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## REMOTE SENSING APPLICATIONS FOR FORECASTING THE AMOUNT OF RAINFALL OVER THE BLUE NILE BASIN

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*The main objective of this study is to forecast the amount of rainfall over the Blue Nile Basin using meteosat satellite images and to establish the reliability of these estimates when compared to observations. The Blue Nile Basin has been selected as a study area because it supplies 85% of the water to Aswan (Up Stream Egypt). Most of the current techniques for estimating rainfall from temperature of the cloud tops associate rainfall with cold (high) clouds, assuming that these are the tops of active storms. Four techniques are applied here for estimating the amount of rainfall over the Blue Nile Basin on daily basis. These techniques have been tested and calibrated with raingage data and the results show that there are some differences between the raingage data and the satellite estimates. Two techniques (Nfs-clim and GPI) gave better results, but some differences vary from month to month and year to year. The correlation coefficient between the satellite estimate and raingage observed mean areal precipitation over the Blue Nile Basin is found to be 0.65. One of these techniques (Nfs-clim) is applied here to forecast the amount of rainfall over the Blue Nile Basin. Work is currently underway to improve rainfall forecasts by collecting more data and including other satellite images.*

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## **INTRODUCTION**

Rainfall is the one of the noisiest meteorological parameters whether considered through space or through time, yet one of the most important in agrometeorology. However, it is vital for many purposes in the fields of environmental monitoring and renewable resources management to evaluate rainfall as accurately as possible.

Of particular importance are evaluations of rainfall in support of hazard monitoring (especially related to flash floods, droughts, and insect pest infestations), hydrology and water management (especially groundwater recharge, reservoir recharge, and basin run-off), and crop production and food security assessments.

The demand for improved information on rainfall is so strong that satellite rainfall monitoring techniques have developed since the late 1970s to ensure that satellite data can be used effectively.

Studies of water balance on a global scale require information on precipitation where gage or radar networks are inadequate or non existent, such as over oceans.

Satellites cannot measure precipitation directly, and their use for estimating it is based on relating brightness of cloud photographs to rainfall intensities. The degree of brightness is an indication of the temperature, or height, of the cloud tops. The brighter the image, the higher the cloud top. The tallest and densest clouds produce the heaviest rainfall intensities. The relation between brightness and rainfall intensity is usually determined by calibration with gage measurements.

The number of rainfall gages located in the Blue Nile Basin are not adequate to estimate the rainfall expected over the area and are not representative of this huge area. Even where rainfall gages exist, the data are not arriving continuously in regular way. This lack of adequate data is a major problem considering that rainfall is the main input to the hydrological models used to predict and simulate the flow, not only at the High Aswan Dam, but also at the hydrological stations located in the Nile Basin. So, it is essential and necessary to use remote sensing applications to forecast the expected rainfall over any selected area.

The main objectives of this study are to:

- 1- Forecast the amount of rainfall expected over the Blue Nile Basin using different techniques.
- 2- Compare the satellite estimates with the observed data at the available stations located in the Blue Nile Basin and on the scale of the mean area precipitation.
- 3- Carry out statistical analysis for the satellite estimates and the observed values to get the best (proper) technique which will be used in the forecasting system.

## **THE STUDY AREA (BLUE NILE BASIN)**

The Blue Nile Basin has been selected to be the study area, because it supplies about 85% of the water to the High Aswan Dam. It has an area of 324,530 km<sup>2</sup>, covering most of the Ethiopian plateau. Most of the rain occurs in a few months, primarily from June through September. There is a very strong influence of the topography on storms during this period, and there is a significant correlation of rainfall with topography as a result. The Blue Nile and its tributaries all rise on the Ethiopian Plateau at an elevation of 2,000 meters. Volume VIII of the Nile Basin (Hurst, 1950) mentions that the source of the Blue Nile is a small spring at an elevation of 2,900 m about 100 km south of Lake Tana.

The Blue Nile has its source at Lake Tana in Ethiopia, enters the Sudan across its eastern border with Ethiopia and flows in a northwesterly direction to Khartoum, where it joins the White Nile to form the Main Nile as shown in Figure 1. The total length of the Blue Nile in the Sudan is about 700 km, and it has two main tributaries, the Rahad and Dinder Rivers, which join it between Sennar and Khartoum.

The Blue Nile derives practically all its flow from the highlands of Ethiopia where there is an intense summer rainy season. This, combined with the steep topography of the catchment, causes the annual flow pattern to have a very sharp seasonal peak in the late August, with 80% of the annual discharge passing in the four months July to October.

### SATELLITE DATA

Since 1992, two kinds of satellite data were received:

1- Satellite images in three different spectral bands, infrared, visible, and water vapor, are received through the Primary Data User System (PDUS). The PDUS is a system for real-time acquisition, processing, quality control, display, storage and automatic transfer of the satellite image data. It provides on-line real-time images every half an hour, where 47 images are received daily (European

