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STREAMFLOW FORECASTING WITH HSPF MODELLING EXPERIENCE

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MANAGEMENT PERSPECTIVE

The HSPF (Hydrological Simulation Program - FORTRAN) is a mathematical computer simulation technique for analyzing and forecasting the movement of water and constituents through a fixed environment and their interaction with each other.

The fixed environments are watersheds, rivers, and well-mixed reservoirs in both natural and man-made water systems.

The model consists of various modules to simulate the motion and interaction processes of different elements. Streamflow is one of the elements.

The main purpose of this report is to demonstrate the HSPF model's general concepts, structures, capability and aspects of flexibility, which are important in practical application. An experience was gained from a study through application of the model to an urbanizing watershed - the Waterford River Basin, located near St. John's, Newfoundland. The request for such study was in response to watershed management problems that had resulted from urbanization of the Waterford River Basin. The primary objective of applying HSPF model was to predict the response of streamflow regimes of the Waterford River to the future land development in the basin. The HSPF model is considered to be the most comprehensive management and planning tool presently available for continuous simulation of hydrology and water quality in watersheds.

The report should be useful to users interested in streamflow forecasting and watershed planners.

PERSPECTIVES DE GESTION

Le HSPF (Programme de simulation hydrologique - FORTRAN) est une méthode de simulation mathématique par ordinateur pour l'analyse et la prévision du déplacement de l'eau et de ses constituants à travers un milieu fixe donné, ainsi que de l'interaction qu'ils exercent les uns sur les autres.

Les milieux fixes sont des bassins hydrographiques, des rivières, et des réservoirs homogènes, aussi bien dans des systèmes hydrographiques naturels qu'artificiels.

Le modèle est constitué de divers modules permettant de simuler les mouvements et l'interaction de différents éléments. Le débit est l'un de ces éléments.

Le but principal du présent rapport est de montrer dans quelle mesure la conception générale, la structure, la capacité et la flexibilité du modèle HSPF sont importantes pour les applications pratiques. On a obtenu des données grâce à une étude dans laquelle le modèle a été utilisé pour un bassin hydrographique urbanisé - le bassin de la rivière Waterford, près de Saint-Jean, à Terre-Neuve. Cette étude avait été commandée pour répondre à des problèmes de gestion du bassin hydrographique, qui résultaient de l'urbanisation du bassin de la rivière Waterford. L'objectif premier de l'application de modèle HSPF était de prévoir quels seraient les futurs régimes de débit de la rivière Waterford, à la suite de l'utilisation des terres prévue dans le bassin. Le modèle HSPF est considéré comme étant l'outil de gestion et de planification le plus complet existant actuellement pour la simulation continue de l'hydrologie et de la qualité de l'eau dans les bassins hydrographiques.

Le rappor devrait se révéler utile pour ceux qui ont besoin de prévoir le débit d'eau, ainsi que pour les planificateurs des bassins hydrographiques.

ABSTRACT

The Hydrologic Simulation Program - Fortran (HSPF) of the U.S. Environmental Protection Agency has been applied for simulation of the hydrological response of an urbanizing watershed.

The calibrated HSPF model was then applied to future land use development scenarios. It was noted that an expected increase in the impervious area in the watershed is unlikely to increase the volume of streamflow, but it would contribute to increases in flow peaks and the incidence of flooding. If the impervious area is doubled in the watershed, the flow peaks may increase by 20%.

RÉSUMÉ

Le programme de simulation hydrologique en Fortran (HSPF) de l'EPA (États-Unis) a été appliqué à la simulation de la réaction hydrologique d'un bassin hydrographique urbanisé.

Le modèle étalonné HSPF a ensuite été appliqué à des scénarios d'utilisation et de développement futurs de terres. On a fait remarquer qu'une augmentation prévisible de la surface imperméable du bassin hydrographique n'entraînerait probablement pas un accroissement du débit des cours d'eau, mais elle contribuerait à intensifier les pics de débit et à augmenter la fréquence des inondations. Si la surface imperméable dans le bassin hydrographique est doublée, les pics de débit peuvent augmenter de 20 %.

