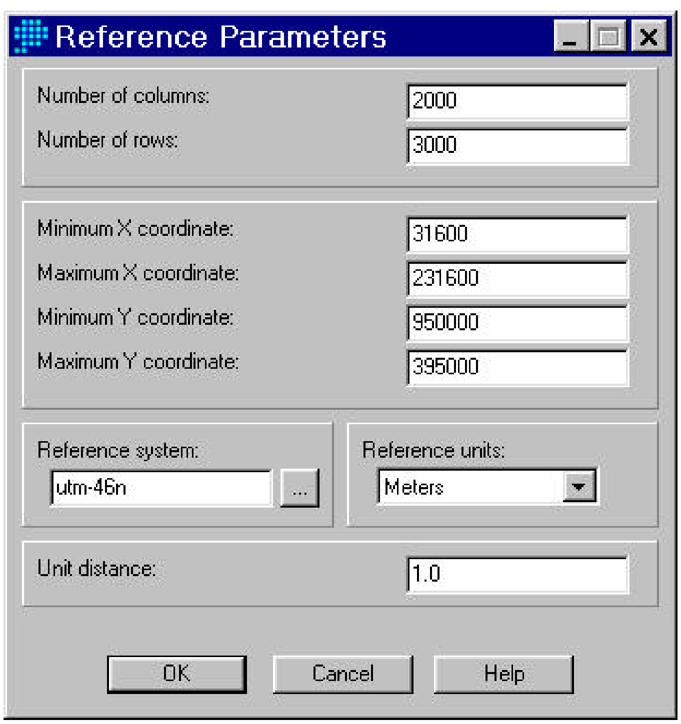


3. To geometrically register the NDVI image, display the IDRISI image and the DEM image (in this case, MEK-UTM3.RST from Appendix A; use NDVI256 palette) and prepare a list in an editor of x and y coordinates for the same points on both images in an ASCII .COR (for correspondence) file. Then use:

\Reformat\RESAMPLE

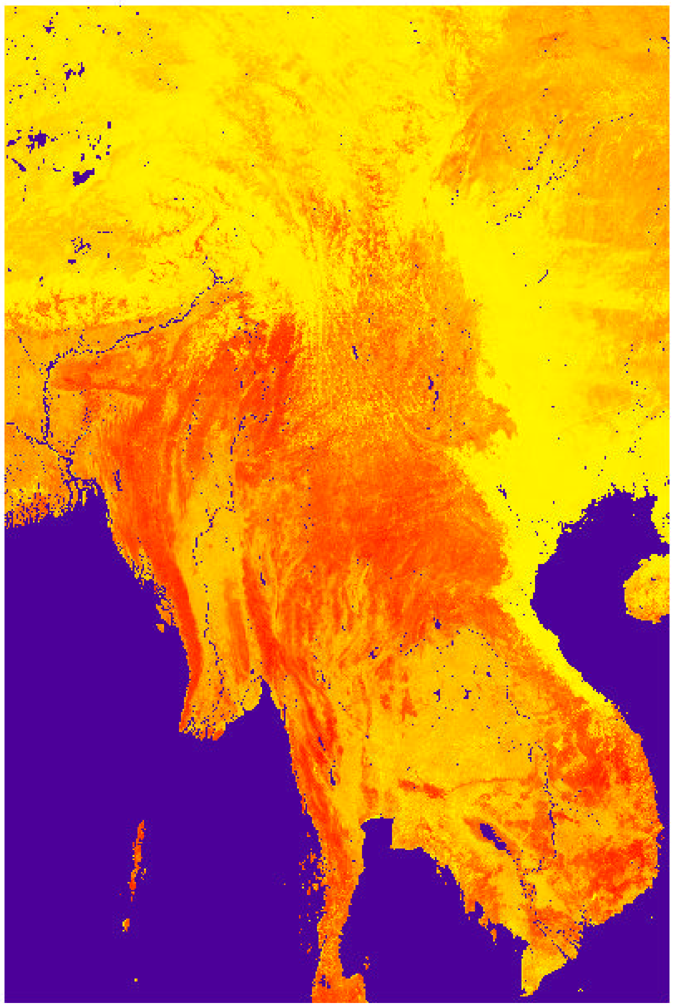
On the second screen, set the Reference Parameters the same as MEK-UTM3. Press OK and, from the next display, select from the display the points giving the minimum standard error and proceed. In this case, 3 points were eliminated from an original .COR containing 20 points.


Idrisi32
File Display Analysis Reformat Data Entry Help
feb31995
mek-utm3
RESAMPLE - image resampling and geome...
Type of file to be resampled
Image
Vector
Input image:
feb31995
Output image:
FEB-UTM
Correspondence file:
ndvi
Mapping function
Linear
Quadratic
Cubic
Resampling type
Nearest neighbor
Bilinear
Background value:
0
Output reference parameters...
Cancel
Help
Start
Windows Comm...
Inbox - Microsoft...
Microsoft Word -...
IDRISI32
11:05 AM


Reference Parameters
Number of columns:
2000
Number of rows:
3000
Minimum X coordinate:
31600
Maximum X coordinate:
231600
Minimum Y coordinate:
950000
Maximum Y coordinate:
395000
Reference system:
utm-46n
...
Reference units:
Meters
Unit distance:
1.0
OK
Cancel
Help

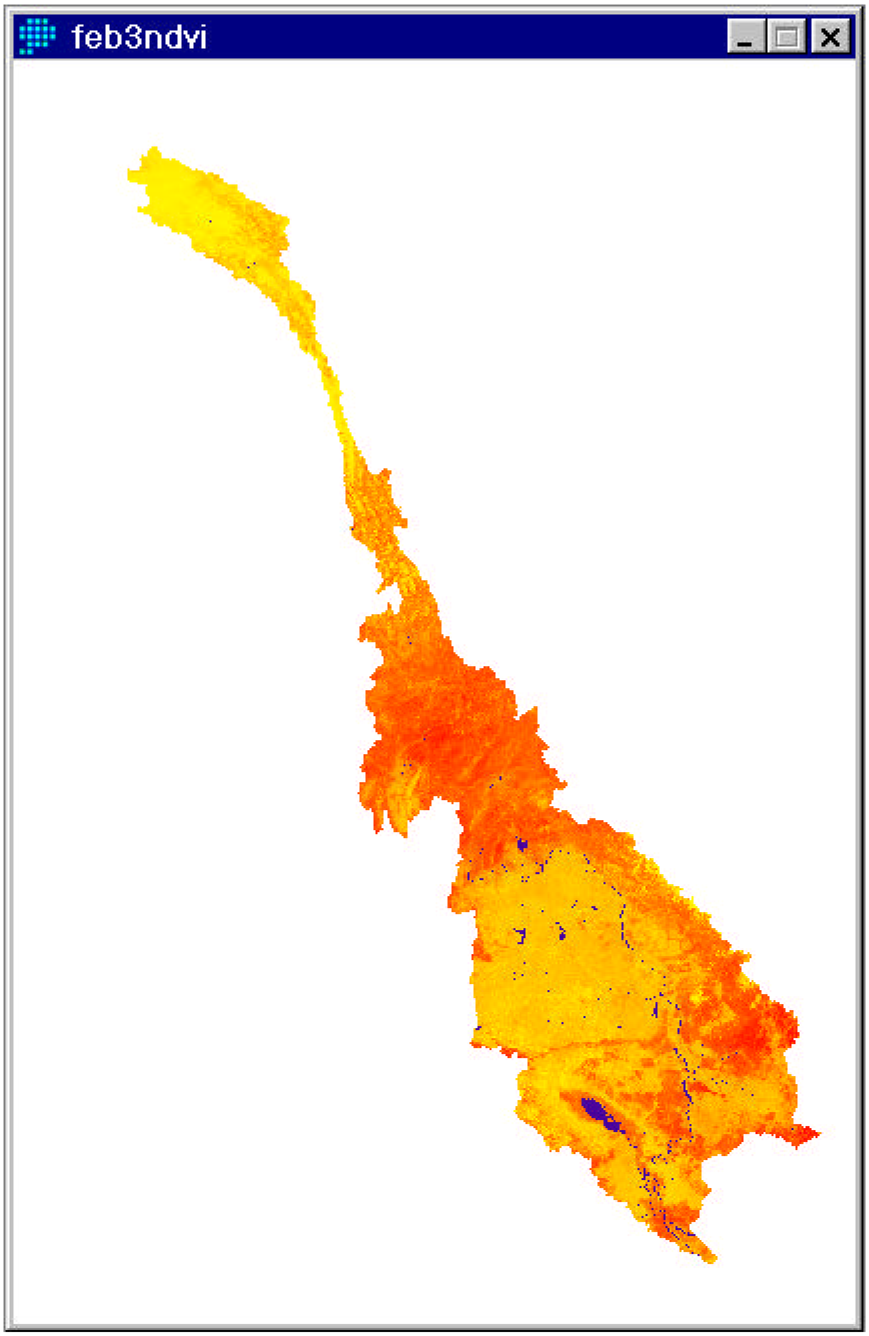
The georegistered NDVI image (for February 1995) shown below clearly identifies the major lakes, including the Ton Le Sap, and the rivers.

FEB31995 resampled



The geometric correction procedure is then repeated using the same correspondence file for all the other NDVI images.

4. The georeferenced images can now be cut to the Mekong Basin outline by multiplying each image by the BOUND image in which pixels inside the basin are 1 and pixels outside the basin are 0 (see Appendix C).


feb3ndvi

5. Next, the NDVI values are extracted for each of the land covers using:

\Analysis\Database Query\EXTRACT

with FINAL_LC as the feature definition image(see Appendix C).

You can use a batch file (.IML) to do activities 3-5. The ASCII batch file is prepared in an editor and is run using:

\File\Run Macro

The lines below show a sample macro.