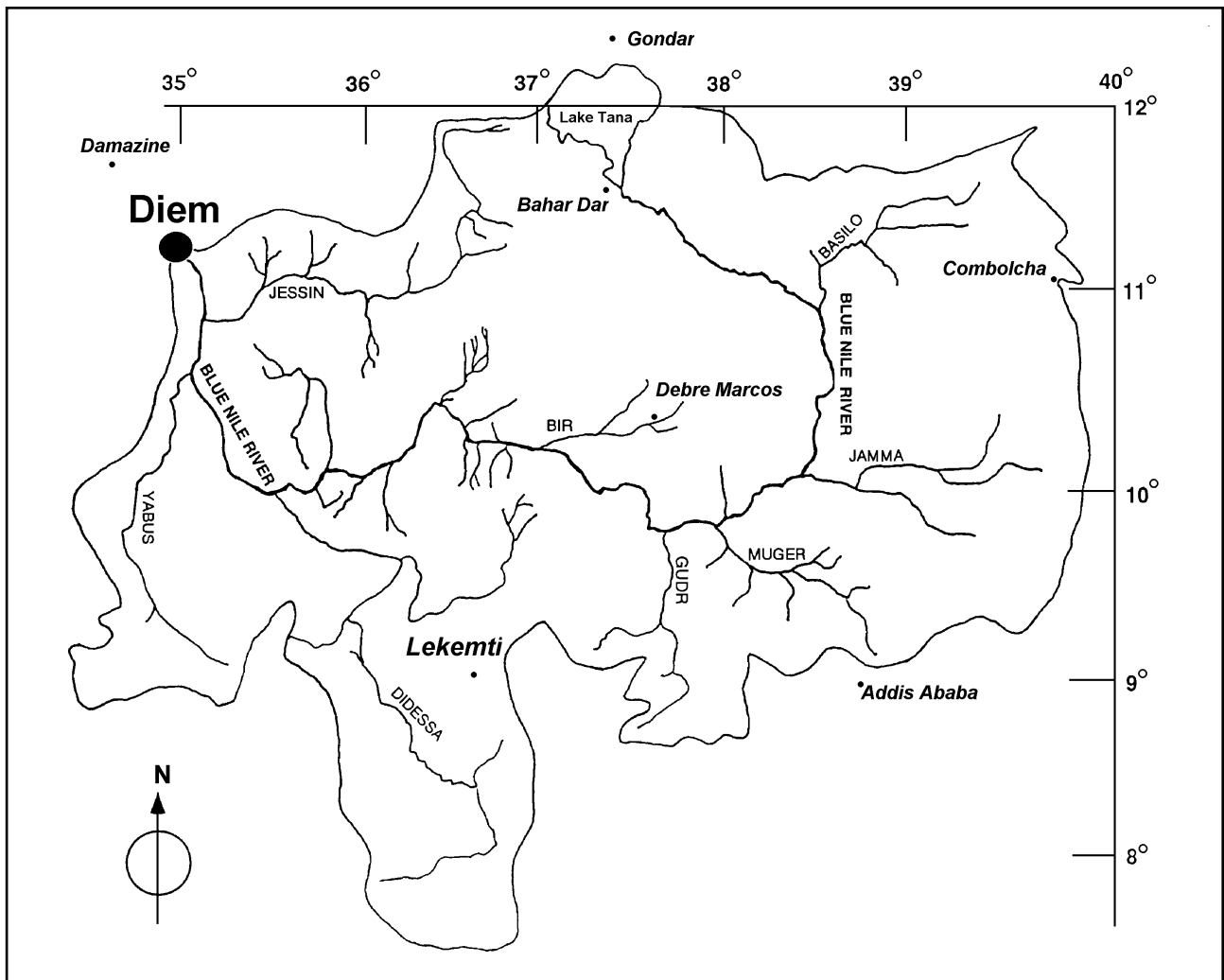


Figure 1. Blue Nile River Catchment with outlet at Diem, Sudan (part of the drainage area of Lake Tana is shown).

Space Operations Center: “Meteosat High Resolution Image Dissemination”, 1989).

2- Real time meteorological data observed at the network of synoptic stations located in the Nile Basin are received through the Meteorological Data Distribution system (MDD). The MDD system is considered the main source of the measured rainfall data from different meteorological stations located in the Nile basin outside Egypt. Similarly, weather forecast and analysis maps received through the MDD are of great importance for assessing present and predicting future meteorological conditions in various areas of the Nile River Basin.

In this study, selected data from these sources were used. Two months in the flood season (June-September) and sample days in July and August from 1992 to 1996 were selected to estimate the daily rainfall for these months. This was done because of the large size and number of satellite images needed for the forecasting techniques (about 0.3 MB for each and 47 IR images /day).

## **PROCEDURE AND RESULTS**

To forecast the amount of rainfall from the satellite images which is expected over a grid point, and validate these estimates using the observed data, the following procedures were used.

### **Restoring the Satellite Images**

These images are on archived 8 mm tapes with specific procedure, order and sequence. Most of the work was done on the IBM workstation to carry out image analysis. In the retrieve program, used to restore the required satellite images, only the infrared for the Blue Nile Basin was used. The satellite images were prepared for image processing in a sequential manner and spatial format. Figure 2 shows one of the infrared satellite images for the Blue Nile Basin during the flood season.

### **Image processing stage**

Before archiving these images, some initial processing was applied :

- Modifying: the image was thresholded according to a selected table. Thresholding is a method of reducing an image into a small number of intervals/levels.

- Filtering:

• Smooth Filtering: the image was smoothed to a simple 3 x 3 kernel with equal weighting of points.

• Edge Filtering: the differences of edges and highlighting were detected.

• Median Filtering: a value was replaced by the median of itself and its neighbors either in a one dimensional horizontal or vertical structure or in a sequence structure and noise errors were removed.

- Contour processing: the points were compared with their neighbors. If the point was equal to any of its neighbors, the point was made as a point on the contour (Bradford University Research Ltd: “Tekor: BURL Processing System for Satellite Data Ver. 3.6”, 1991).

Some image processing to control the quality of the images was executed after restoring the satellite images. The quality control processor identifies lines that are bad in the image, but does not correct these bad lines. It uses the quality control information provided by the PDUS within each image line and then corrects the image when possible. The images from the PDUS are transmitted at a scheduled time and stored. The quality control processor begins processing, using the stored satellite data on the previous day’s PDUS images, thus making relatively sure that a full day’s data are available.