INTRODUCTION

The HSPF (Hydrologic Simulation Program-Fortran) is a comprehensive continuous simulation model for predicting watershed hydrological response, water quality, agricultural chemicals migration, and environmental risk assessment. The model was developed under the sponsorship of the U.S. Environmental Protection Agency (7).

There are numerous models for streamflow forecasting. The basic forecast models fall into two categories, statistical and deterministic. Statistical models are good for seasonal forecasts, but their use is limited by the use of short term records until a reasonable length of record is established (6). Deterministic forecasts are based on the hydrological response of the watershed representing the prototype.

The HSPF model falls into the deterministic category. It utilizes all the available physical information and meteorological input parameters within the watershed to represent the behaviour of the total hydrological system.

The purpose of this report is to show the HSPF model's structure, its ability and flexibility gained from a study of a watershed undergoing urbanization. The studied watershed is the Waterford River Basin, which is located near St. John's, Newfoundland (Figure 1).

EXAMPLES OF APPLICATION

HSPF Model Structure

The HSPF model is a set of computer codes that continuously perform simulation on pervious and impervious land surfaces and in streams and well-mixed reservoirs. The HSPF is built on a systematic framework which consists of a set of modules. The modules are arranged in a hierarchical mode that permits continuous simulation of a range of hydrologic and water quality processes. The modules are further divided into three application and five utility modules. The capabilities of each module are outlined and shown in Figure 2. Included in Figure 2 is a stand-alone program, NEWTSS, which creates or copies a time series data set to a data file called Time Series Storage (TSS). This TSS is to be used by the HSPF model for the calibration, verification and forecasting. As seen from Figure 2, the functions and capabilities of HSPF are complex and diversified. Each block under the heading of the module function contains the elements that an individual module can perform simultaneously.

HSPF Operation

The HSPF model operation is controlled by a user's control input (UCI) file which specifies the modules to be run (i.e. PERLND, IMPLND, RCHRES, COPY, PLTGEN, DISPLY, DURANL, and GENER) along with hydrologic, hydraulic and atmospheric parameters required as input to the model. An overview of the HSPF operation is presented in Figure 3.

DESCRIPTION OF THE WATERSHED STUDIED

The Waterford River Basin is located near St. John's, Newfoundland. The watershed area is 53 km^2. More than 50% of the watershed area is covered by forest. Other land use types and physical features of the watershed include agricultural, urban, and recreational areas, ponds, bogs, river channels, and gravel pits.

The main stream in the basin, the Waterford River, flows northeasterly over a distance of about 14 km and discharges into St. John's Harbour. The largest tributary, South Brook, flows through the forested parts of the basin.

The general physiographic features of the Waterford River Basin are given by the fact that all rocks are of the Precambrian Age and are generally overlain by Clastic sediments of slate-siltstone, sandstone, conglomerate and granitic rocks (1, 5). About 90% of the watershed is formed by a veneer of till and rocky ridges, which run parallel to the bed-rock structures, suggesting that rainwater and snowmelt will be largely transformed into runoff with little loss by infiltration into the ground.

The soils are generally classified as of the humoferric and ferro-humic podzol great group. These soils exhibit rapid surface drainage but are poor in internal drainage. This leads to fast hydrological response during rainfall or snowmelt.

The climate in the watershed area is moderated by the sea, consequently, temperature variations are fairly limited and contribute to relatively mild winters and cool summers. The average daily maximum and minimum temperatures are 8.6°C and 1.0°C, respectively.

Precipitation occurs on 207 days, thus there are about 57% of wet days in a year. The total average annual precipitation is 1514 mm.

High streamflows usually occur in spring as a result of combined effect of rainfall and snowmelt. Low flows usually occur in summer from June to August. During the ten-year period from 1974 to 1984, the maximum and minimum instantaneous flows, observed at the Kilbride hydrometric station were 66.1 m^3/s on November 26, 1981 and 0.15 m^3/s on August 13, 1982, respectively.

The watershed is partially urbanized with the urbanized part representing about 20% of the total area. The total impervious area is about 5% (2.65 km^2) of the total watershed area.

The average crown cover over the four seasons is 34%.

The total population within the watershed area is 28,000.

