COMPARISON OF ACRU AND HEC-HMS MODELS IN RUNOFF PREDICTION IN A WATERSHED, SOUTHWEST NIGERIA

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ABSTRACT

The frequency in the occurrence of hydrological extremes has necessitated the use of models to forecast and mitigate such disasters. Agricultural Catchments Research Unit (ACRU) model and Environmental Hydrology, University of Natal and the Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) were used to simulate runoff from Agbogbo catchment in Ile-Ife (Southwestern Nigeria). The objective of the study was to compare both models performance in simulating streamflow in the Agbogbo catchment. Model input data for both models were obtained and used for model simulation. Three years streamflow records were obtained for Agbogbo catchment and used for calibrating and validating the models. Data for the first hydrologic year (April 1987–March 1988) was used to calibrate the two models while that of the two remaining years was used for validating the models. When the Nash-Sutcliffe Model Efficiency Coefficient was used to evaluate the performance of the models, a value of 0.83695 and 0.78232 was obtained for the ACRU model simulation for the 2nd and 3rd hydrologic years while values of 0.87748 and 0.54706 were obtained by the HEC-HMS model for the two periods. ACRU model performed better with an overall (April 1988–March 1990) model efficiency coefficient of 0.81218 when compared with that of HEC-HMS which was obtained to be 0.71498. When the hydrographs of the observed and simulated streamflow were compared, ACRU model showed more sensitivity to changes within the catchment as demonstrated by the similarity in the timing of the peaks than HEC-HMS, which implies that ACRU model can be used for flood forecasting in Agbogbo catchment.

KEYWORDS: Digital elevation model, agrohydrology, unguaged catchments.

1. INTRODUCTION

Continued land development and land-use changes within cities and at the urban fringe present considerable challenges for environmental management (Muthukrishnan et al, 2006). With increasing population and industry, the demand for water has increased prodigiously thereby imposing a higher efficiency in the planning and management of water resources. With streamflow accounting for only 0.006% of freshwater resources (Gleick, 1996), realistic and accurate streamflow forecasts have become an essential tool for water resources planning and management (Hobson, 1997). The prospect of adverse climate change is not going to diminish in the near future (Downing et al, 1997). Climate change could alter the timing, magnitude and duration of rainfall and other weather events. All evidence shows that climate variability has increased to such a degree that predictability of water availability has been reduced dramatically: weather extremes are shifting and intensifying, and thereby introducing greater uncertainty in the quantity and quality of our water supplies over the short and the long term (United Nations, 2009).

Hundreds of rainfall-runoff models have been developed throughout the world, especially in Europe to provide river flow forecasting (Beven, 2001). Hydrological models have been developed to improve our understanding of surface runoff generated from complex watersheds, make efficient and cost effective quantitative estimates of water resources of unguaged catchments, and to plan, design, operate and manage water related structures.

Our ability to predict the hydrology of streams in future climates depends in part on our ability to model present circumstances. The comparison of observed to modelled streamflow provides insight into model performance and the ability to predict hydrologic attributes that might be of interest in future scenarios and extreme events (Whitfield *et al*, 2003).

To gauge how well simulations perform requires rigorous assessment, and setting benchmark against which to measure success. Model validation is essential to the interpretation of simulation results. It illuminates under what circumstances a model reproduces events accurately and under what circumstances it performs unsatisfactorily. Validation is also critical to the improvement of models; the modelling community cannot improve models if it does not know how, where, and when they fail (Gordon *et al*, 2004).

The objective of the study was to compare performance of the HEC-HMS and ACRU models in simulating stream flow in Agbogbo catchment, south eastern Nigeria.

ACRU model (Schulze, 1989) was used in this comparison because it was developed in Africa and has been validated for several catchments in many parts of Africa. As a result of the dendritic drainage pattern of Agbogbo catchment, HEC-HMS (Scharffenberg and Fleming, 2010) which is a model developed for that kind of drainage geomorphology was also selected for this study.

2. MATERIALS AND METHODS

2.1 ACRU Model

Agricultural Catchments Research Unit (ACRU) model (Schulze, 1989) was developed by the former Department of Agricultural Engineering, now School of Bioresources Engineering and Environmental Hydrology, of the University of Natal in South Africa. It is a physical-conceptual rainfall-runoff model that simulates stormflows and baseflows explicitly, with a modification enabling the simulation of through flow (New, 2002).