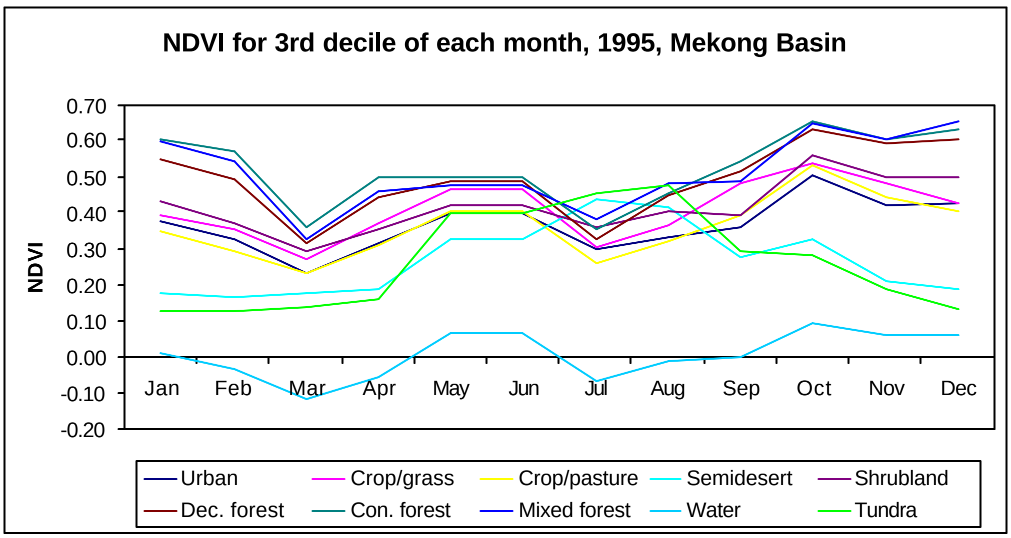
```
resample x i feb31995 feb3UTM ndvi-17 UTM-46N deg 1.0 0 316000 2316000 950000 3950000 2000 3000 2 1
resample x i mar31995 mar3UTM ndvi-17 UTM-46N deg 1.0 0 316000 2316000 950000 3950000 2000 3000 2 1
resample x i apr31995 apr3UTM ndvi-17 UTM-46N deg 1.0 0 316000 2316000 950000 3950000 2000 3000 2 1
resample x i may31995 may3UTM ndvi-17 UTM-46N deg 1.0 0 316000 2316000 950000 3950000 2000 3000 2 1
resample x i jun31995 jun3UTM ndvi-17 UTM-46N deg 1.0 0 316000 2316000 950000 3950000 2000 3000 2 1
resample x i jul31995 jul3UTM ndvi-17 UTM-46N deg 1.0 0 316000 2316000 950000 3950000 2000 3000 2 1
resample x i aug31995 aug3UTM ndvi-17 UTM-46N deg 1.0 0 316000 2316000 950000 3950000 2000 3000 2 1
resample x i sep31995 sep3UTM ndvi-17 UTM-46N deg 1.0 0 316000 2316000 950000 3950000 2000 3000 2 1
resample x i dec31995 dec3UTM ndvi-17 UTM-46N deg 1.0 0 316000 2316000 950000 3950000 2000 3000 2 1
overlay x 3 bound feb3UTM feb3NDVI
overlay x 3 bound mar3UTM mar3NDVI
overlay x 3 bound apr3UTM apr3NDVI
overlay x 3 bound may3UTM may3NDVI
overlay x 3 bound jun3UTM jun3NDVI
overlay x 3 bound jul3UTM jul3NDVI
overlay x 3 bound aug3UTM aug3NDVI
overlay x 3 bound sep3UTM sep3NDVI
overlay x 3 bound dec3UTM dec3NDVI
extract x final_lc feb3ndvi 1 4 feb3
extract x final_lc mar3ndvi 1 4 mar3
extract x final_lc apr3ndvi 1 4 apr3
extract x final_lc may3ndvi 1 4 may3
extract x final_lc jun3ndvi 1 4 jun3
extract x final_lc jul3ndvi 1 4 jul3
extract x final_lc aug3ndvi 1 4 aug3
extract x final_lc sep3ndvi 1 4 sep3
extract x final_lc dec3ndvi 1 4 dec3
```

6. The .VAL files, which have been created by the .IML batch file can now be combined into a spreadsheet. The values of NDVI for January 1995 (for which an image was not available) can be interpolated between the December and the February values.

For compact storage, the 10-day composite NDVI data downloaded from the NOAA website are in a byte format and should now be converted back to the original range (-1.0 to +1.0) using the following conversion:

$$\text{NDVI} = (\text{byte NDVI} - 100)/100.$$

Thus, a byte NDVI value of 151 in the byte format is equivalent to a real NDVI value of 0.51.



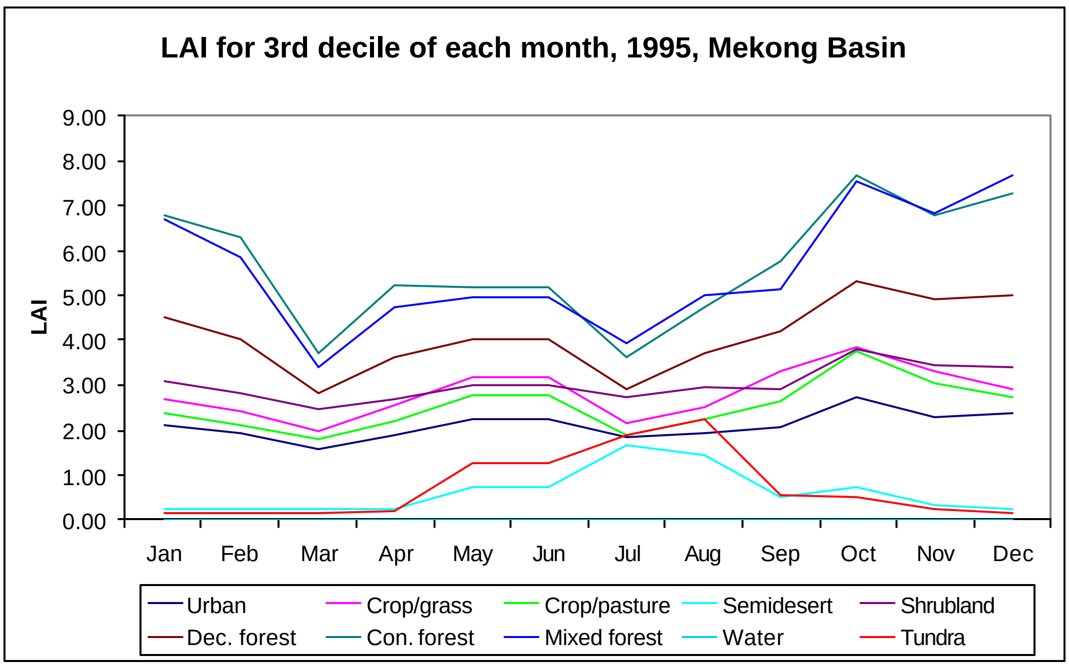
Note from this figure how the NDVI values for water fluctuate about 0 as expected—minor changes may be due to small areas of vegetation on the water at certain times of the year. The remaining land classes can be put into two groups: those peaking in July and August such as semidesert and tundra, which occur at the northern end of the basin (North), and those which peak during October–December, such as the forest and grass classes in the south of the basin (South).

7. The re-scaled NDVI can now be converted to the LAI values needed by the SLURP hydrological model. The relationships between LAI and NDVI vary according to seasonal changes based on phenological changes in LAI, proportions of surface cover types contributing to overall reflectance and effects resulting from large variations in solar zenith angle (Spanner et al. 1990). Relationships are usually specific to vegetation type. For example, Running et al. (1989) give the following equation for mature coniferous forest:

$$NDVI = \ln\left(\frac{LAI}{1.625}\right) x0.34$$

For the Mekong Basin, since none of the NDVI-LAI relationships are known, we used the above equation for coniferous forests, scaled versions of the above equation for the other land covers in the South group and the following relationship (Kite and Spence 1994) for the North group of land classes:

$$NDVI \ ? \ 0.13x\ln(LAI) \ ? \ 0.37$$



Appendix H

DEVELOPING A DEM FOR THE TONLE SAP

The SLURP hydrological model generates river flows and river and lake levels. In order to determine the area and type of land flooded on a given day, we must develop a digital elevation model of the area.

For the Tonle Sap, we first obtained from the Mekong River Commission two types of elevation data: digitized contours of flood levels from SOGREAH/UNESCO (1966) and a set of 110 spot levels taken from 1:250,000 topographical maps (Sopharith 1997).

The digitized contour lines were processed in IDRISI (Eastman 1997) to give a raster DEM as follows:

1. a blank image was created using

    \Data Entry\INITIAL

with the number of columns and rows calculated from the minimum and maximum X and Y values of the vector file using a pixel size of 100m.

2. the vector file was rasterized using:

    \Reformat\Raster/vector conversion\LINERAS

3. the pixels were interpolated between the contours using

    \Data Entry\Surface interpolation\INTERCON

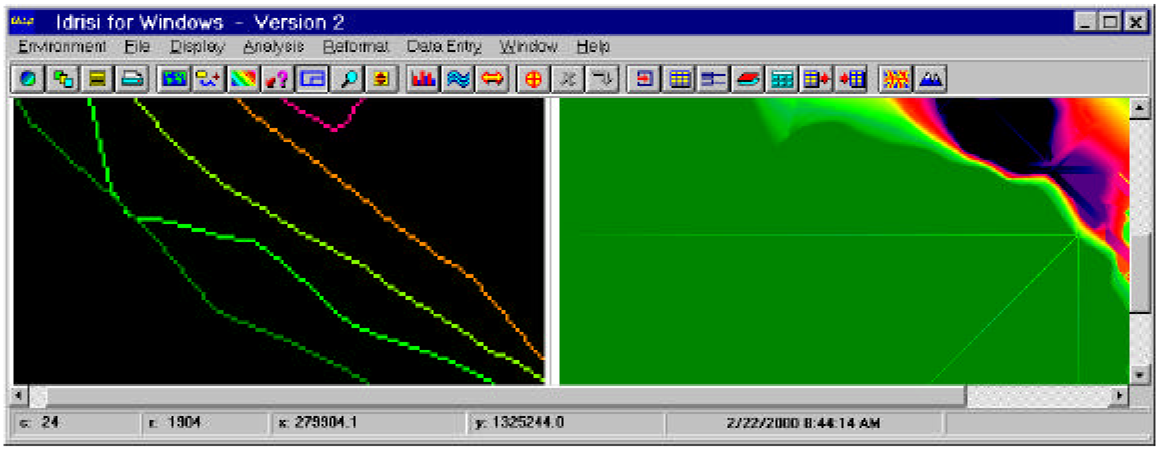
In this case, problems were found with the interpolated raster image because the original contour lines had not all been closed. Corrections to the rasterized contour image were made using program TOPRIVER.EXE. In order to use this program, the rasterized contour image must be converted to ASCII using:

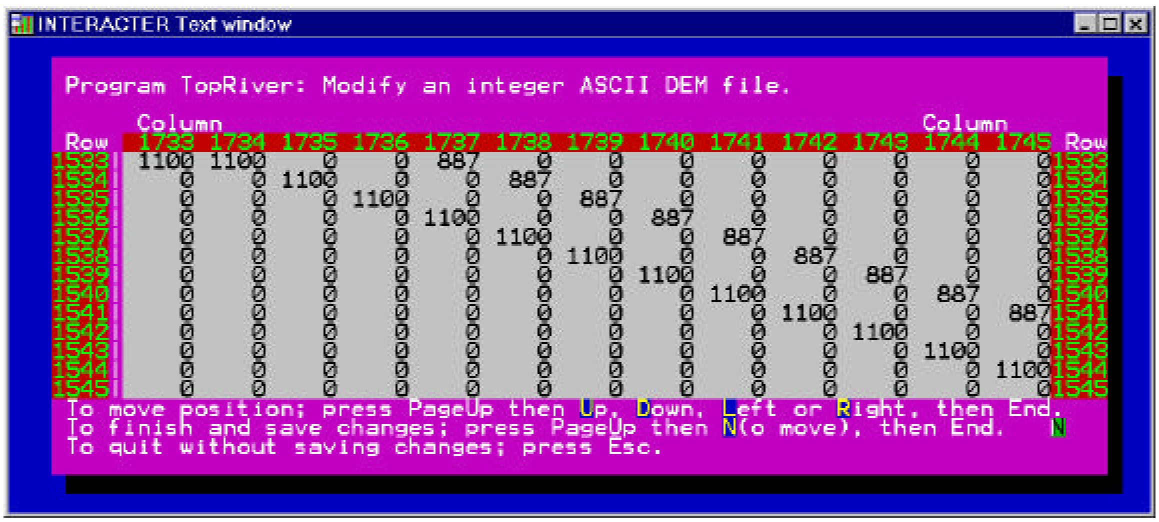
\Reformat\CONVERT

After using TOPRIVER, the corrected image should be reconverted back to binary using