HSPF DATA BASE

The Waterford time series data base available for HSPF application covers a period of 2-1/2 years from January 1, 1981 to May 31, 1983 in the form of hourly values for all parameters, except evaporation rates which were in the form of daily values available for the period from June 1 to October 31 of each study year.

The time series data base includes the following parameters:

- precipitation
- evaporation
- air temperatures (wet and dry bulbs)
- wind movement
- solar radiation
- cloud cover
- streamflow record

The time series data were obtained from St. John's west station at the Canada Department of Agriculture Farm located in the Waterford River Basin (Figure 1), except for wind movement and air temperatures which were obtained at St. John's airport and streamflow records which were obtained at the Kilbride hydrometric station. The time series data are then copied to the time series storage by using the NEWTSS program as mentioned earlier.

WATERSHED SEGMENTATION DATA FOR HSPF MODEL SIMULATION

The watershed area was subdivided into two pervious and one impervious land segments. The impervious segment is an aggregation of roof areas, parking lots, driveways, streets, highways and paved areas on the land surface. The areas of the above segments are as follows:

Segment 1	30.25 km^2
Segment 2	20.13 km^2
Impervious Segment	2.65 km^2

The primary consideration in the segmentation includes drainage patterns, the spatial distribution of impervious and pervious surfaces, the spatial distribution of overburden and the distribution of forest canopy and seasonal variation in the watershed.

CONNECTIVITY OF ROUTING REACHES AND LAND SEGMENTS

The connectivity of routing reaches and land segments is shown in Figure 1 and described below.

Pervious land segment 1 drains to reach 1; impervious segment 1 and pervious segment 2 drain to reach 2 which also receives flow from reach 1; reach 2 has an outlet at the hydrometric station in Kilbride; the river flow routing reaches are described by their basic geometric and hydraulic properties (7) (listed in the FTABLE - functional table).

CALIBRATION AND VERIFICATION OF THE HSPF MODEL

The calibration is critical for the application of the HSPF model. For water quantity simulation, the calibration is divided into two parts, i.e. hydrologic and hydraulic calibrations. Hydrologic calibration includes the comparison of volumes of flow, for monthly and annual values, and hydrograph of individual events. Hydraulic calibration is more specific to hydrographs and flow peaks. Further details on calibration of HSPF can be found elsewhere (3). After calibration, the model is usually verified against another data set.

The calibration of the HSPF model was a major task in the study of the Waterford River Basin. It consumed about 30% of the total resources.

During the calibration process, the users need to establish the desired levels of goodness of fit indicating when the calibration goal is achieved. For Waterford River Basin calibration, the criteria were adopted from ref. (3) and presented below.

Phenomena	Calibration Results (%) - Goodness of Fit		
	Fair	Good	Very Good
Hydrology/Hydraulics	15-25	10-15	<10

The important HSPF hydrologic calibration parameters are listed in Table 1. Calibration procedures have been given in (3, 5, 7). In the overall evaluation, the monthly streamflow was reproduced on the average within ±15% of the observed values. Such results would be considered as "good" using the criteria set out earlier. The individual storm hydrographs particularly their flow peaks matched the observed ones within -5%. The minus sign indicated that the simulated flow peak was slightly underestimated. But such results would be evaluated as "good" to "very good". A comparison of observed and simulated hydrographs is plotted in Figure 4, and the flow peaks are presented in Table 2. The simulated flow peaks from Table 2 are further plotted against the measured precipitation as shown in Figure 5. The plot serves to indicate the range of expected flow peaks for measured precipitation events. It should be noted that this plot covered only 2-1/2 years of historical precipitation records. Extrapolation or interpolation of the data points may be unreliable. The plot is also used to characterize the watershed's hydrologic response. Following hydrograph calibration, the HSPF model was considered to be well calibrated, for the available data base and that specific watershed. It is now suitable for simulation of streamflow and a number of other simulation options, including among others, simulation of land use development scenarios, and low and high flows of the water year.

RESULTS OF APPLICATION

For the purpose of interpretation of HSPF simulation results for streamflow, it may be worthwhile to discuss briefly the relationships between runoff and streamflow. The runoff, in general, may include surface runoff, subsurface runoff, and groundwater runoff. While the components of runoff are confined in stream channels, it is called the streamflow. This is the flow collected from the drainage basin or watershed.