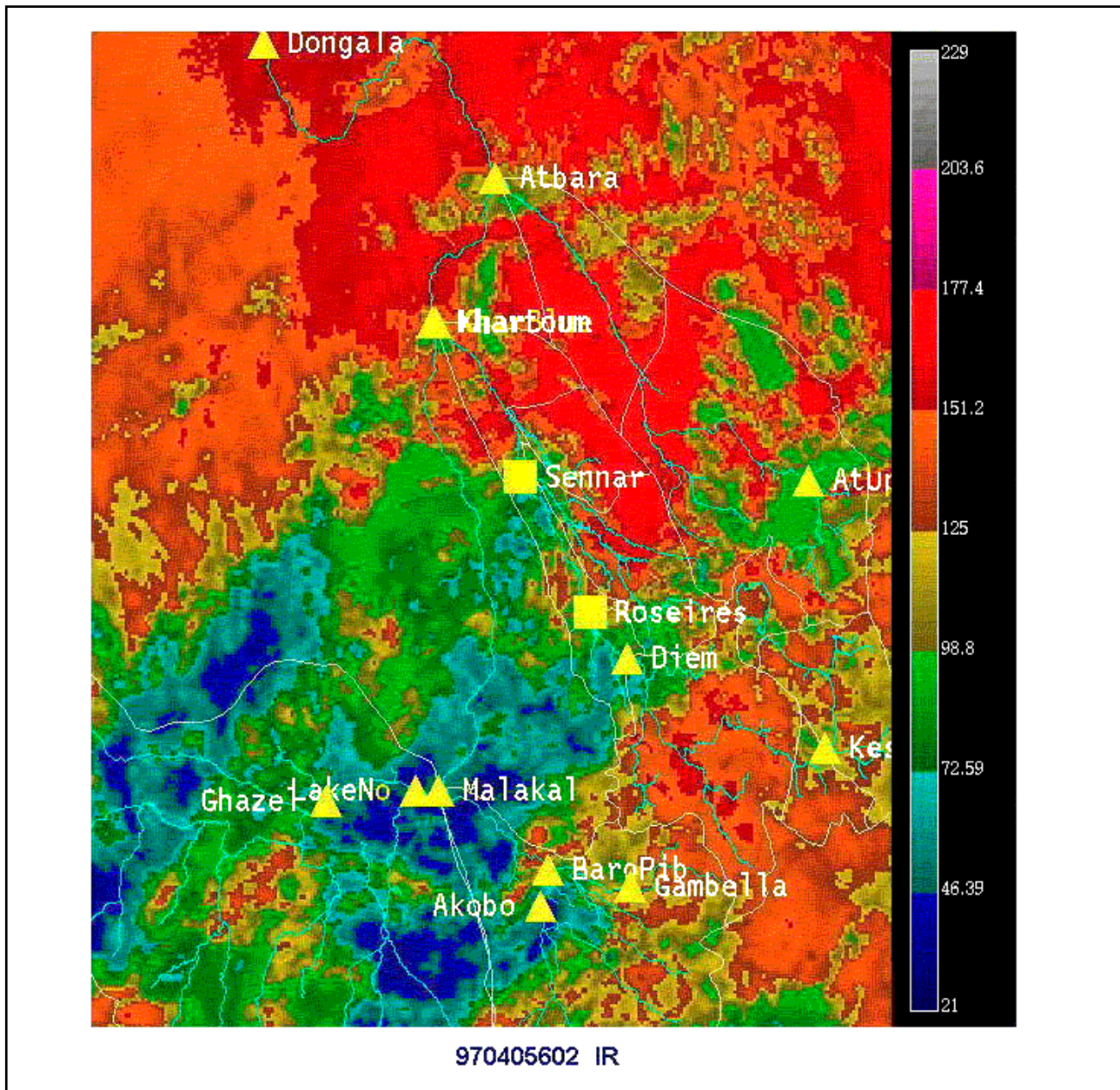


Figure 2. One of the infrared satellite images for the Blue Nile Basin during the flood season (1997).

The quality control processing also removes bad data lines that were damaged due to communications (Green-Newby, 1992). Images that contain bad lines are corrected by replacing the bad lines with lines above and below the affected line. Images with data gaps of more than eight lines are not being used at this time. If the first image line is bad, it is replaced with the next line. Likewise, if the last line in an image is bad, it is replaced with the previous line.

### Compute Cold Cloud Duration (CCD) for the Processed Images

The computation of the CCD for the processed images defines the number of hours that the infrared brightness temperature is colder than a given temperature. The threshold temperature may be expected to vary for different types of rainfall situations.

Most of the climatological techniques base their estimates on the premise that cold cloud durations are proportional to rain amounts. Therefore, long cold cloud durations would relate to more rainfall. This is shown in Figure 3.

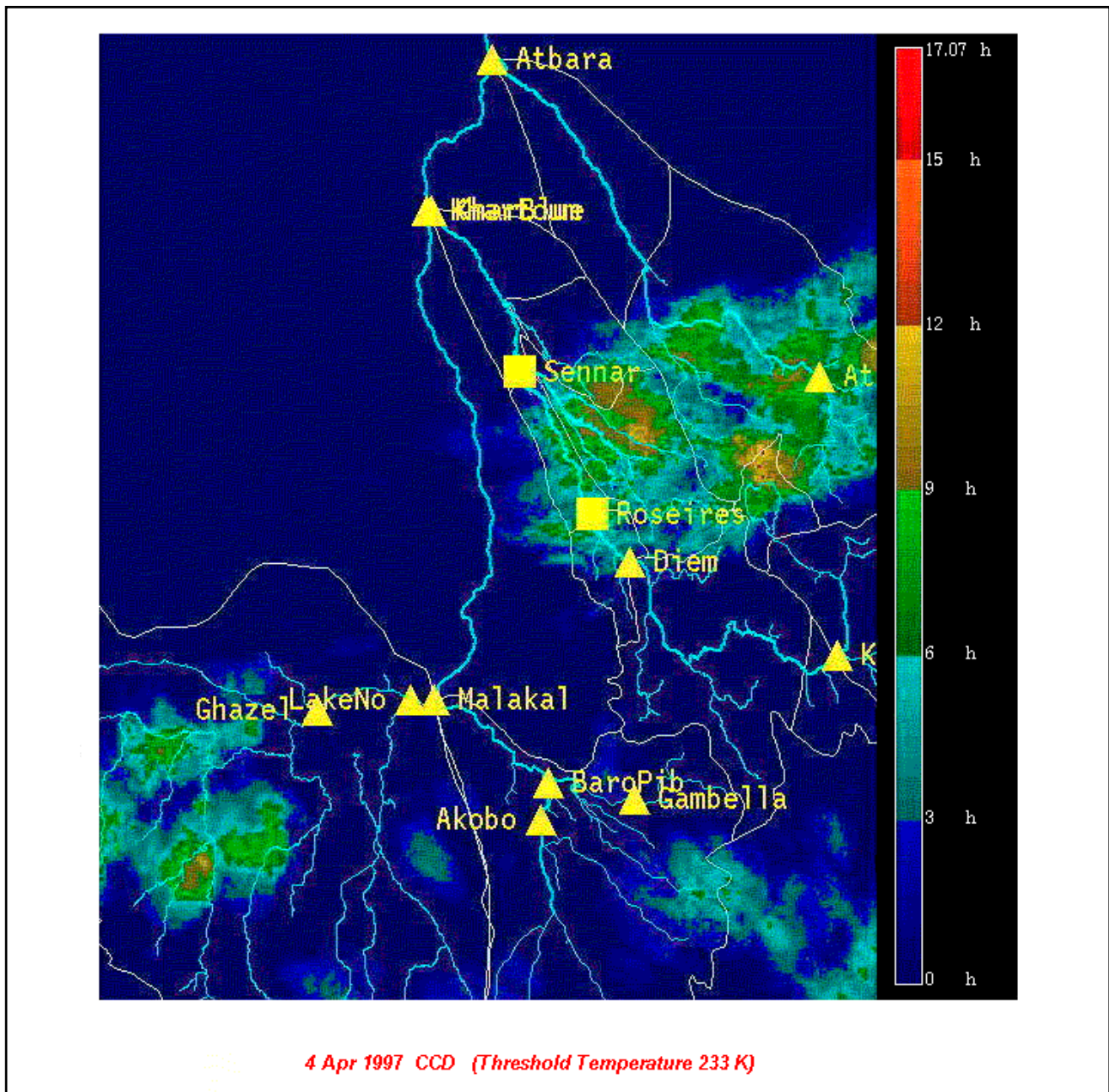


Figure 3. Cold cloud duration (CCD) image for the Nile Basin during the flood season (1997).