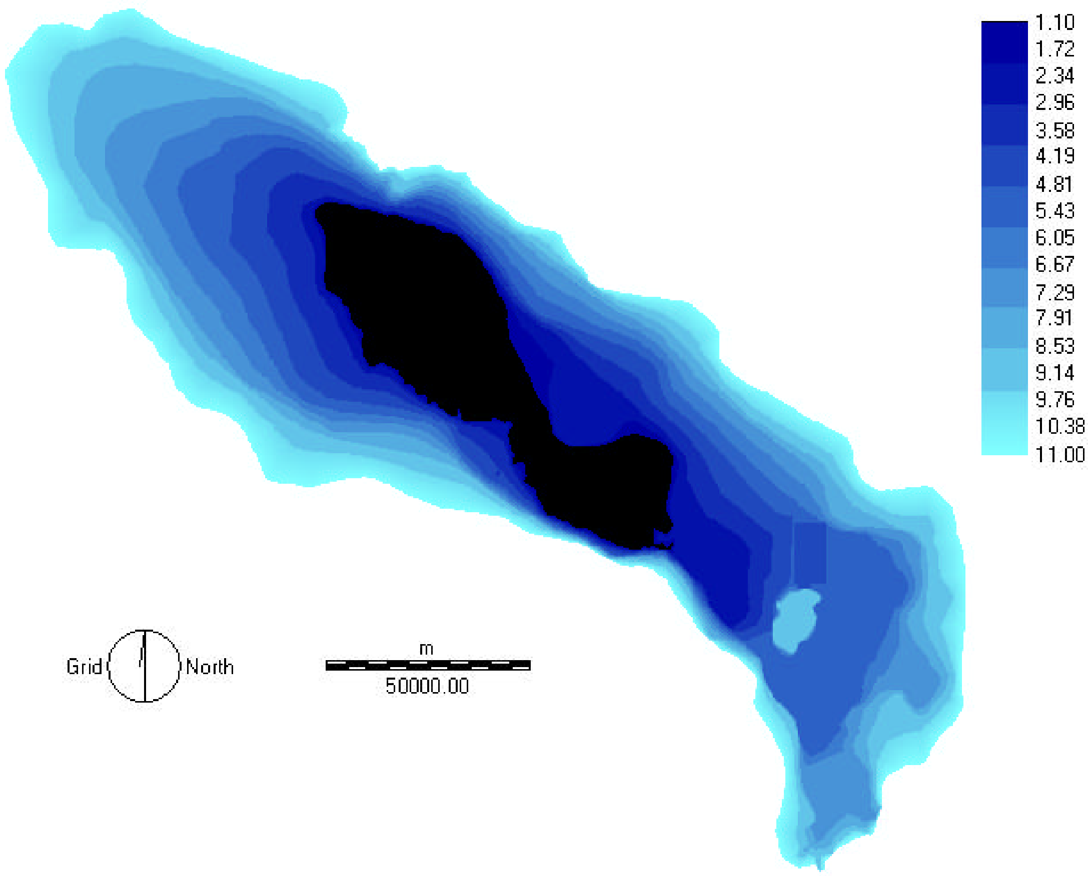
\Reformat\CONVERT.

.

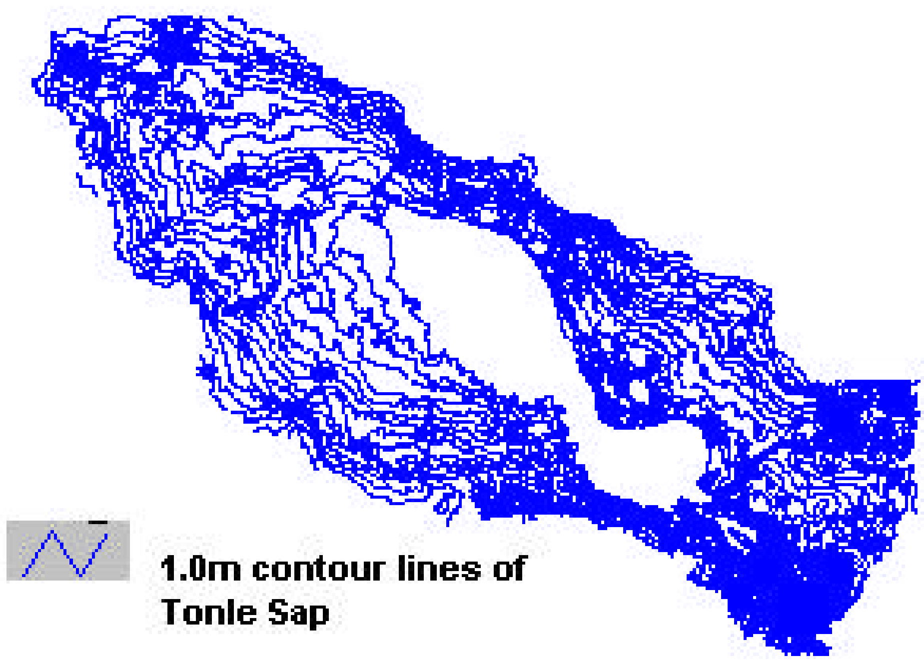


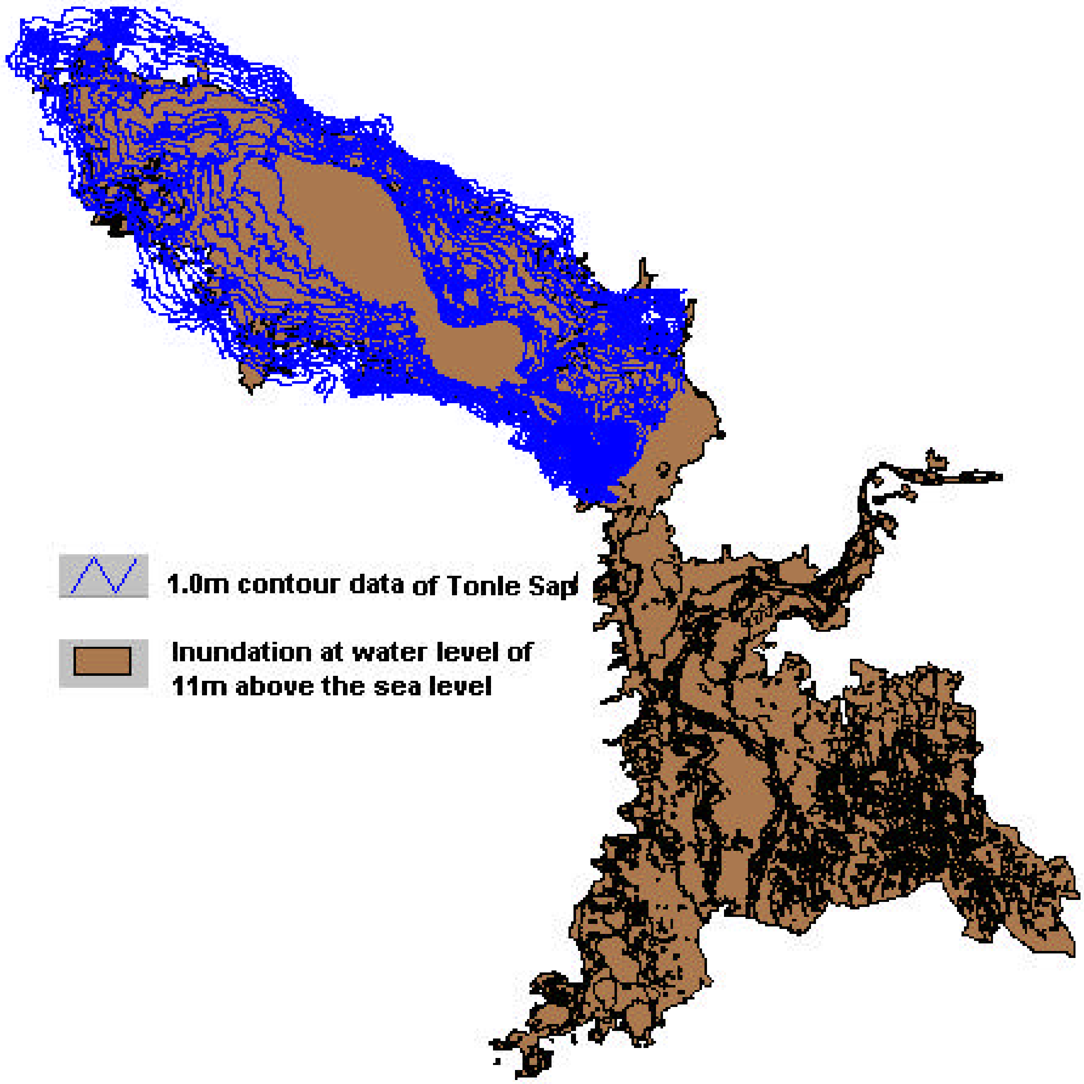


Even with these corrections, the IDRISI function INTERCON gave a very poor result with many unexplained features. The interpolation was eventually done using ERDAS IMAGINE software and then re-exported to IDRISI. It was found that the spot levels did not add any information

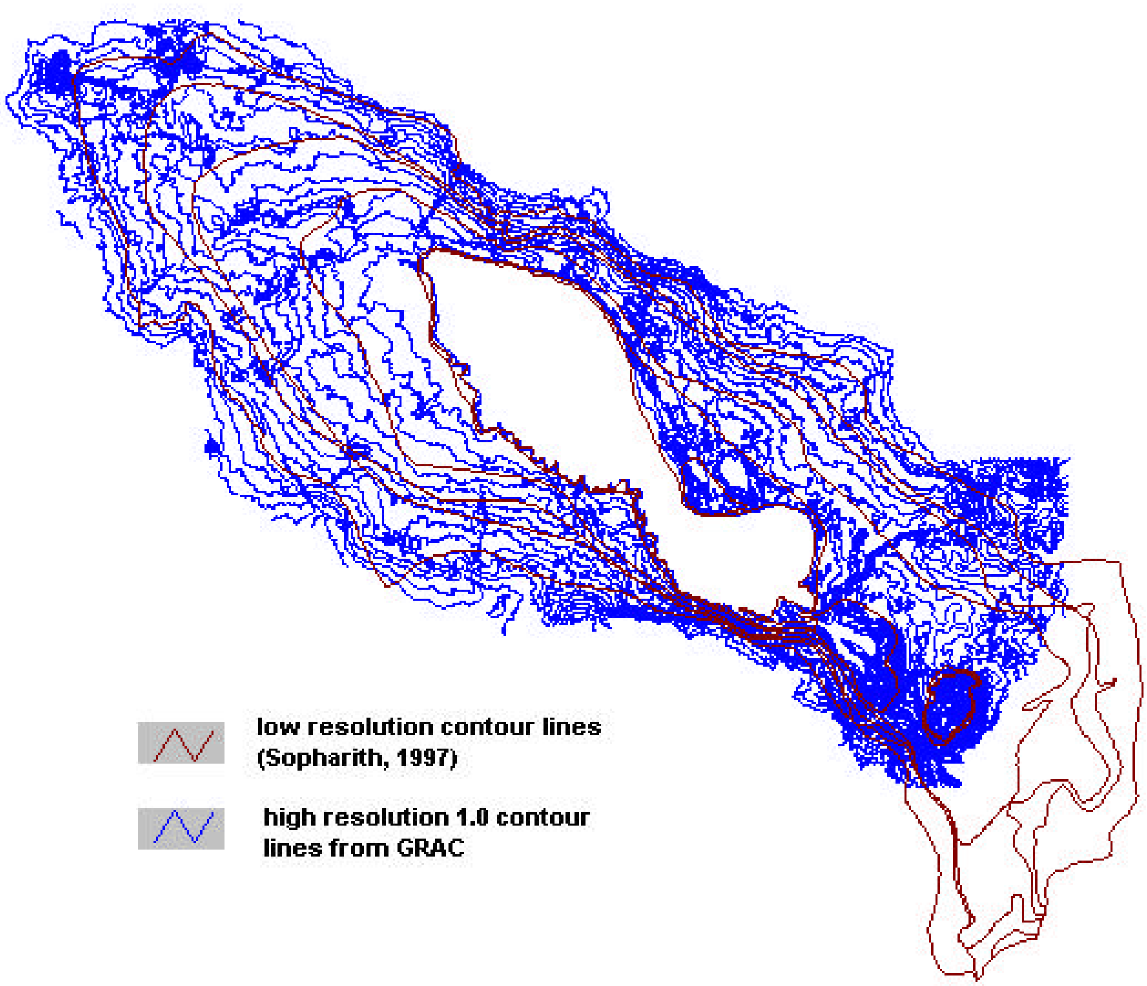

1.10
1.72
2.34
2.96
3.58
4.19
4.81
5.43
6.05
6.67
7.29
7.91
8.53
9.14
9.76
10.38
11.00
Grid
North
m
50000.00

To add more detailed contours, two additional sets of data were purchased from the GIS and RS Applications Center (GRAC), Phom Penh, Cambodia as Arc/Info .e00 files. These data are i) 1.0m contour lines for the Tonle Sap digitized from a source scale of 1:100,000 (Certeza 1964), and ii) the area of inundation at a water level of 11 m above mean sea level for the entire Tonle Sap-Mekong Delta region





When the area of inundation was overlayed on the contour lines it was evident that the elevation profiles of the southern extent of the Tonle Sap was missing from the contour line dataset. To rectify this, the original contour lines (Sopharith 1997) were used for the southern part of the lake.