To this end, the measured steamflow at an outlet represents the flow collected from the watershed. The flow at the outlet for a given time interval may be integrated as volume. This volume, when divided by the watershed basin area, is expressed as the depth of runoff which is yielded from the watershed. In addition, it is more convenient to measure the aggregated runoff at a confined stream channel than to measure the individual components of runoff.

For comparison purposes, and for consistency of units of other parameters (such as precipitation and evaporation), which are customarily expressed in terms of depth in millimetres, the streamflow volume can easily be converted to match the units of these parameters. For this reason, the simulation results of monthly streamflow converted to the units of depth of flow for the Waterford River Basin at the outlet of Kilbride are readily matched with the units of depth of measured precipitation from the same watershed. The results are plotted in Figure 6(b). Figure 6(a) and Figure 6(b) have a common x-axis in months. Note that the precipitation and streamflow values are monthly hourly averages. The plot also shows the upper and lower limits of the flow, for a given precipitation depth, in a particular month. Subsequently, it depicts the seasonal cycle of the hydrologic response for the Waterford River Basin. It is interesting to note that during the months of March and April, precipitation is low but streamflow is high as a result of snowmelt contribution. However, this plot represents only 2-1/2 years of historical precipitation records, the confidence of limits of this plot may widely vary until longer historical data records become available for the HSPF data base.

The HSPF model was further applied to land use development scenarios, which were projected for increases of impervious areas in three stages of development. The projected future land use scenarios were evaluated in terms of annual and monthly flows, and flow peaks. The simulated annual and monthly flows are listed in Table 3 and the flow peaks are plotted in Figure 7. The simulation results for flow peaks show more sensitivity to the progressing develoment of the basin than streamflow volumes. It would appear that if the impervious area is doubled the flow peaks would increase, on the average, by about 10%. The increases for the larger flow peaks seem to be relatively larger in the range from 15 to 25%. Such increases in flow peaks would be significant in terms of incidence of flooding.

CONCLUSIONS

The HSPF model has been applied to reproduce the hydrologic response of an urbanizating watershed with a very good match between the observed and simulated results. The model provides a variety of options for users to simulate other phenomena in the watershed area.

The model requires large resources to prepare the data base for Time Series Storage. Calibration is also a major effort in the application processes. The above two major tasks take about 60% of the total resources and efforts. Once the model is satisfactorily calibrated and suitable data base is established, simulations for various scenarios can be easily accomplished. The accuracy of simulation can be achieved as high as to 95%.

REFERENCES

1. Batterson, M.J. 1984. Surfacial geology of the Waterford River Basin. Technical Report No. 1, Urban Hydrology Study of the Waterford River Basin, Newfoundland Departmentof Environment, St. John's, Nfld., 29 pp.
2. Daurie, Glenn 1984. Waterford River urban hydrology study, HSPF database compilation. J.E. Peters Management Limited, Dartmouth, Nova Scotia, Feb. 1984.

3. Donigian, A.S.Jr., J.R. Imhoff, B.R. Bicknell, and J.L. Kittle Jr. 1984. Application guide for hydrological simulation program - FORTRAN (HSPF). Environmental Research Laboratory, U.S. EPA, EPA-600/3-84-065, Athens, Georgia 30613, June 1984.

4. King, A.F. 1984. Geology of the Waterford River Basin. Technical Report No. 2, Urban Hydrology Study of the Waterford River Basin, Newfoundland Department of Environment, St. John's, Nfld., 25 pp.

5. Ng, H.F.Y. and J. Marsalek. 1987. Streamflow modelling in Waterford River Basin using HSPF model. Technical Report No. 5, Urban Hydrology Study of the Waterford River Basin, Newfoundland Department of Environment, St. John's, Nfld., 56 pp.

6. Quick, M.C. 1985. Forecast Errors. Proceedings of the Technical Workshop on Streamflow Forecasting, Montreal, Quebec, June 3-4, 1985.

7. Users Manual for Hydrological Simulation Program-FORTRAN (HSPF). EPA-600/9-80-015, April 1980, Environmental Research Laboratory, Athens, Georgia 30605, U.S.A.