**Estimate the amount of rainfall over every grid point (5x5 km):**

Four techniques to forecast the rainfall from the infrared satellite images are used. These are:

1- The Nile Climatological Method (Nfs-clim)

The Nile Climatological Method (Nfs-clim) technique produces precipitation estimates that match the climatology of precipitation estimates based on analysis of rain gage observations.

Each of the existing CCD-based methods assumes there is a linear relationship between precipitation, P, and CCD:

$$Y = B + A * X \tag{1}$$

Where Y is P and X is CCD. The strategy used in this technique estimates gridded fields of the

statistics for least squares or regression analysis and translates these into gridded fields of the parameters  $A$  and  $B$ . The regression equations for  $A$  and  $B$  are:

$$A = P_{XY}(d_Y/d_X) \quad (2)$$

$$B = Y' - A\bar{X} \quad (3)$$

These equations involve the climatological means and standard deviations of  $X$  and  $Y$  and the coefficient of correlation  $P_{XY}$  between them. Alternative, equivalent equations for  $A$  and  $B$  are:

$$A = P_{XY}(Y'/\bar{X})(C_{VY}/C_{VX}) \quad (4)$$

$$B = Y'(1 - P_{XY}(C_{XY}/C_{VX})) \quad (5)$$

This form of the parameter equations is particularly useful because the means and coefficient of variation can be estimated from 10-day and/or monthly P and CCD data.

In the case study of the Blue Nile,  $Y'$  and  $C_{VY}$  were estimated from the available monthly average precipitation data and available monthly precipitation data, while  $\bar{X}$  and  $C_{VX}$  were estimated from available 10-day CCD data.

Estimating the correlation coefficient ( $P_{XY}$ ) is not a simple matter. The strategy in the Nile Climatological Method is to treat  $P_{XY}$  as a variable parameter. First a value is assumed, gridded estimates of  $A$  and  $B$  are produced and estimates of 10-day P are made from 10-day CCD using equation (1). The correlation coefficient between areally averaged values of these estimates and corresponding gridded estimates of P is computed. The correct correlation coefficient is assumed to be the value that occurs when the computed value of the correlation coefficient agrees with the assumed correlation coefficient.

This method was applied to 10-day data for the Blue Nile for the years 1988 and 1989, when reasonably accurate estimates of the basin average 10-day P were available. The correlation coefficient between gage-based estimates of basin average precipitation and satellite-based estimates for all of the available 10-day periods in 1988 and 1989 is about 0.8 and this is roughly equal to the assumed correlation coefficient used to estimate the satellite parameters for each pixel (Schaake and Newby, 1993).

When this method was applied for the Blue Nile Basin in July and August (1992-1996) to estimate the daily rainfall over every grid point it gave good results compared with the observed. Figure 4 shows one of the outputs for the daily satellite estimates using the Nile Climatological Method over the Nile Basin.

## 2- Goes Precipitation Index (GPI)

The Goes Precipitation Index (GPI) is a straightforward technique that assigns a 3 mm/hr rain rate to every pixel that passes the 235 K threshold (Arkin, 1979).

The Arkin equation is modified to :

$$R_{GPI}(mm) = 3.CCD \quad (7)$$

As the Nile River Basin is a small area in relation to global estimates, the rain amounts are directly