The ACRU model is a multi-purpose and multi-level integrated physical conceptual model that can simulate streamflow, total evaporation, and land cover/management and abstraction impacts on water resources at a daily time step. ACRU is highly versatile with potential applications ranging from streamflow simulation, to crop yield estimations, irrigation estimations, risk analysis etc. It has been mostly applied in the temperate and humid parts of South Africa and has been frequently used for assessing the impacts of various land use modifications, specifically commercial afforestation (Hugh, 2002).

The ACRU modelling system is made up of a number of discrete, but interlinked components. The linkages and components are illustrated in Fig 1.

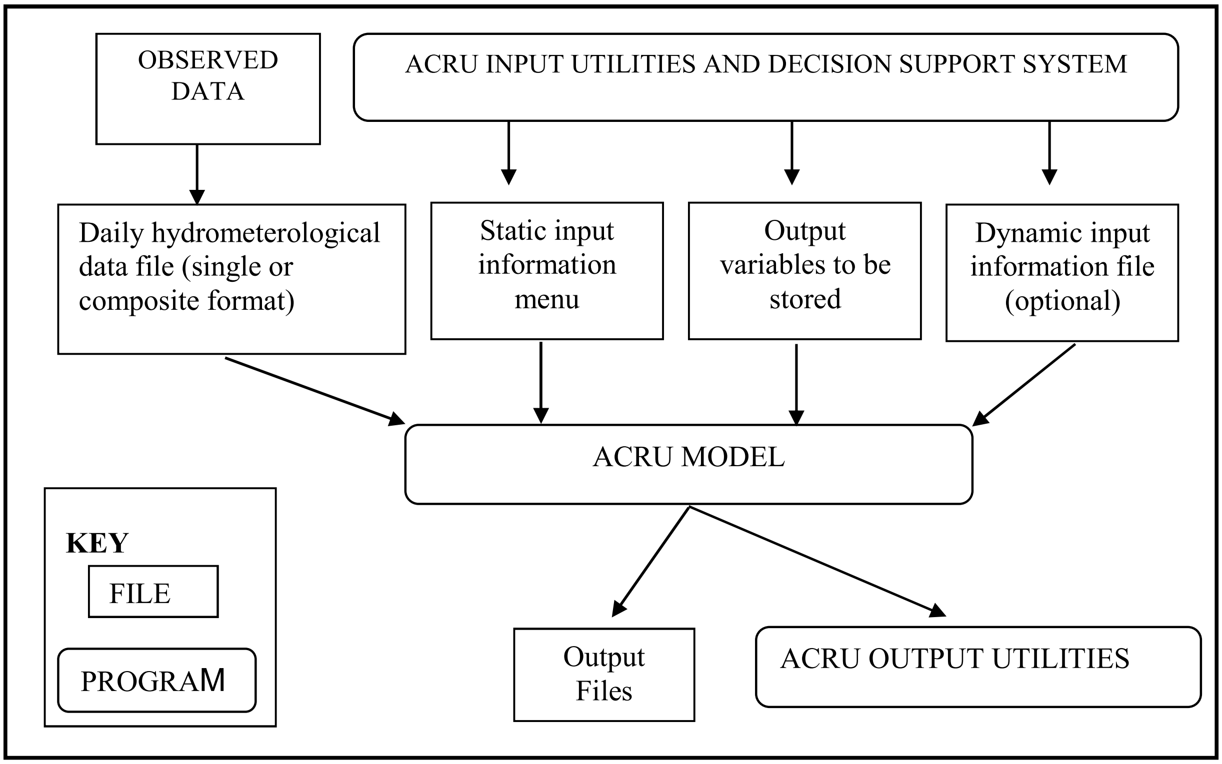


Fig. 1**:** Components and Linkages of ACRU Modelling System (Smithers *et al*, 1994)

The minimum daily input requirements are precipitation and potential evaporation. Parameter values for evapotranspiration, soil moisture budgeting and runoff generation are also required. ACRU simulates soil moisture in a vertical, two-layer soil column. Incoming rainfall is subject to interception by vegetation depression storage. The remaining rainfall infiltrates the upper soil horizon, and subsequently, moisture in excess of drained upper limit (that is field capacity) drains to the subsoil horizon. Similarly excess water in the subsoil horizon drains, either laterally as throughflow to the stream channel, or vertically to a groundwater store. Evapotranspiration occurs from both the topsoil and subsoil horizon, and is a function of potential evaporation (A-pan), leave area and soil moisture availability. When soil moisture is not a limitation, evapotranspiration occurs at the potential rate, but decrease linearly with increasing water stress once a critical fraction of plant-available water is reached.