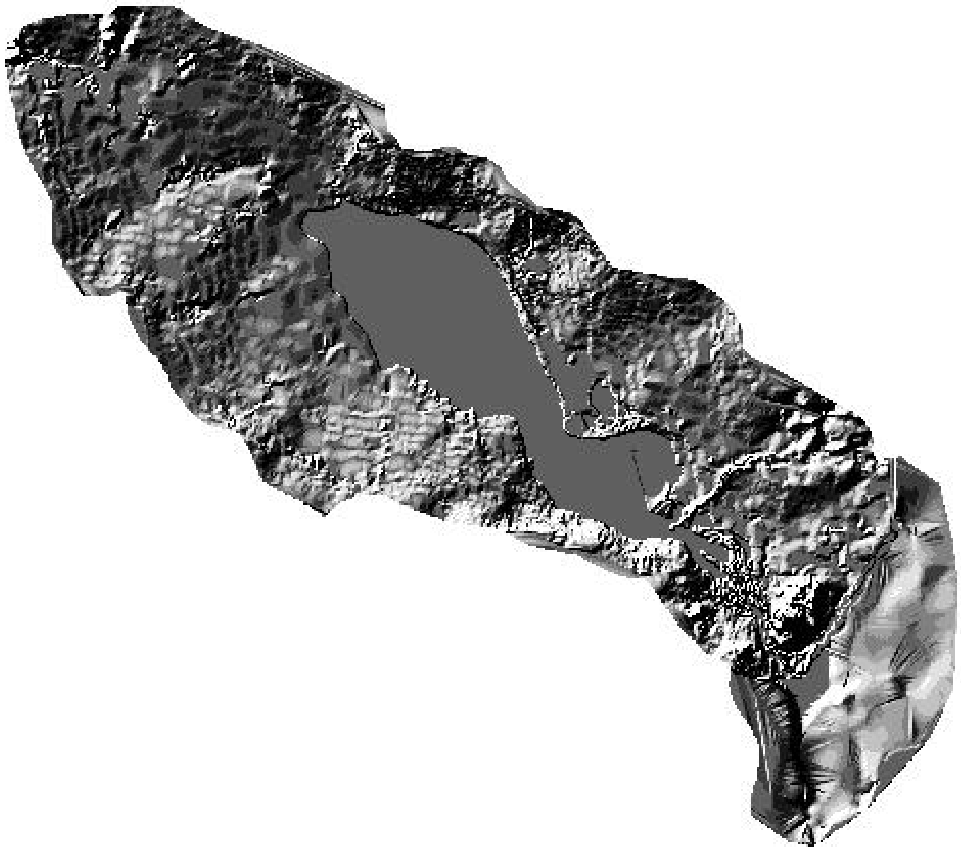


The above two sets of digitized contour lines were processed as two separate files using ARC/INFO to obtain a Digital Elevation Model and then converted it to a raster data base as follows:

First each of the above digital contour coverages was used to build a TIN (Triangulated Irregular Network) as:

ARCTIN <in_cover> <out_tin> {ALL | POINT | LINE} {spot_item}
{weed_tolerance} {proximal_tolerance} {z_factor} {device}

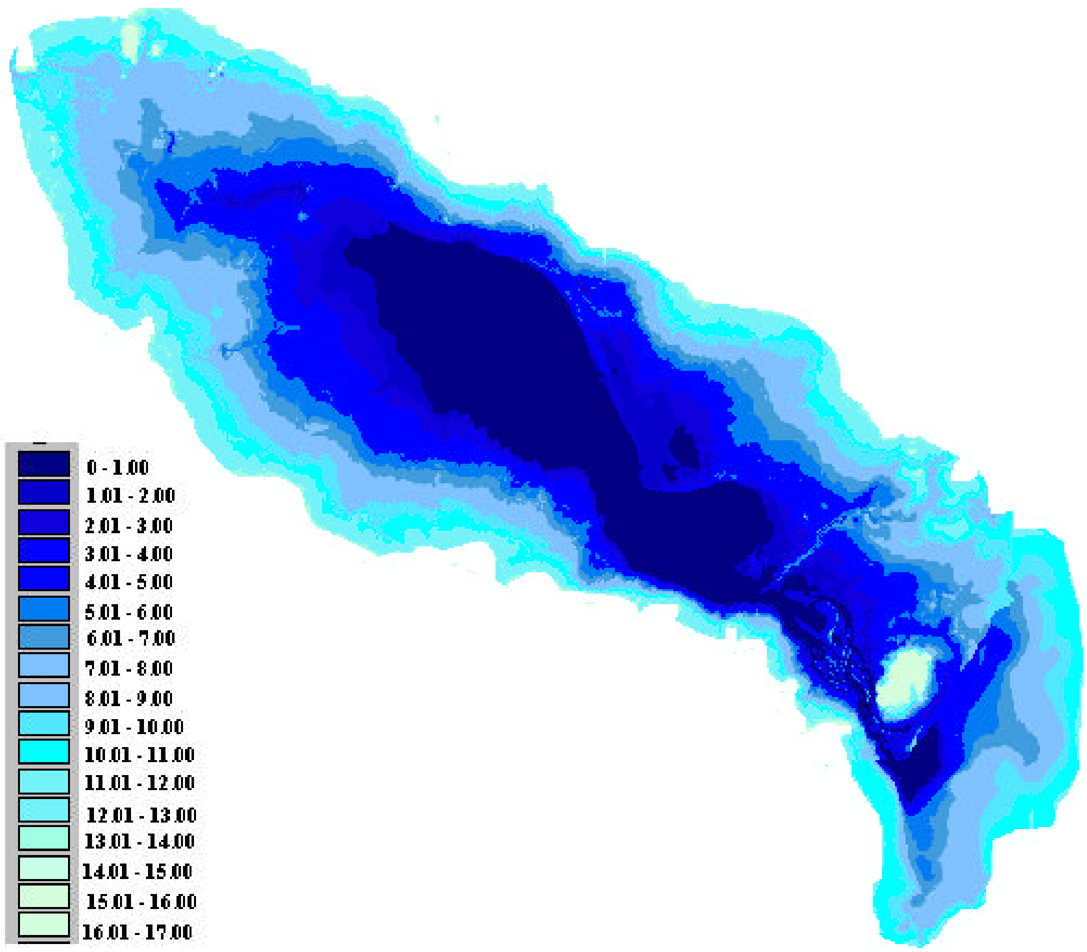
A TIN is a surface representation derived from irregularly/regularly spaced sample contour lines and includes topological relationships between points and their neighboring triangles by connecting points on the contours to form a set of non-overlapping triangles used to represent the surface. The figure below shows a surface draped over the TIN model obtained from the contour data.



Next, a raster elevation grid of 200 m resolution was obtained by overlaying a lattice of 200m by 200m and sampling the DEM at every 200 m as:

TINLATTICE <in_tin> <out_lattice> {LINEAR | QUINTIC} {z_factor} {FLOAT | INT}

A lattice is a surface representation that uses a rectangular array of mesh points spaced at a constant sampling interval in the x and y directions relative to a common origin. A lattice is stored as a grid, but represents the value of the surface only at the mesh points rather than the value of the entire cell.



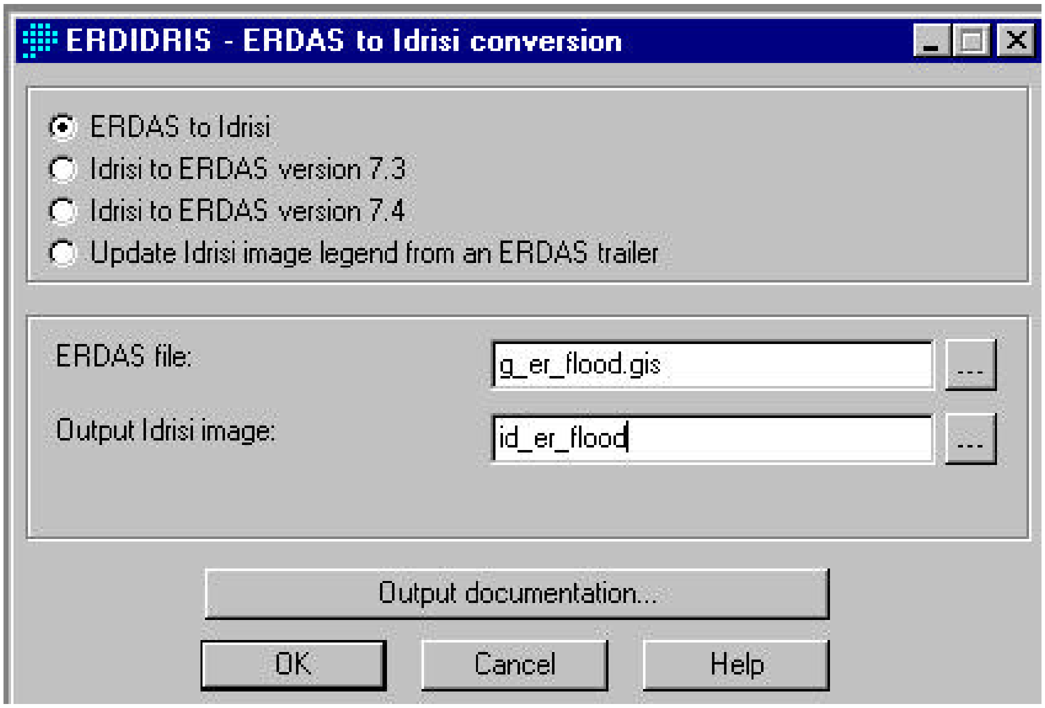
The values of the lattice were multiplied by hundred and then it was converted to a grid of integers using the TABLE function in Arc/Info. Using the above raster profile the number of pixels that would be inundated for the rise of every one hundredth of a meter was calculated. By multiplying each pixel by the pixel area (200 m by 200 m) in kilometers the area of inundation for every one hundredth of a meter was calculated and plotted (below). The resulting elevation vs. area relationship agrees closely with that derived from SOGREAH/UNESCO (1966).