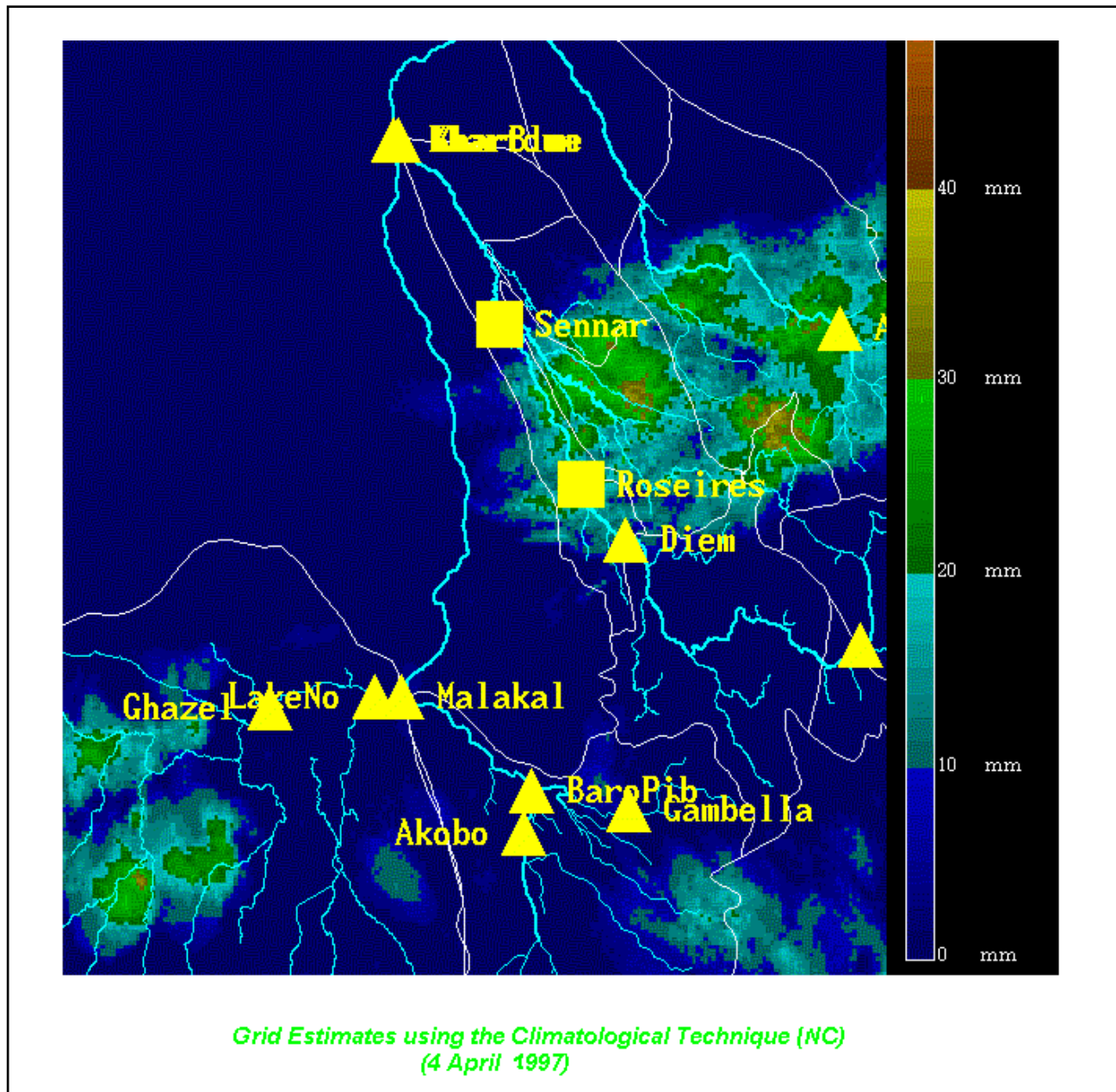


Figure 4. Output for the daily satellite estimate over the Nile Basin.

assigned to each pixel that passes the threshold temperature. Cold cloud duration grids are produced for  $-38^{\circ}\text{C}$  (235K). Daily rain estimates are produced and summed for 30-days to be used with the Nile Hybrid (using a correction factor for any daily technique).

The results obtained from this technique are also not bad if compared with the observed as shown in Figures 5 to 8.

### 3- Convective-Stratiform Technique (CST)

The Convective-Stratiform Technique (CST) uses Meteosat infrared imagery to identify thunderstorm cloud tops and assign corresponding rainrates (Adler and Negri, 1988).

Minima in the brightness temperatures are determined to be convective centers (thunderstorms). If a minimum, less than 235 K, encompasses more than one infrared (IR) pixel, the location of its



centroid is used. An empirically derived slope parameter is calculated for each minimum to exclude cirrus clouds.

The average rain rate over the rain area of a cell is based on calculations using volume rainfall rates (generated by the model) and dividing by the convective rain area. The rain rates are assigned in a spiral fashion, from the convective center outward until the calculated areal extent is filled.

To separate convective from stratiform precipitation, a mode temperature is derived from the satellite data. These pixels that are not convective but have passed the cirrus slope tests are assigned a stratiform rain rate.

The rain rates are calculated based on a one dimensional cloud model. This takes into account such physical properties as ambient temperature, moisture and shear conditions, that provide a stronger physical basis for the cloud-height/rain relationships.

The convective rain area,  $A_r$ , is assumed to be five times the model updraft area (Adler and Mack, 1984):

$$A_r = 5p r^2 \quad (7)$$

Where  $r$  is the model updraft radius. Based on cloud model runs using Florida data, average rainrates are computed for the total area of the cell as:

$$R_{mean} = 74.89 - 0.266T_c \quad (8)$$

$$T_c = .717T_{min} + 56.6 \quad (9)$$

Where  $T_c$  is a new corrected small scale temperature. Also, some runs were done by this technique for July and August (1992-1996) to estimate the daily amount of rainfall over every pixel, but there were big differences between the estimates and the observed. Most of the estimates were above the observed value and the long term average mean, but the trends were the same.

#### 4- Nile Hybrid (HB)

The Nile Hybrid (HB) technique is a specific application of the Progressive Refinement Technique (Bellerby and Barrett, 1993). It is a strategy designed to combine short-term and long-term satellite rainfall estimates.

All satellite techniques are based on the concept that cold temperatures in the satellite imagery identify convective clouds that produce rainfall. Therefore, a common factor to all techniques is the identification of the cold clouds. The duration of the cold clouds is a factor incorporated into the Nile Hybrid technique as a basis for a climatological estimate of rainfall.

It is conceivable that monthly climatological estimates could be divided into daily estimates and used in the hydrological models. However, this method would not address the problem of distribution of rainfall on a daily basis.

The HB technique combines the advantages of a longer term 30-day climatological estimate with the temporal variability of CST. Although CST is a complex technique, it was designed to be used on smaller temporal scales, limited only by how often the satellite imagery is received. This fact, coupled with a discrimination function to eliminate cirrus clouds commonly associated with thunderstorms in the Blue Nile Basin, led to the use of this technique as the basis for daily satellite estimates. The HB technique will take the following form:

$$HB \text{ Daily Rainfall} = CST_{day} * [S \text{ Climate}(D) / S \text{ CST}(D)] \quad (10)$$

The 30-day climate estimates are derived using cold cloud duration (CCD) gridfiles.

$$\text{Where Climate} = \{a(x,t) * CCD(t) * Orographic \text{ Correction}\} \quad (11)$$

The first term has been statistically derived specifically for the Blue Nile Basin using available raingage gridfiles from the office of Hydrology, historical cold cloud duration data from the University of Reading, and archive PDUS data from the University of Bristol. This factor varies from pixel to pixel and the value at each pixel will change for the flood and non-flood season.

In addition, the climate estimates will use an orographic correction factor developed by Schaake (1993) that statistically relates elevation, historical rainfall and cold cloud duration data.

The runs which were done using this method for July and August (1992-1996) gave good results but they tended to be below the observed and the long term mean average.

### Analysis of results

After getting the estimates using different techniques over the grid points, we developed a small program to read the gridfiles and get the corresponding rainfall value at the six stations located in the Blue Nile Basin. The average value for the satellite estimates, which represent the Blue Nile catchment area and the corresponding observed average, were taken to test the reliability of the satellite estimates.

On the scale of the rainfall gages as shown in Figures 5 and 6, when the observed and satellite estimates at every station point are compared, the following was found:

The CST technique results, for the period 1992-1996, were above the observed values with large differences and with a correlation coefficient of 0.47. The HB technique results, for the period 1992-1996, were below the observed values with some differences, especially at the peaks, with a correlation coefficient of 0.43. Nfs-clim and GPI results fluctuate around the observed values with a correlation coefficient of 0.69 and 0.56 respectively.

On the scale of the average basis as shown in Figures 7 and 8, the graphs show a comparison between the satellite estimate and the observed values (average basis). The difference between the observed and the estimated is noticeable. This difference varies from day to day and month to month but the trend was found to be almost the same.