Surface runoff and infiltration are simulated using a modified form of the SCS equation (Schmidt and Schulze, 1987), *viz.*

$$Q = (P_n - cS)^2/[P_g + S(1 - c)] \qquad 1$$

Q is the runoff depth; P_n is the net daily rainfall (i.e. gross rainfall P_g, less canopy interception, plus contributions from impervious areas); S is the potential maximum retention (a function of soil texture and antecedent soil moisture); and c is the coefficient of initial abstraction.

ACRU employs the continuity equation in routing flow through reservoirs (Smithers and Caldecott, 2004). The equation written in finite difference form is expressed as:

$$S_{n+1} - S_n = (I_n + I_{n+1})\Delta t/2 - (Q_n + Q_{n+1})\,\Delta t/2 \qquad 2$$

Where:

S_n	=	channel or temporary storage (m^3) at time increment = n
I_n	=	inflow rate ($m^3.s^{-1}$) at time increment = n
Q_n	=	outflow rate ($m^3.s^{-1}$) at time increment = n
Δt	=	routing period (s).

The subscripts (n) and (n+1) refer to the number of increments in time interval Δt. To route a hydrograph through a non-linear reservoir, the storage, outflow relationship and the continuity equation (Eqn 2) are combined to determine the outflow and storage at the end of every time step.

$$(2S_{n+1})/\Delta t + Q_{n+1} = I_n + I_{n+1} + (2S_n/\Delta t - Q_n) \qquad 3$$

Other than in Southern Africa (South Africa, Botswana, Namibia, Lesotho, Swaziland and Zimbabwe), the model had been applied internationally in research in Botswana Chile, Germany Lesotho, Namibia Swaziland and the US (Shulze *et al*, 2004).

2.2 HEC-HMS Model

HEC-HMS (Scharffenberg and Fleming, 2010) which is the acronym for Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) is hydrologic modelling software developed by the US Army Corps of Engineers Hydrologic Engineering Centre (HEC). It is designed to simulate the precipitation runoff processes of dendritic watershed systems in a wide range of geographic areas such as large river basins and small urban or natural watersheds (Scharffenberg and Fleming, 2010). The system encompasses losses, runoff transform, open channel routing, and analysis of meteorological data, rainfall-runoff simulation, and parameter estimation. HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, models of direct runoff, and models of base flow. Each model run combines a basin model, meteorological model, and control specifications with run options to obtain results. The system connectivity and physical data describing the watershed are stored in the basin model. The precipitation data necessary to simulate watershed processes are stored in the meteorological model (Kumar et al, 2011). HEC-HMS includes models of infiltration from the land surface but it does not model storage and movement of water vertically within the soil layer. It implicitly combines the near surface flow and overland flow and models this as direct runoff. HEC-HMS considers that all land and water in a watershed can be categorized as either directly connected impervious surface or pervious surface. The curve number method provides relationships between initial abstractions, *Ia*, and curve numbers, CN, based on experiments carried out in small experimental watersheds. The equations are presented as:

$$S = 1000/CN - 10 \qquad 4$$

$$I_a = 0.2S \qquad 5$$

Also, a relationship for excess rainfall has been established as:

$$P_e = (P - I_a)^2/(P - I_a + S) \qquad 6$$

Where S is potential maximum retention in inches, P is the total precipitation in inches and e P is excess precipitation in inches. The curve number is varying from 0 to 100. The curve number is zero for perfectly pervious surfaces and thus Q = 0. The curve number is 100 for perfectly impervious surfaces and thus Q = P. HEC-HMS transforms the rainfall excess into direct surface runoff through a unit hydrograph or by the kinematics wave transformation. In the present study, SCS unit hydrograph (SCS UH) model has been applied for estimating direct runoff. Research by the SCS suggests that the UH peak (UP) and time of UH peak (TP) are related as:

$$q_p = CA/T_p \quad 7$$

Where C= 483.4 in English system, and A is the drainage area square miles.