To export the Arc/Info DEM file to IDRISI it has to be converted to ERDAS/Imagine raster format using:

> **GRIDIMAGE** <in_grid | in_stack> {NONE | NOMINAL | GRAY | in_colormap_file} <out_image> {BIL | BIP | BMP | BSQ | ERDAS | GRASS | IMAGINE | JFIF | RLC | SUNRASTER | TIFF} {NONE | COMPRESSION | G4 | LZW}

This will create a file with a gis extension which can be directly imported to IDRISI suing:

\File\Import\Software specific formats\ERDIDRIS



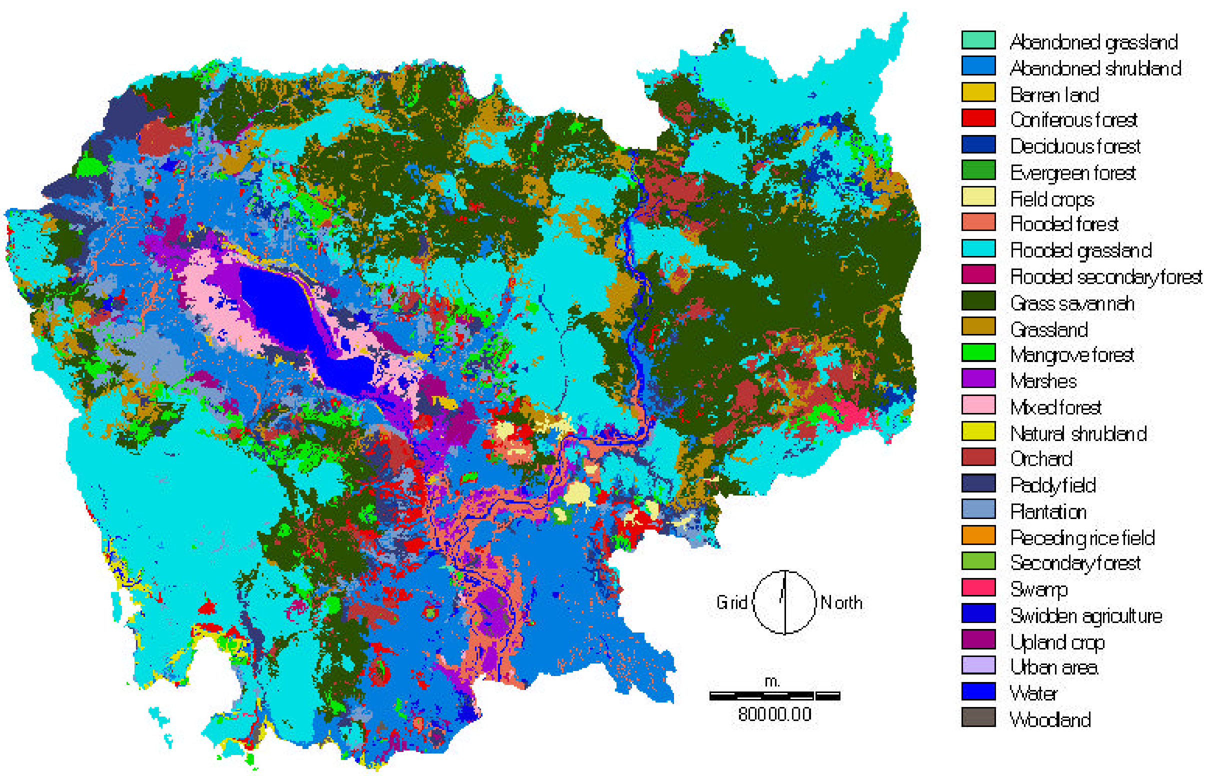
Appendix I

PREPARING A LAND COVER MAP FOR TONLE SAP

An Arc/Info polygon coverage of the land use in 1992-1993 produced by MRC in cooperation with LUMO was purchased from GRAC (Gis & Remote sensing Applications Center), Phnom Penh, Cambodia. This land cover map was developed by classifying 30 m resolution Landsat TM images. The part of the map for the Tonle Sap area was clipped and converted to a raster format with horizontal resolution of 200m using the ARC/INFO Grid Module as:

POLYGRID(<cover>, {item}, {lookup_table}, {weight_table}, {cellsize})

The figure below shows the extent of the original map and the clipped area.

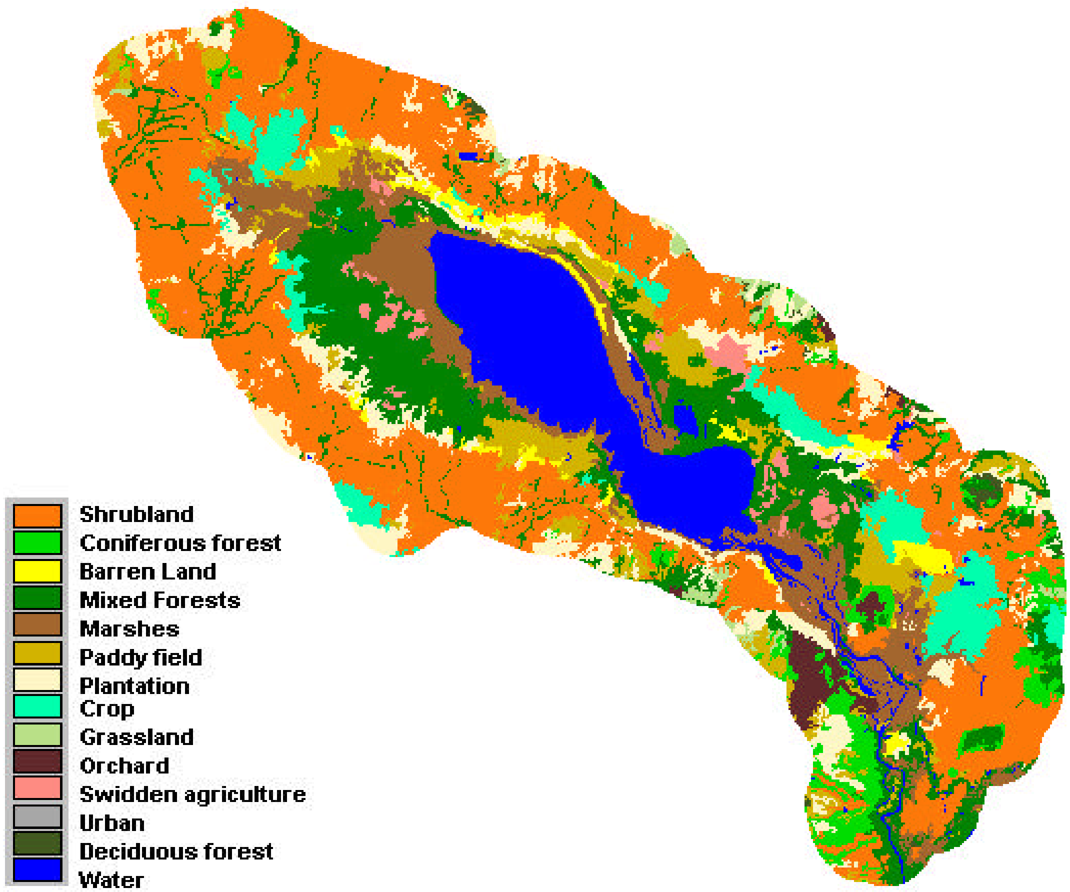


The Tonle Sap area was reclassified to give fewer classes as in the following table using the ARC/INFO command:

RECLASS(<grid>, <remap_table>, {DATA | NODATA}, {in_item}, {out_item})

which changes the value of the input cells using a remap table (created in an editor) on a cell-by-cell basis of the coverage. The land use type of each cell was changed to a new landuse code id. The simplified classification is shown below

Land class	Includes these previous land classes
101 Shrubland	Abandoned Shrublands & Natural Shrublands
102 Coniferous forest	Coniferous forest & Evergreen forest
103 Barren Land	
104 Mixed Forests	Mixed forests, Flooded Forests, Mangrove forests & Woodlands
105 Marshes	Marshes & swamps
106 Paddy field	Paddy field & receding rice fields
107 Plantation	
108 Crop	Field crop & upland crops
109 Grassland	Abandoned grassland, Flooded grasslands, Grass Savannah & grassland
110 Orchard	
111 Swidden agriculture	
112 Urban	
113 Deciduous forest	
114 Water	

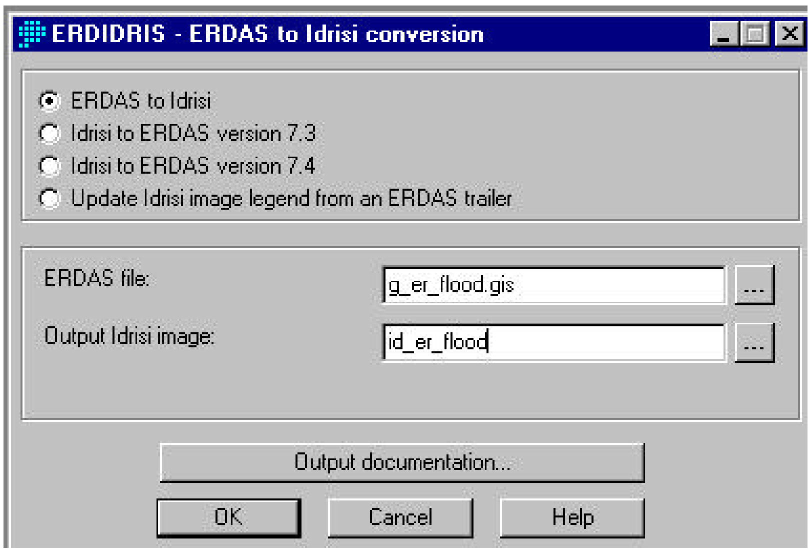

Shrubland
Coniferous forest
Barren Land
Mixed Forests
Marshes
Paddy field
Plantation
Crop
Grassland
Orchard
Swidden agriculture
Urban
Deciduous forest
Water

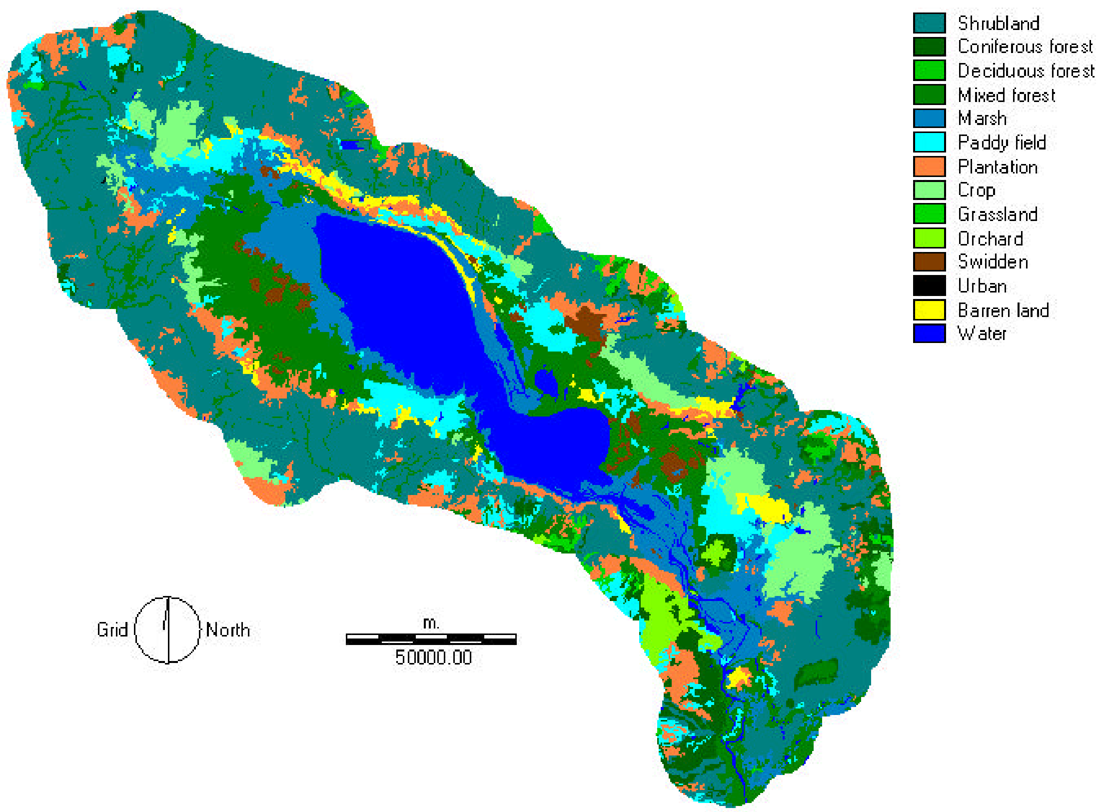
To export the Arc/Info land use file to IDRISI it has first to be converted to ERDAS/Imagine raster format using:

GRIDIMAGE <in_grid | in_stack> {NONE | NOMINAL | GRAY | in_colormap_file} <out_image> {BIL | BIP | BMP | BSQ | ERDAS | GRASS | IMAGINE | JFIF | RLC | SUNRASTER | TIFF} {NONE | COMPRESSION | G4 | LZW}

This will create a file with a gis extension which can be directly imported to IDRISI suing:

\File\Import\Software specific formats\ERDIDRIS





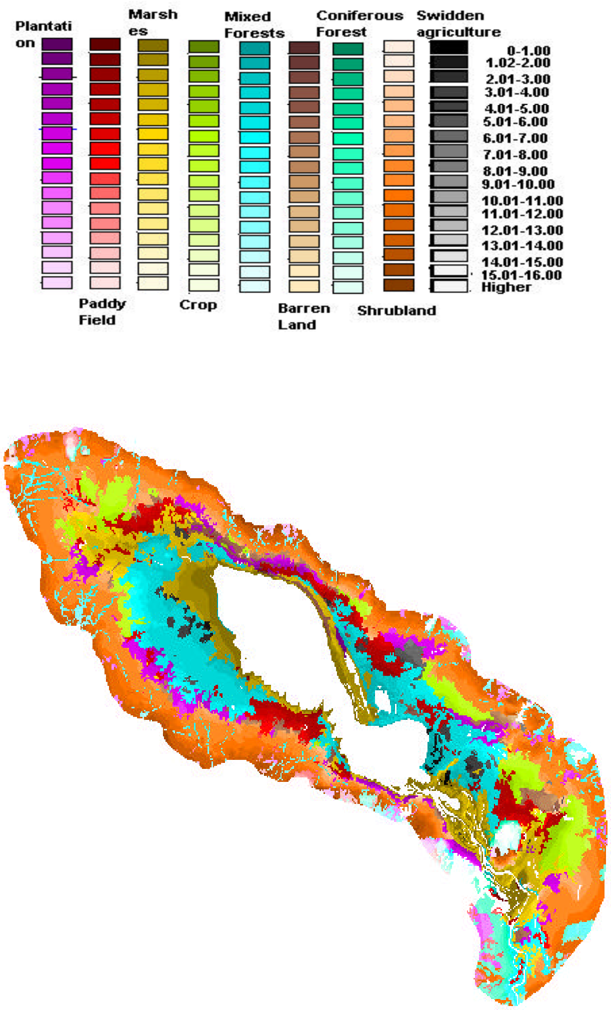
Once the reclassification for the Tonle Sap area was completed, each land use type was selected in GRID (ArcInfo) using the following command

SELECT(<grid>, <logical_expression>, {o_value_item})

For each land use type in the land use grid, the appropriate elevations were assigned on a cell-by-cell basis using the following command in GRID

SELECTMASK(<grid>, <mask_grid>)

Once this had been done for each cell of a particular land use type, an additional item containing the elevation above mean sea level was assigned to each cell. The following figure shows the more prominent land use types categorised by elevation:

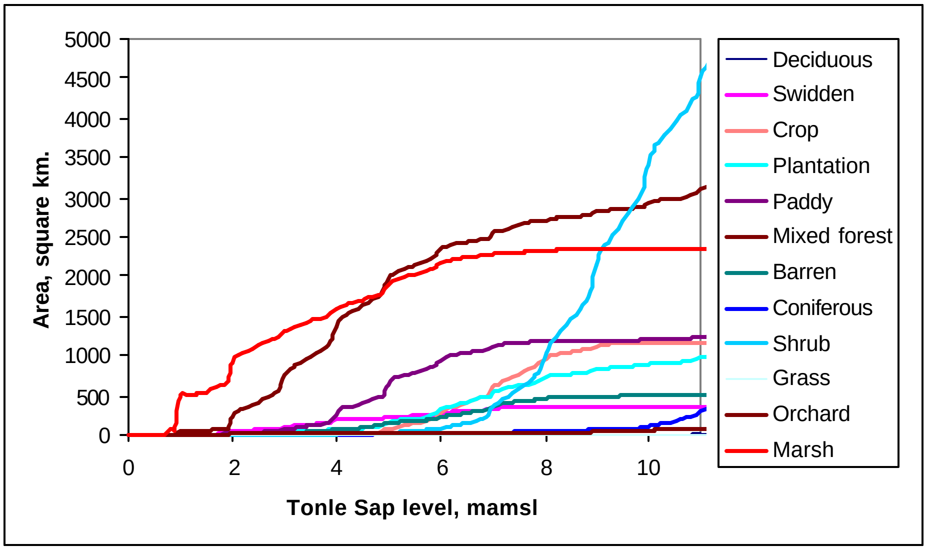


To obtain a table containing the elevation and the number of cells pertaining to a particular elevation, the value attribute tables (VAT) were exported as *.dbf tables in ArcView. This was carried out using ‘tables’ in the project window that is used to manage the views, tables, charts, layouts, scripts, and other components in a project.

A value attribute table (VAT) contains attributes pertaining to each cell of a grid. In addition to user-defined attributes, the VAT contains the values assigned to cells in the grid and a count of the cells with those values.

Once the value attribute tables were exported they were converted to Excel files and a commutative addition of the pixels vs. elevation was graphed. Equations describing the area-elevation relationship were obtained slicing the elevation range into several sections. The graphs and the equations with the ceiling and floor values for each equation are included in the graphs for each land use shown on the following pages.

These equations were then built in to the SLURP hydrological model to derive the areas of each land cover flooded on each day of the model run.



Two other land use maps were purchased from GRAC, for 1973-76 and 1985-87. The land covers from each of these datasets were compared to those from 1992-93 for the Tonle sap area as follows

Tonle Sap Landuse	1973-76	1985-87	1992-93
Abandoned grasslands		0.0733	34.1508
Abandoned shrublands		28.21605	
Barren lands	0.137369	1.365219	2.070925
Coniferous forest	31.40712	1.768371	3.040212
Deciduous forest	2.083429	0.274876	0.44377
Evergreen forest	0.293054	0.064138	0.17128
Fields crops	0.027474	0.022906	0.471019
Flooded forest	0.119	1.241525	5.644439
Flooded grasslands		0.352758	0.576122
Grass Savannah	1.859059	0.219901	0.770758
Grasslands		0.050394	0.163494
Mangrove forest		0.852117	1.919109
Marshes		26.53473	10.17167
Mixed forest		0.146601	9.918642
Orchards	0.654792 (incl. Plantation)	0.119113	1.136667
Paddy field	30.92632 (incl. Ricefield)	1.452263	5.804041
Plantation		8.374565	6.625404
Receding rice fields		0.444383	0.058391
Swidden agriculture		1.58512	1.405271
Upland crops	10.04625	13.84002	4.62844
Water surface	13.03631	12.95584	10.75168
Woodlands	0.348001 (incl. Shrub	0.045813	0.031142
Urban/city	9.06177		0.003893
Natural Shrublands			0.003893
Swamps			0.38927

Similarly, the land covers from the detailed 1992-93 dataset was compared to the less detailed data from NOAA AVHEE satellite images, which was used for the whole Mekong Basin. The NOAA percentages for the Tonle Sap area areas follows:

Percentage	Tonle Sap Land use from NOAA
0.252958	Urban and Built-up land
6.896015	Dryland cropland and Pasture
56.75981	Irrigated Cropland and Pasture
0.175125	Cropland/Grassland Mosaic
9.413917	Cropland/Woodland Mosaic
0.385274	Grassland
5.635118	Shrubland
0.902864	Savanna
4.529888	Deciduous Broadleaf forest
1.626712	Evergreen Broadleaf Forest
0.435866	Mixed Forest
12.98646	Water bodies

The data from the lake level vs. flooded area for each land cover were extracted from the GIS as ASCII files labelled <LAND COVER>.H-A which are then used by the hydrologic model to derive time series of flooded areas for each land cover.

Appendix J

LEVELS OF TONLE SAP

Level-area and level-volume relationships for the Tonle Sap were developed using level data from the Kompong Luong gauging station. However, this gauge is no longer used and, instead, levels of the Tonle Sap are now taken at Kompong Chhnang and Prek Kdam. These must be converted to levels at Kompong Luong. Sopharith (1997) used the following relationship between the two gauges based on data from Carbonnel and Guiscafre (1963):

$$H_{KL} \ ? \ (1.0068H_{KC}) \ ? \ 0.50$$

where H_{KL} and H_{KC} are the levels in metres at Konpong Luong and Kompong Chhnang respectively. Sopharith (1997) noted that the correlation coefficient of this regression, when used for annual maxima, was only 0.838. The figure below shows, for the two years 1924 and 1965 (the first and last years of the record at Kompong Luong), that the relationship overestimates the level at Kompong Luong. This figure also shows that data at Kompong Chhnang have inconsistent jumps in level (e.g., day 92, April 1, in 1924 the Kompong Chhnang level drops from 6.9 m. to 3.02 m.).

The Kompong Chhnang data were cleaned up as best as possible, eliminating unexplained jumps. Data from Kompong Chhnang and Prek Kdam were then used to fill in missing values in the record at Kompong Luong. For the years, 1924-1960, a general regression (R^2 of 0.94) was used:

$$H_{KL} \ ? \ (0.950519H_{KC}) \ ? \ 0.806588$$

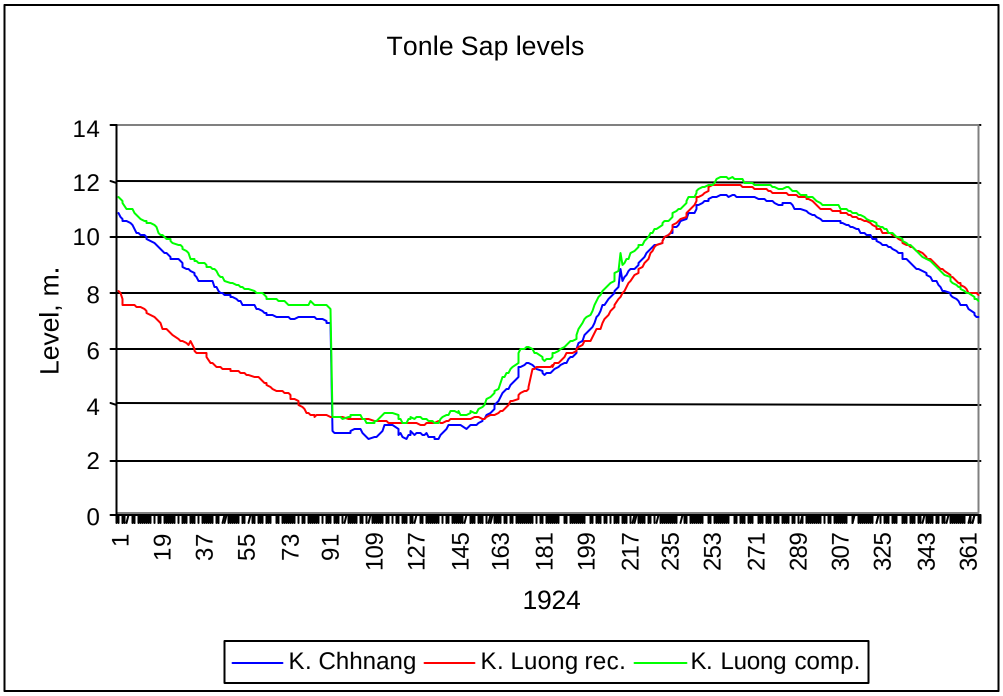
For the period 1960-1998, a regression equation based on data from 1960-1965 (R^2 of 0.92) was used:

$$\mathrm{H}_{\mathrm{KL}} \ ? \ (0.926343\mathrm{H}_{\mathrm{KC}}) \ ? \ 0.522631$$