For example, in July and August 1994, the results of the CST technique were high above the observed values and the results of the Nile-Hyb technique were slightly lower than the observed values. The results of the two other techniques were close to the observed values.

In July and August 1995, there were significant differences between the CST and Nile-Hyb estimates and the observed values. On the other hand, slight differences were seen between the two other techniques and the observed values.

In 1996, large differences between CST and Nile-Hyb and the observed values were seen. Nfs-clim and GPI results were close to the observed values with correlation coefficients of 0.65 and 0.47 respectively.

From the above results the reliability of the Nfs-clim and GPI techniques estimates was evaluated. They tended to give better results when compared to the observed values.

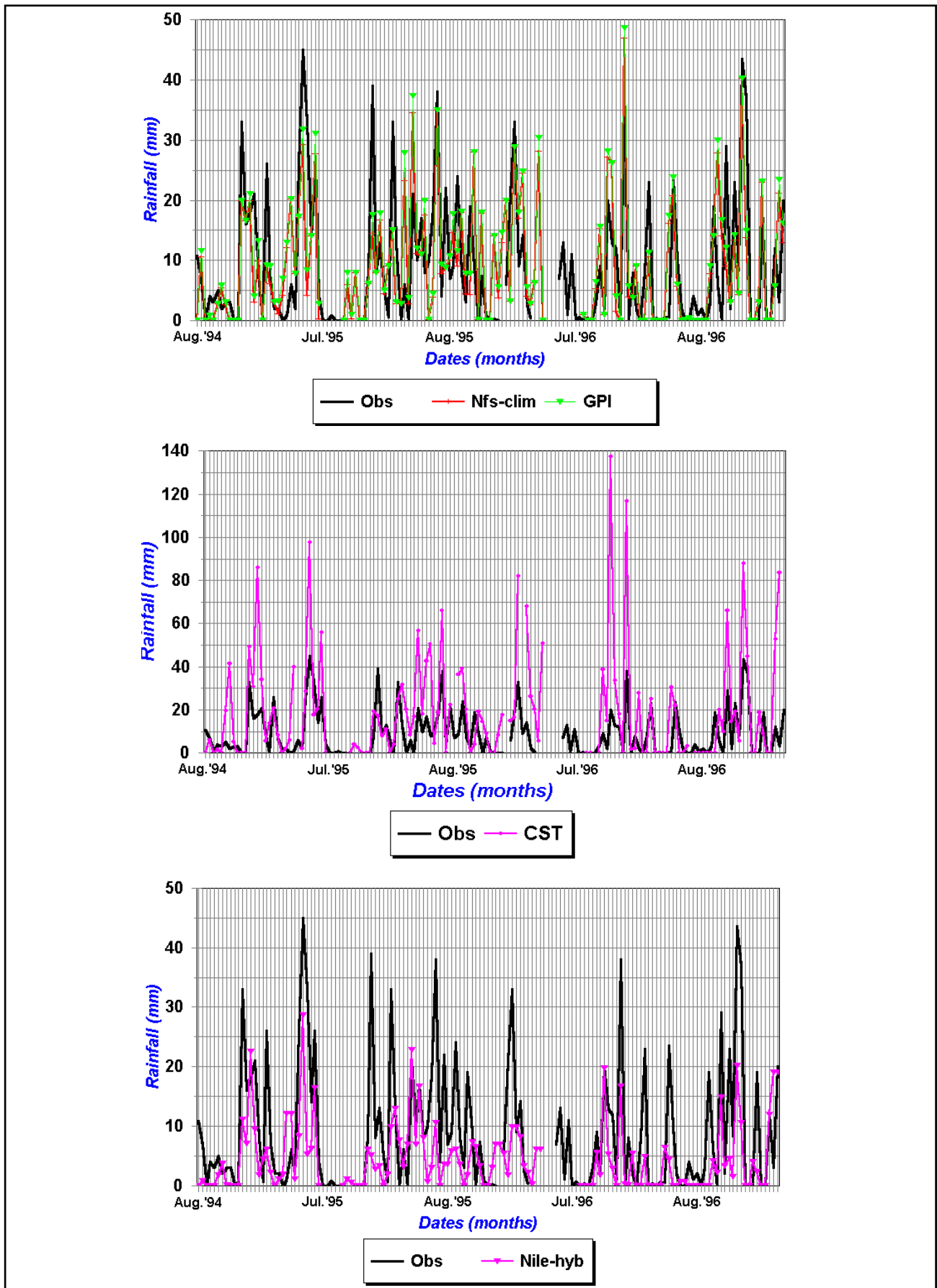


Figure 5. Comparison between satellite estimates and the observed (Camblocha Station).