T_p is expressed as:

$$T_p = t_r/2 + t_{lag} \quad 8$$

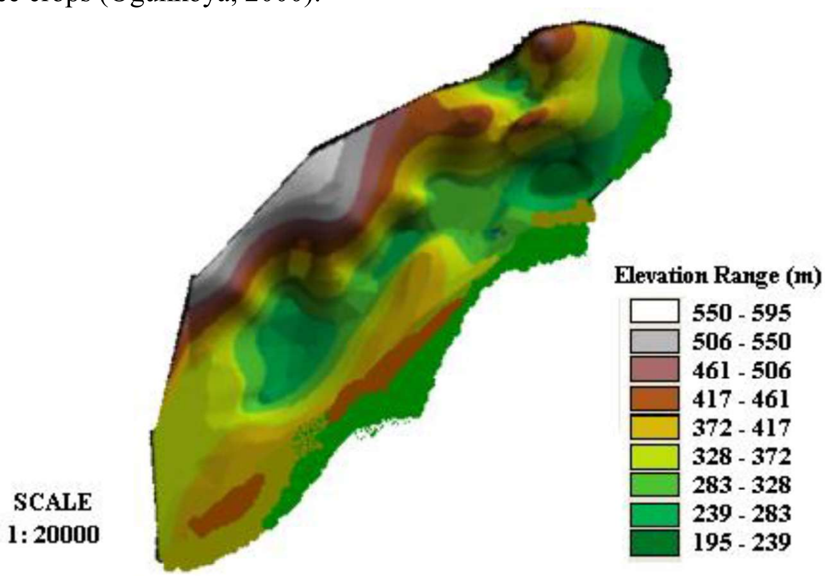
Where, t_r is the excess rainfall duration in hours and t_{lag} is the basin lag time in hours. The basin lag time is defined as the difference in time between the centre of mass of rainfall excess and the peak discharge of the unit hydrograph. The time parameters used in the models were time of concentration and sub basin lag time.

$$T_{lag} = (L^{0.8}\frac{(1000)}{CN} - 10^{0.7})/1900 \times \sqrt{y} \quad 9$$

Where T_{lag} is equal to the lag time (in hours) between the centre of mass of rainfall excess and the peak of the unit hydrograph, L is the watershed length in m, CN is the curve number (dimensionless) and Y is the watershed slope in percent (HEC, 1998).

2.3 Catchment Description

Agbogbo catchment (Fig 2) of Ile-Ife, a city in Southwest Nigeria is at the intersection of Latitude $7^0$32'N and Longitude $4^0$32'E (Ogunkoya, 2000). Agbogbo stream has a basin area of 0.4 km^2 and a perimeter of 3630.8m that is underlain by the Pre-Cambrian Basement Complex bounded by elongated inselbergs. Soil in the drainage basin reflect the underlying geology and is shallower than 2m. The climate in the drainage basin consists of two seasons: the dry season, extending from November to March, and the wet season, from April to October. Temperatures in the dry season range from a night-time mean of 21^0C to a day-time mean of 30^0C and the catchment is covered mainly by farms planted to a variety of tropical food and tree crops (Ogunkoya, 2000).



(Scale 1:20000)
Fig. 2: Digital Elevation Model of the Catchment

2. 4 Data Collation Method

Rainfall data for Agbogbo catchment was collected using the Dines tilting syphon rain recorder while current meter was used to obtain streamflow discharge data. The digital elevation model of the catchment developed from the contour map of Agbogbo catchment was also obtained and streamflow discharge records from January 1987 to March 1990 were used for model calibration and validation.

Streamflow data for the 1st hydrologic year (April 1987 – March 1988) were used to calibrate the models by adjusting parameters in the ACRU and HEC-HMS models independently to achieve reasonable agreement between the predicted and observed streamflow. By reasonable agreement is meant an order of magnitude correspondence between the simulated and the recorded series, which is consistent within the duration of an event (Mbajiorgu, 1995). After several simulations, the values of these parameters that provide the closest match and similarity in the hydrographs of the simulated and the observed streamflows for the 1st hydrologic year were used in simulating flows for the 2nd and 3rd hydrologic years (i.e. April 1988 – March 1989 and April 1989 – March 1990)

For the ACRU Model, Agbogbo catchment was divided into 3 subcatchments (Agb1, Agb2 and Agb3) with areas 0.1, 0.1, and 0.2km^2. In applying the HEC-HMS model, the catchment was divided into 'Basin 1', 'Basin 2' and 'Basin 3'with areas 0.1, 0.1, and 0.2km^2. Streamflow is routed from the subcatchment Agb1 (Basin 1 in the case of HEC-HMS) down through Agb2 (Basin 2 for HEC-HMS) to the stream outlet (at which point discharge measurements were taken) at Agb3 (i.e. Basin 3) as depicted in Fig 3.