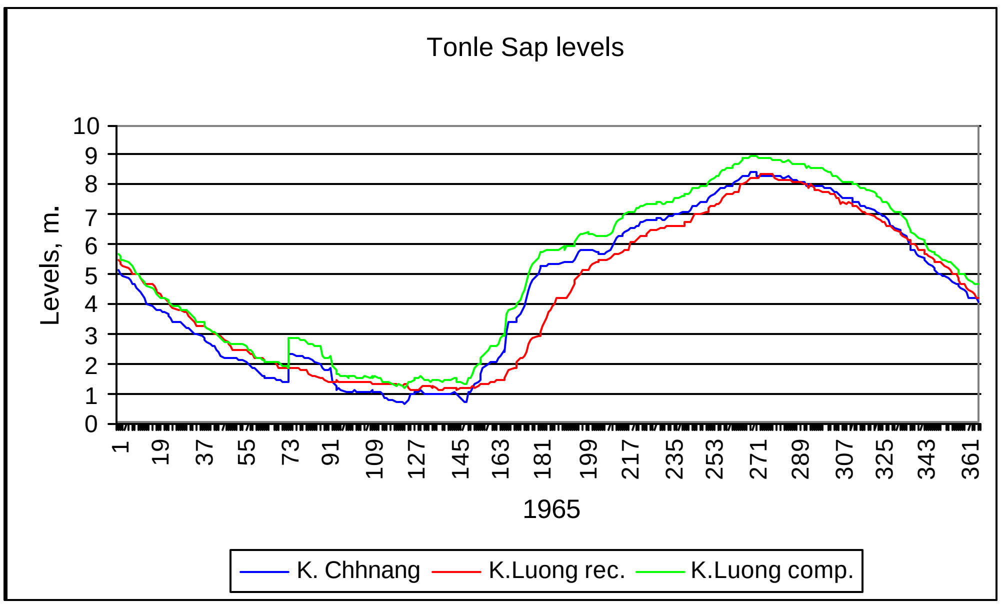
If data at Kompong Chhnang were also not available, missing data were filled from the record at Prek Kdam, where available, using:

$$H_{KL} \ ? \ (0.905533H_{PK}) \ ? \ 1.235901$$

with an R^2 value of 0.84.



Tonle Sap levels
Level, m.
14
12
10
8
6
4
2
0
1
19
37
55
73
91
109
127
145
163
181
199
217
235
253
271
289
307
325
343
361
1924
K. Chhnang
K. Luong rec.
K. Luong comp.



Tonle Sap levels
Levels, m.
10
9
8
7
6
5
4
3
2
1
0
1
19
37
55
73
91
109
127
145
163
181
199
217
235
253
271
289
307
325
343
361
1965
K. Chhnang
K.Luong rec.
K.Luong comp.

Sopharith (1997) used data from SOGREAH/UNESCO (1966) to establish relationships between lake level, lake area and lake volume as follows:

$$A \;?\; 0.0814 \; H^{2} \;?\; 0.4078 \; H \;?\; 1.9795$$

$$V \;?\; 0.0338 \; H^{3} \;?\; 0.0908 \; H^{2} \;?\; 2.5116 \; H \;?\; 2.3646$$

where *H* is the lake level at Kompong Luong in metres, *A* is the lake area in thousand square kilometres (10^9 m^2), *V* is the lake volume in cubic kilometres (10^9 m^3). Sopharith (1997) qualified the use of these curves, noting that lake level data at Kompong Luong are only available for the period 1924-1965 and that levels for the period 1925-1961 must be corrected for errors in datum. In addition, the DEM used to determine flooded area and volume was digitized from 1962-1963 topographic maps.

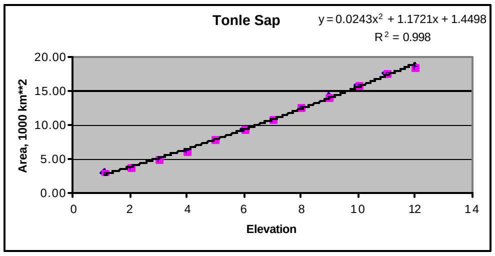
Later, as the detailed DEM of Tonle Sap was developed from the contour data provided by MRC, these equations were replaced by comparable relationships derived in the GIS. Only very small differences were recorded. The curves developed are plotted on the next page.

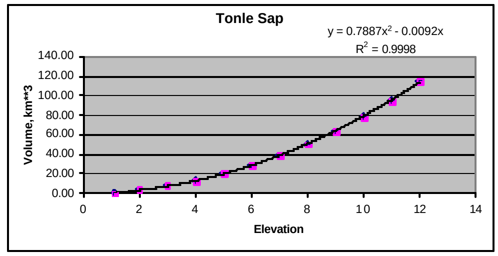
The next step was to develop a method of simulating flows in the Tonle Sap river from the flows in the Mekong at Kratie and the volume of the Tonle Sap lake.. A relationship was developed using data for 1962 (the only data for which we had recorded Tonle Sap outflows for all months) as follows:

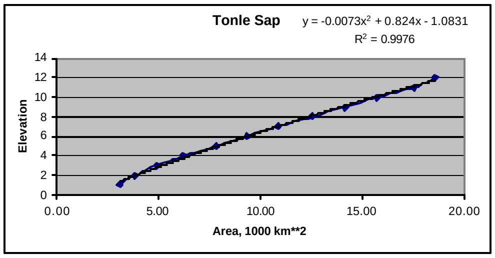
$$Q_{ts} = -33.66 - 0.667\,Q_k + 150\,V^{1.17}$$

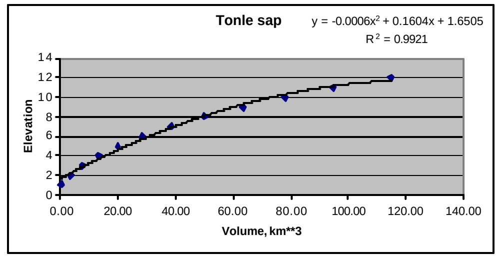
where Q_{ts} and Q_k are in m^3/s and V is in $m^3 \times 10^9$.

The comparison between the observed and computed Tonle Sap outflows for the year 1962 and the flows in the Mekong at Kratie and in the Tonle Sap computed by the SLURP model using this algorithm for the years 1995-1999 are shown in the main report.


Tonle Sap
y = 0.0243x2 + 1.1721x + 1.4498
R2 = 0.998
Area, 1000 km**2
Elevation
0.00
5.00
10.00
15.00
20.00
0 2 4 6 8 10 12 14


Tonle Sap
y = 0.7887x2 - 0.0092x
R2 = 0.9998
Volume, km**3
Elevation
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
0 2 4 6 8 10 12 14


Tonle Sap
y = -0.0073x2 + 0.824x - 1.0831
R2 = 0.9976
Elevation
Area, 1000 km**2
0 2 4 6 8 10 12 14
0.00 5.00 10.00 15.00 20.00


Tonle sap
y = -0.0006x2 + 0.1604x + 1.6505
R2 = 0.9921
Elevation
Volume, km**3
0 2 4 6 8 10 12 14
0.00 20.00 40.00 60.00 80.00 100.00 120.00 140.00

BIBLIOGRAPHY

Anderson, J. R.; E. E. Hardy; J. T. Roach; and R.E. Witmer. 1976. *A land use and land cover classification system for use with remote sensor data*. U.S. Geological Survey Professional Paper 964, 28 p.

Baird, I. 1995. *Investigations of the Xe Kaman and Xe Xou rivers, with special reference to freshwater fish and river ecology, and a review of the potential social and environmental impacts of large dam projects being considered for these two rivers in Attapeu province, Southern Lao PDR*. Report prepared for the Protected Areas Division of the Department of Forestry, Vientiane, January 1995.

Belward, A. S. (Ed.). 1996. *The IGBP-DIS global 1 km land cover data set (DISCover)-proposal and implementation plans.* IGBP-DIS Working Paper No. 13. Toulouse, France.

Brown, J. F.; T. R. Loveland; J. W. Merchant; B. C. Reed; and D.O. Ohlen. 1993. Using multisource data in global land cover characterization: Concepts, requirements and methods. *Photogrammetric Engineering and Remote Sensing* 59: 977-987.

Carbonnel, J.P. and J. Guiscafre. 1964. Grand Lac du Cambodge: Sedimentologie et hydrologie, 1962-1963.

Compagnie Nationale du Rhone. 1994. Mekong mainstream run-of-river hydropower, Annex 1 Concepts and analysis, Figure 1-3-4, Mekong Secretariat, Phnom Penh.

Certeza Surveying. 1964. Report to Committee for Coordination of Investigations of the Lower Mekong Basin, Quezon City, The Philippines.

Choung Phanrajasavong. 1986. *HYSSR model*. Report to the Interim Mekong Committee, Bangkok.

de Voogt, K.; G.W. Kite; P. Droogers; and H. Murray-Rust. Modelling water allocation between a wetland and irrigated agriculture in the Gediz Basin, Turkey. *Journal of Water Resources Development* (Forthcoming).

Defense Mapping Agency. 1992. *Development of the digital chart of the world.* Washington D.C.: U.S. Government Printing Office.

Droogers, P.; G. W. Kite; W. G. M. Bastiaanssen. 1998. *Land cover classification using public domain datasets: An example for the Gediz Basin, Turkey*. Proceedings of the International Symposium on Arid Region Soils, Izmir, Turkey, 21-24 September, 34-40.

Droogers, P.; and G. W. Kite. 1999. Water productivity from integrated basin modeling. *Irrigation & Drainage Systems* 13: 275-290.

Droogers, P.; and G. W. Kite. 1999. Remotely sensed data used for modeling at different hydrological scales. *Hydrological Processes* (Forthcoming).

Eastman, J. R. 1997. *IDRISI for Windows user's guide, version 2.0*. Clark Labs for Cartographic Technology and Geographic Analysis. Worcester, MA, USA.

Eastman, J. R.; and M. Fulk. 1993. Long sequence time series evaluation using standardized principal components. *Photo*. *Eng. Rem. Sens*. 59: 1307 – 1312.

Eidenshink, J. C.; and J. L. Faundeen. 1994. The 1 km AVHRR global land data set-first stages in implementation*: International Journal of Remote Sensing* 15(17): 3,443-3,462.

FAO. 1998. *Digital soil map of the world and derived soil properties*. Rome: FAO.

FAO. 1999. Flood Management and Mitigation in the Mekong river basin. *Food and Agriculture Organization of the United Nations*, RAP Publication 199/14, Bangkok.

Garbrecht, J.; and L.W. Martz 1997. *TOPAZ version 1.20: An automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation and subcatchment parameterization – overview. Rep.# GRL 97-2.* El Reno, Oklahoma, USA : USDA Grazinglands Research Laboratory, Agricultural Research Service.

Gholz, H. L.; F. K. Fitz; and R. H. Waring. 1976. Leaf area differences associated with old growth forest communities in the eestern Oregon cascades. *Can. J. For. Res* 6:49-57.