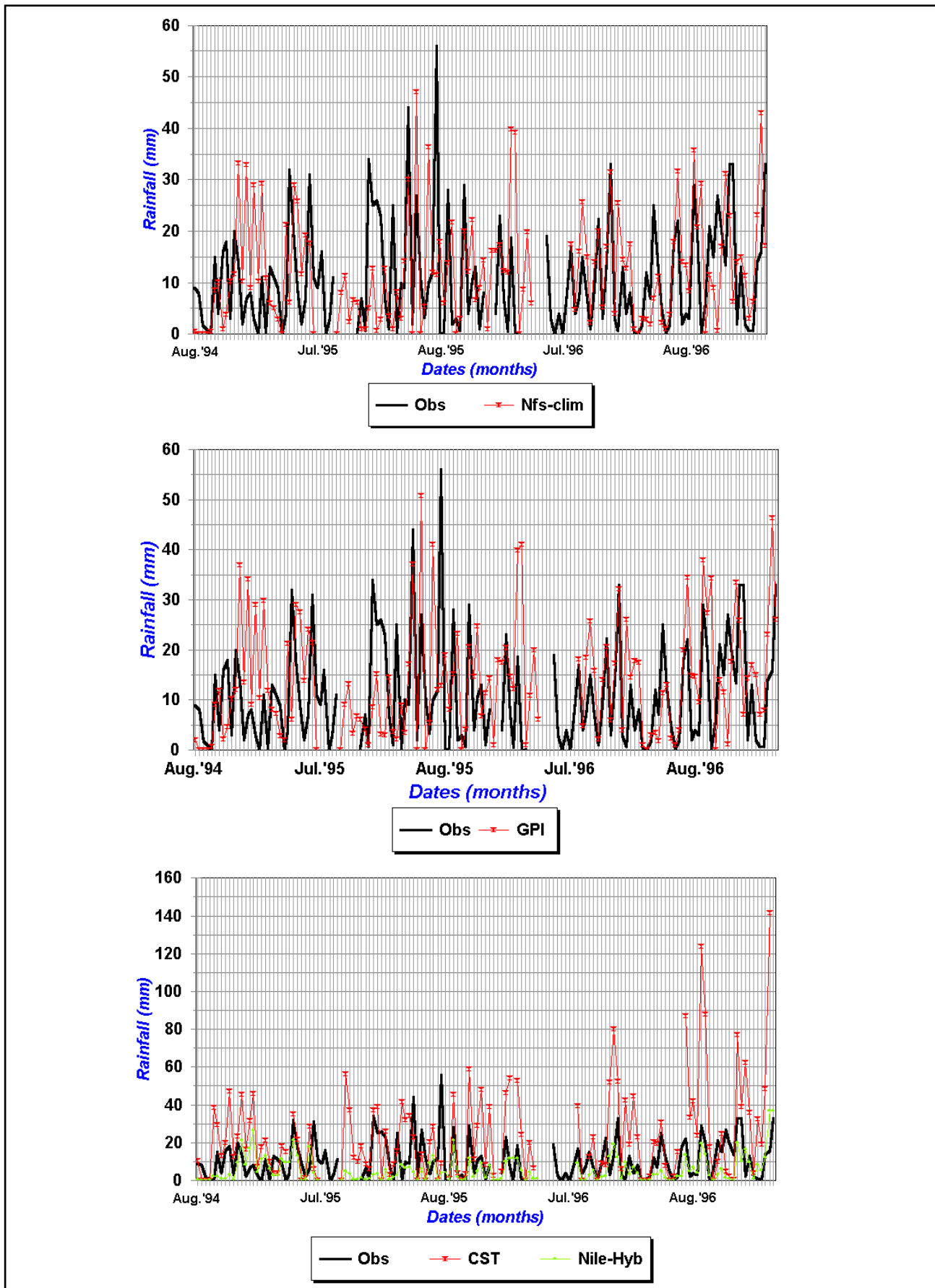


Figure 6. Comparison Between satellite estimates and the observed (Bahar-Dar Station).

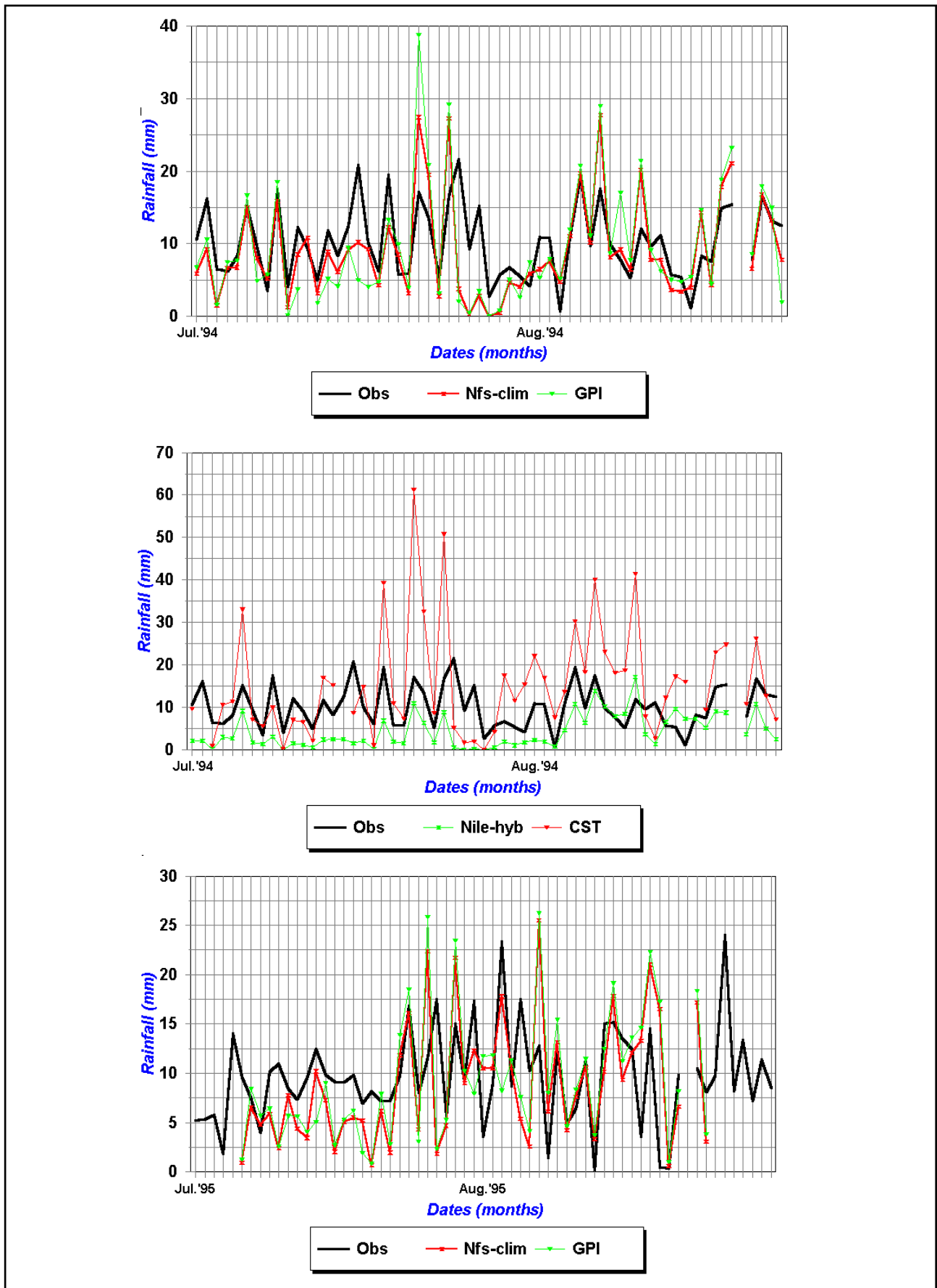


Figure 7. Comparison between satellite estimates and the observed (average-basis).