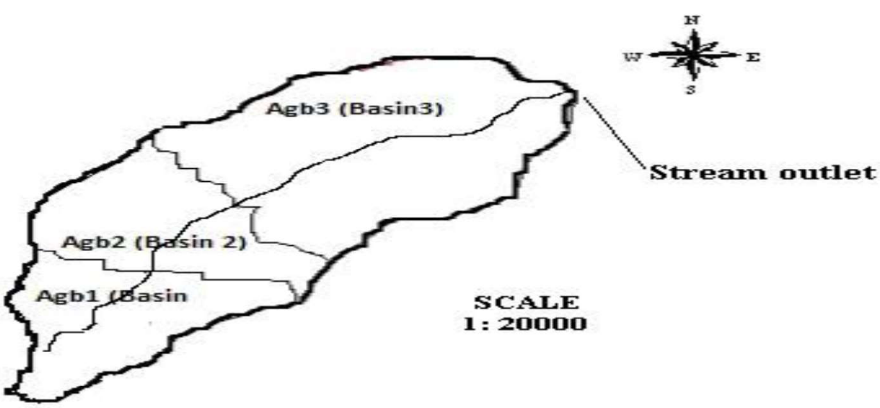


Fig. 3: Sub-catchments Configuration of Agbogbo Catchment

3. RESULTS AND DISCUSSION

After the calibration run (April 1987 – March 1988), ACRU Model over-predicted streamflow (Fig. 4) for the two successive hydrologic years (April 1988–March 1989 and April 1989–March 1990). The timing of the peaks for the observed and simulated streamflow during the simulation run however coincide which demonstrates that the model is sensitive to changes within the catchment. The Nash–Sutcliffe model efficiency coefficient (Nash *et al*., 1970) which is a measure of the predictive power of hydrological models and defined as;

$$E = 1 - \frac{\sum_{t=0}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=0}^{T}(Q_o^t - \overline{Q_o})^2}$$

was also used to compare the observed discharge (Q_o) and the predicted discharge (Q_m) at time t. The model efficiency coefficient E, for the ACRU model simulation was obtained to be 0.83695 for the 2nd hydrologic year (April 1988 to March 1989) while simulation by HEC-HMS model for the same period yielded 0.87748. For the 3rd hydrologic year (April 1989 to March 1990), ACRU model simulation yielded a model efficiency coefficient of 0.78232 while that of HEC-HMS yielded 0.54706 (full simulation result is given in Appendix 1). Overall (April 1988 to March 1990), ACRU model performed better with a model efficiency coefficient of 0.81218 when compared with the simulation performed by HEC-HMS which gave a value of 0.71498. The hydrograph of the observed and simulated streamflow (Fig. 4) also shows that HEC-HMS is less sensitive to changes within the catchment when compared with ACRU model is illustrated by the mismatch in the timing of the peaks of the hydrograph.