Gower, S. T.; and J. N. Norman. 1991. Rapid Estimation of Leaf Area Index in Conifer and Broad-Leaf Plantations. *Ecology* 72(5): 1896-1900.

Hien, Nguyen Xuan. 1999. Hydraulic modelling and flood control planning in the Mekong Delta. In: Flood Management and Mitigation in the Mekong river basin. *Food and Agriculture Organization of the United Nations*, RAP Publication 199/14, Bangkok, 131-143.

Hill, M.T.; and S. A. Hill. 1994. *Fisheries ecology and hydropower in the Mekong River: An evaluation of run-of-the-river projects*. Report prepared for the Mekong Secretariat, Bangkok, September 1994.

Institute of Hydrology. 1988. Investigation of dry season flows. Water Balance Study Phase 3 Report to the Interim Committee for Coordination of Investigations of the Lower Mekong Basin, Institute of Hydrology, Wallingford.

Institute of Hydrology. 1995. *Assessment of global water resources, preliminary report. Report to the Overseas Development Administration.* ODA Report 95/2. Wallingford, UK: Institute of Hydrology.

ISLSCP. 1995. *Global datasets for land-atmosphere models*, *Initiative 1, Volume 1, CD-ROM USA_NASA_GDAAC_ISLSCP_001*.Washington: NASA.

Jacobs, J.W. 1998. The United States and the Mekong Project. Water Policy, 587-603.

Jenne, R. 1999. Selected datasets and data issues for hydrology. In *Proceedings of the IUGG/IAHS Workshop HW1, Birmingham, England.*

Kineman, J. J.; and D. A. Hastings. 1992. Monthly Generalized Global Vegetation Index (April 1985 - December 1988). In *NOAA-EPA, 1992, Global Ecosystem Database Version 1.0 (in CD-ROM), Documentation Manual, Disc A*. Boulder, Colorado: National Oceanic and Atmospheric Administration, National Geophysical Data Center.

Kite, G. W. 1993. Application of a land-use hydrological model to climatic change. *Water Resources Research* 29(7): 2377-2384.

Kite, G. W. 2000. *Manual for the SLURP model.* Colombo, Sri Lanka: International Water Management Institute.

Kite, G. W.; and C. D. Spence. 1994. *Land cover, NDVI, LAI and evapotranspiration in hydrological modelling.* Canada: National Hydrology Research Institute.

Kite, G. W.; A. Dalton; and K. Dion. 1994. Simulation of streamflow in a macro-scale watershed using GCM data. *Water Resources Research* 30(5):1546-1559.

Kite, G. W.; and P. Droogers. 1999. Irrigation modelling in the context of basin water resources. *J. Water Resources Development* 15:44-54.

Kite, G.W.; M. Danard; and B. Li. 1998. Simulating long series of streamflow using data from an atmospheric model. *Hydrol. Sciences J.* 439(3): 391-408.

Kreuze, J.P.F. 1998. Report on consultancy on relationship between Mekong River floodlevels, inundations and fish yields. Mekong River Commission, Phnom Penh.

Lacroix, M. P.; and L. W. Martz. 1997. Integration of the TOPAZ landscape analysis and the SLURP hydrologic models. In *Programs and abstracts, scientific meeting of the Canadian Geophysical Union.* Banff, Alberta, Canada.

Lacroix, M; G. W. Kite; and P. Droogers. 1999. *Using datasets from the Internet for hydrological modeling: An example for the Kucuk Menderes Basin, Turkey*. Paper presented at Remote Sensing and Hydrology Symposium, Santa Fe New Mexioco, USA.

Laroche, A.; and S. Wilcox. 1992. *Environmental issues and natural resource management in Cambodia: Final report and annotated bibliography*. Report prepared for USAID ASIA/DR/TR, by Development Technologies, Inc. Washington D.C.

Mekong River Commission. 1999. Lower Mekong Basin Forest & Land Cover, 1997. Edition 1, MRC & GTZ, Phnom Penh.

Mekong Secretariat. 1990. *Mekong mainstream development possibilities: Summary report*. Prepared for the Interim Mekong Committee for Coordination of Investigations of the Lower Mekong Basin, Bangkok.

Mekong Secretariat. 1992a. *Fisheries in the lower Mekong Basin.* Bangkok: Mekong Secretariat.

Mekong Secretariat. 1992b. *The lower Mekong Basin suspended sediment transport and sedimentation problems*. Report prepared by P.O. Harden and A. Sundborg for the Mekong Secretariat, Bangkok.

Mekong Secretariat. 1994. *Mekong mainstream run-of-river hydropower*. Bangkok: Mekong Secretariat.

MRC. 1994. *Lower Mekong hydrologic yearbook, 1994.* Phnom Penh : Mekong River Commision.

Nemani, R. R.; and S. W. Running. 1989. Estimation of Regional Surface Resistance to Evapotranspiration from NDVI and Thermal-IR AVHRR data. *J. Appl. Met.* 28: 276 – 284.

Nguyen Tat Dac. 1987. *Mathematical model of the tidal flow and salinity intrusion in the Mekong main branches by fractioned step method*. Report No. 9. Ho Chi Min City: Institute for Water Resources Planning and Management.

Olson, J. S. 1994a. *Global ecosystem framework-definitions*. USGS EROS Data Center Internal Report. Sioux Falls, SD, 37 p.

ORNL. 1999. *Hydro-climatic data network (HCDN): Streamflow data set.* Tennesee: Oak Ridge National Laboratory.

Osborne, M. 1996. *River road to China: The search for the source of the Mekong, 1866-73.* Singapore: Archipelago Press.

Oud, E. and T. Muir. 1999. Reservoir management and options for flood control. In: Flood Management and Mitigation in the Mekong river basin. *Food and Agriculture Organization of the United Nations*, RAP Publication 199/14, Bangkok, 165-168.

Pantulu, V. R. 1988. *Environmental problems associated with water resources development in the lower Mekong basin*. Proceedings of Management of Environmental Impacts of Water Resource Projects. Moscow, June 1988.

Pantulu, V. R. 1981. *Effects of water resource development on wetlands in the Mekong Basin.* Bangkok: Mekong Secretariat.

Pantulu, V. R. 1986. Fish of the lower Mekong Basin. In *The ecology of river systems* eds., B. R. Davies and K. F. Walker. Dordrecht, The Netherlands: W. Junk Publishers.

Piper, B. S.; A. Gustard; C. S. Green; and P. Sridurongkatum. 1991. Water resource developments and flow regimes on the Mekong river, In *Hydrology for the water management of large river basins*. Proceedings of the Vienna Symposium, August 1991. IAHS Publication 201, 1991.

Plinston, D. and H. Daming. 1999. Water resources and hydropower. Chapter in*: Policies and Strategies for the Sustainable Development of the Lancang River Basin,* Project TA 3139-PRC.

Roberts, T.R. 1993. Artisanal fisheries and fish ecology below the great waterfalls of the Mekong River in southern Laos. *Nat. Hit. Bull. Siam Soc*. 41: 31-62.

Rothert, S. 1995. *Lessons unlearned: Damming the Mekong River*. Working Paper 6. Berkeley, CA: International Rivers Network.

Running, S. W.; and R. R. Nemani. 1988. Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates. *Rem. Sens. Env.* 24: 347 - 367.

Running, S. W., D. L. Patterson; M. A. Spanner; and K. B. Teuber. 1986. Remote sensing of coniferous forest leaf area. *Ecology*: 67: 273 - 276.

Running, S. W.; R. R. Nemani; D. L. Peterson; L. E. Band; D. F. Potts; L. L. Pierce; and M. A. Spanner. 1989. Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. *Ecology* 70: 1090 - 1101.

SOGREAH/UNESCO. 1966. Mathematical model of the Mekong Delta: Comprehensive report of the different determinations of the Grand Lac capacity, Cambodia.

Sopharith, T.. 1997.Hydrological study of the Tonle Sap Great Lake. Report under Project CMB\95\003 "Natural Resources-Based Development Strategy for the Tonle Sap Area", Mekong River Commission, Phnom Penh.

Spanner, M. A.; L. L. Pierce; S. W. Running; and D. L. Peterson. 1990. The seasonality of AVHRR data of temperate coniferous forests: Relationship with leaf area index. *Rem. Sens. Envt*. 33: 97 - 112.

Su, M.; W.J. Stolte; and G. van der Kamp. 1997. *Modelling wetland hydrology using SLURP.* Proceedings of the scientific meeting of the Canadian Geophysical Union, Banff, Alberta, p. 198. Calgary: University of Alberta Press.

Tanaka, H.. 1999. Flood forecasting of the Mekong River in 1997. In: Flood Management and Mitigation in the Mekong river basin. *Food and Agriculture Organization of the United Nations*, RAP Publication 199/14, Bangkok, 109-117.

U.S. Army. 1972. *SSARR model, streamflow synthesis and reservoir regulation*. Portland: U.S. Army Corps of Engineers .

UNESCO/UNDP. 1969. *Mekong River Delta model study*. Report No. 9. Bangkok: UNDP.

University of Michigan. 1976. *Fisheries and integrated Mekong River Basin development.* Ann Arbor: University of Michigan, School of Natural Resources.

USAID. 1995. *Environmental assessment of the Lao PDR*. Washington D.C.: United States Agency for International Development.

Van mierlo M .C. L. M.; and H. J. M. Ogink. 1991. *Mekong master model, Volume 1.* General report prepared for the Mekong Secretariat, Bangkok.

Van Parreeren, D. 1977. *Computer program for the one-dimensional tidal model of the Mekong Delta.* Report to the Interim Mekong Committee, Bangkok.

Verhoef, A.; and R.A. Feddes. 1991. *Preliminary review of revised FAO radiation and temperature methods*. Report 16. Wageningen: Landbouwuniversiteit Wageningen.

Vreugdenhil, C.B. 1987. *Report of a mission on mathematical modelling for the Mekong River Basin.* Mission Report prepared for the Mekong Secretariat, Bangkok.

WMO. 1984. Proceedings of World Meteorological Organization workshop on MIT simulation model, MITSIM. Anna University, Madras.

Woodruff, D.; W. Rainboth; G. Davis; and S. Kuankachorn. 1993. *Recommendations for the Pak Mun Project.* Report submitted to the World Bank, November 19, 1993.

International Commission on Large Dams (1998). World Register of Dams, 1998. ICOLD, Paris.

Internet (References)

1. USGS GTOPO30 DEM: http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html
2. USGS land cover: http://edcwww.cr.usgs.gov/landdaac/glcc/glcc.html
3. NCDC climate data: http://www.ncdc.noaa.gov/cgi-bin/res40.pl
4. ORNL streamflow data: http://www-eosdis.ornl.gov
5. TOPAZ http://grl.ars.usda.gov/topaz/TOPAZ1.HTM
6. EROS http://edcwww.cr.usgs.gov/landdaac/glcc/glcc.html
7. NDVI http://edcdaac.usgs.gov/1km/comp10d.html
8. GDS (NCDC): http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?WWNolos~Product~CD-009
9. GDS/GSOD (IWMI Atlas): http://www.iwmi.org/p0000gds001.html
10. UEA Climate model outputs: http://ipcc-ddc.cru.uea.ac.uk/
11. GRDC http://www.bafg.de/grdc.htm
12. ORNL http://www-eosdis.ornl.gov
13. Long.P.P. (1999). The existing and future dangers to the Tonle Sap and the Mekong Delta. Mekong Forum, Bangkok. http://www.mekongforum.org/long5e.html.
14. Huang,G. and N. Tamai (1999). Application of Mike 11 to the lower Mekong River. http://www.dhi.dk/softcon/papers/013/DHI.html

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