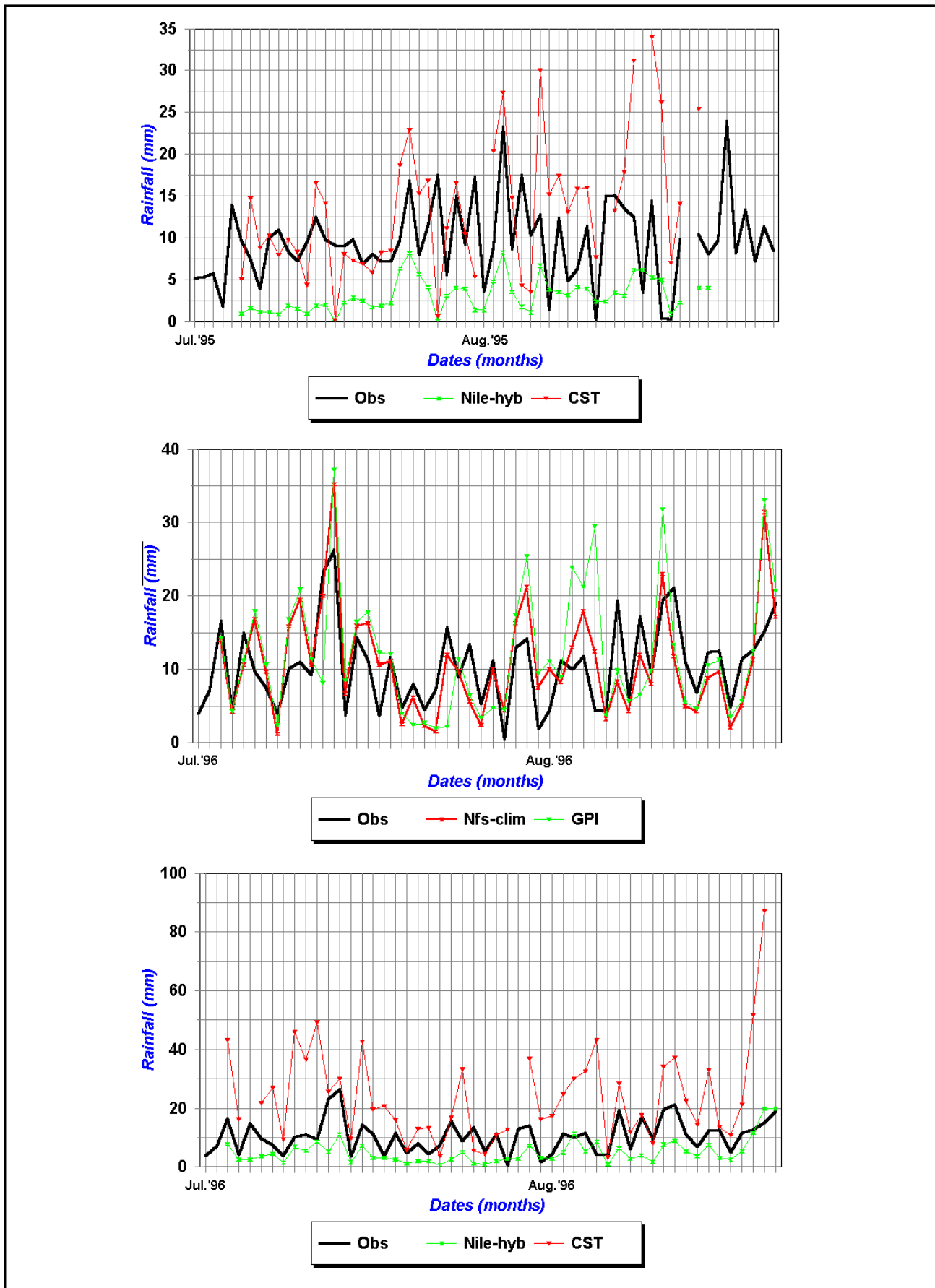


Figure 8. Comparison between satellite estimates and the observed (average-basis).

## CONCLUSION AND RECOMMENDATIONS

A 300-day series of satellite rainfall estimates for the Blue Nile Basin catchment area was used to identify the rain gauge-satellite rainfall error structure and find the proper technique which best matches with the observed. Good results were obtained.

Satellite rainfall was estimated for the July and August period (1992-1996) as sample days for the flood season. Rain gauge data were used to evaluate the reliability of the satellite estimates. The principal conclusions are:

Most of the study results had the same trend, but there was a difference between the estimates and the observed values. Factors which should be taken into account in the analysis of these results are:

1- The uncertainty in the rainfall estimate technique due to calibration and the lack of data needed to make some validation and calibration.

2- The reliability and accuracy of the observed rainfall at the gage stations located in the study area.

3- The number of rainfall gages in the Blue Nile Basin is not sufficient to represent the huge catchment area, the availability of data is not continuous, and there were some missing data.

4- Transformation from the meteosat coordinates to latitude and longitude coordinates.

5- Transmitting the satellite images from the European Space Agency after the initial processing.

The above factors should be taken into account during studying and analyzing the results to validate the estimates.

From this study, it was found that only two techniques of the four applied could be used to estimate the amount of rainfall expected at every grid for the Blue Nile catchment area. These techniques are:

- Nfs-clim (Nile Climatological Method) is the most suitable technique for the Nile Basin, as it gave good results (on the average basis or at every rainfall gage). The correlation coefficient varies from 0.58 to 0.69 which is good at this stage in rainfall estimation.

- GPI (Goes Precipitation Index) is also a quite good method that may be easier to apply than the Nfs-clim technique, but is less accurate. The correlation coefficient varies from 0.32 to 0.56.

- The two remaining techniques (CST and HB) did not give good results. Significant differences existed and low correlation coefficients were found.

For these reasons, only the Nfs-clim technique is now used in the Nile forecasting system to forecast the rainfall at every grid point. This is the main input to the hydrological model to predict and simulate the flow at some predefined stations along the Nile Basin.

## RECOMMENDATIONS

The recommendations for this study are as follows:

1- Encourage the availability of a significant continuous record of satellite data to support study and research.

2- Passive microwave measurements for adjusting infrared rainfall estimates with microwave measurements should be used (Adler *et al.*, 1994).

3- The two other kinds of satellite images (visible and water vapor) are to be used with the infrared image to make some enhancement and improvement in the interpretation of the clouds.

4- The application of other techniques (recent methods), which is under study and development in the United States, to improve the satellite estimates using a pair of satellite infrared and visible images, is a necessity.

5- Future research should address 1) the issue of reducing the impact of satellite errors in simulation and prediction by using stream flow measurements and state estimators to update soil water estimates in real time, and 2) merging satellite rainfall estimates with sparse raingage data to improve mean-areal rainfall estimates.

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