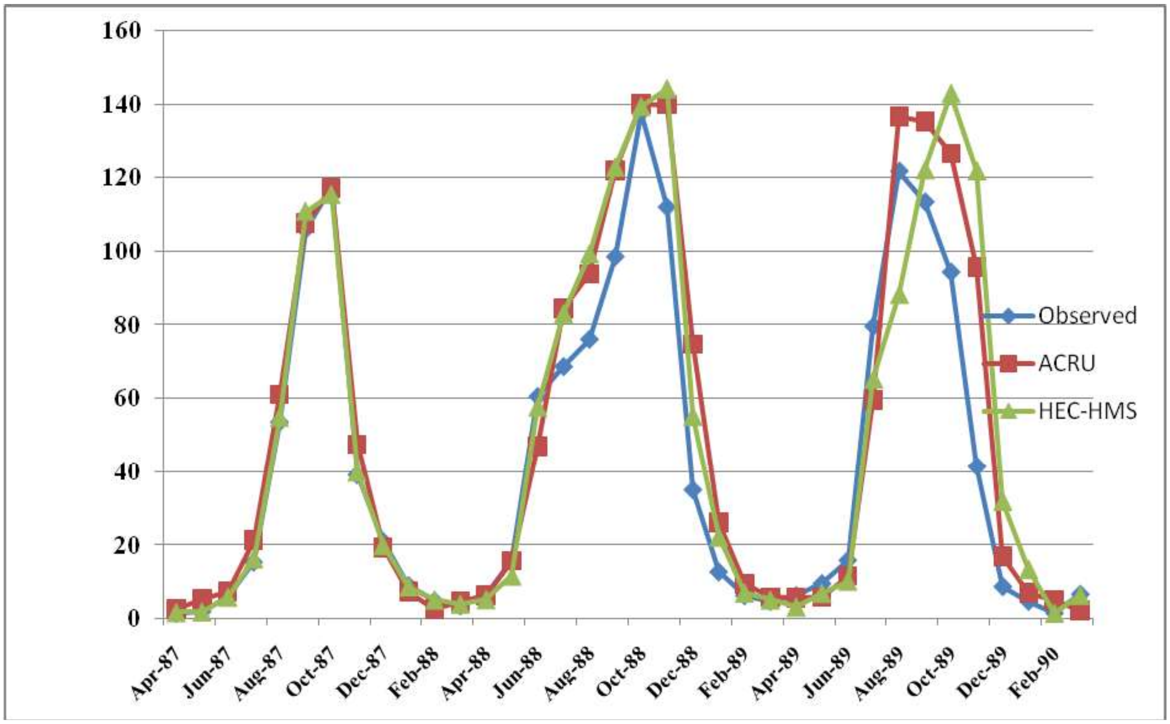


Fig. 4: Comparison between Simulated and Observed Hydrographs

The similarity in the occurrence of the timing in the peaks of the hydrographs of the ACRU model simulated streamflow and the observed streamflow shows that the model can be trusted to give reliable flood forecast for the catchment.

4. CONCLUSIONS

Data obtained from the field and those generated from a digital elevation model of the catchment were used in modelling streamflow for Agbogbo catchment. Data obtained for the 1st hydrologic year April 1987–March 1988 was used to calibrate the ACRU model and HEC-HMS while data for the next two hydrologic years (April 1988 to March 1990) was used for model validations. When Nash–Sutcliffe Model Efficiency Coefficient was used for the analysis. ACRU Agrohydrologic Model performed better than HEC-HMS over the two years and also showed significant sensitivity to changes within the catchment by the similarity in the timing of the occurrence of peaks for the observed and simulated hydrographs. However, the 3-year duration of the data used for this study (which were the only complete set of data available at the time this study was conducted) is a limitation to the validation exercise.

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APPENDIX

Comparison of the observed and the simulated flow for the period under study

Date	Observed Streamflow	ACRU Simulated Streamflow	HEC-HMS Simulated Streamflow
Apr-87	1.54	2.7	1.8
May-87	1.96	5.3	2
Jun-87	5.98	7.3	6
Jul-87	15.43	21.3	16.4
Aug-87	53.69	61.2	55
Sep-87	106	107.7	111
Oct-87	117.81	117.43	115.6
Nov-87	39.2	47.55	40
Dec-87	21.11	19.33	20
Jan-88	9.06	7.47	8.8
Feb-88	4.88	2.7	5.2
Mar-88	3.54	4.7	4.1
Apr-88	6.38	6.3	5.3
May-88	15.95	15.7	11.7
Jun-88	60.65	47	57.8
Jul-88	68.8	84.6	83.2
Aug-88	76.2	94	99.4
Sep-88	98.7	122.1	123
Oct-88	137.9	140.3	139.5
Nov-88	112.2	140	144.3
Dec-88	35.1	74.9	55.3
Jan-89	12.78	26.2	22.3
Feb-89	6.33	9.4	7.1
Mar-89	4.78	5.8	5.2
Apr-89	6.33	5.6	3.3
May-89	9.58	5.8	7
Jun-89	15.95	11.6	10.3
Jul-89	79.78	59.6	65.4
Aug-89	122	136.8	88.4
Sep-89	113.6	135.4	122.3
Oct-89	94.5	126.8	143
Nov-89	41.5	95.9	122
Dec-89	8.8	16.9	32
Jan-90	4.78	7.1	13.5
Feb-90	1.6	5.1	1.6
Mar-90	6.7	2.2	6.5