Table 1. Important HSPF Hydrologic Calibration Parameters

Parameter	Definition
General Hydrologic Parameters	
LZSN	- The lower zone nominal storage
INFILT	- The infiltration capacity of the soil
AGWRC	- The groundwater recession rate
UZSN	- The upper zone nominal storage
IRC	- The interflow recession parameter (today's outflow rate/yesterday's outflow rate)
INTFW	- The interflow inflow parameter
LZETP	- The lower zone evapotranspiration parameter
FOREST	- The fraction of the pervious land area covered by forest (may be kept constant throughout the year, if there is no difference between the summer and winter forest cover)
DEEPFR	- The fraction of groundwater inflow entering deep (inactive) groundwater storage which cannot be recovered. In the Waterford River Basin, the majority of geological structures are bedrocks and this parameter was set equal to zero.
Snowmelt Parameters	
TSNOW	- The air temperature below which precipitation occurs in the form of snow, under saturated conditions
CCFACT	- A parameter used to correct the condensation/convection melt equation for field conditions
MWATER	- The maximum water content of the snowpack
MGMELT	- The maximum snowmelt rate due to ground heat
Initial Water Storages	
UZS	- The upper zone storage
LZS	- The lower zone storage
CEPS	- The interception storage
SURS	- The surface storage (on the overland flow plane)
IFWS	- The interflow storgae
AGWS	- The active groundwater storage
GWVS	- An index relating the antecedent active groundwater inflow to the groundwater table slope

Table 2. Comparison of Observed and Simulated Flow Peaks

Event Number	Date	Measured Precipitation (mm)	Q_{obs} m³/s	Q_{sin} m³/s	$Q_{sin}-Q_{obs}/Q_{obs}$ %
1	15/3/81	46.1	12.7	13.5	6.3
2	18/3/81	30.0	17.1	17.5	2.3
3	9/7/81	44.9	13.5	14.4	6.7
4	25/9/81	37.4	12.4	12.4	0.0
5	5/10/81	30.0	10.1	8.5	-15.8
6	10/10/81	54.6	39.7	33.0	-16.9
7	12/10/81	24.0	34.1	26.6	-22.0
8	17/10/81	45.4	29.5	21.9	-25.8
9	8/11/81	57.1	27.6	28.3	2.5
10	26/11/81	87.4	66.1	62.5	6.0
11	8/03/82	5.8	31.8	21.8	-31.4
12	27/03/82	16.6	11.0	12.6	14.5
13	22/4/82	14.4	16.6	10.6	-36.1
14	13/5/82	43.4	34.0	27.0	-20.6
15	14/5/82	27.8	16.9	15.0	-11.2
16	21/6/82	63.1	37.0	50.4	36.2
17	1/7/82	35.0	12.0	10.7	-10.8
18	19/9/82	51.6	43.0	57.9	34.7
19	24/9/82	26.2	18.6	19.4	4.3
20	3/10/82	47.0	22.9	29.4	28.4
21	4/10/82	43.2	53.2	29.5	-45.0
22	30/11/82	11.8	10.7	11.6	8.4
23	7/01/83	25.9	15.8	16.0	1.3
24	15/01/83	18.4	12.9	8.9	-31.0
25	3/3/83	64.8	19.3	33.1	71.5
26	13/3/83	14.9	15.3	10.3	-32.7
27	15/3/83	3.6	10.7	6.8	-36.4
28	26/3/83	25.7	15.0	10.7	-28.7
29	20/4/83	20.6	11.9	11.2	-5.9
Average		36.0	23.0	21.8	-5.2

Q_{obs}: observed flow peak
Q_{sin}: simulated flow peak

Table 3. Simulated streamflow volume for various land use scenarios

Percentual Increase in Impervious Area	Streamflow Volume (mm)												Annual Total
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
0	135	89	187	160	86	91	63	47	130	184	148	120	1440
50	135	89	187	160	85	91	63	47	130	184	148	120	1339
100	135	90	188	160	86	92	63	48	133	185	149	120	1449
200	135	91	188	160	85	94	64	51	134	183	150	120	1454

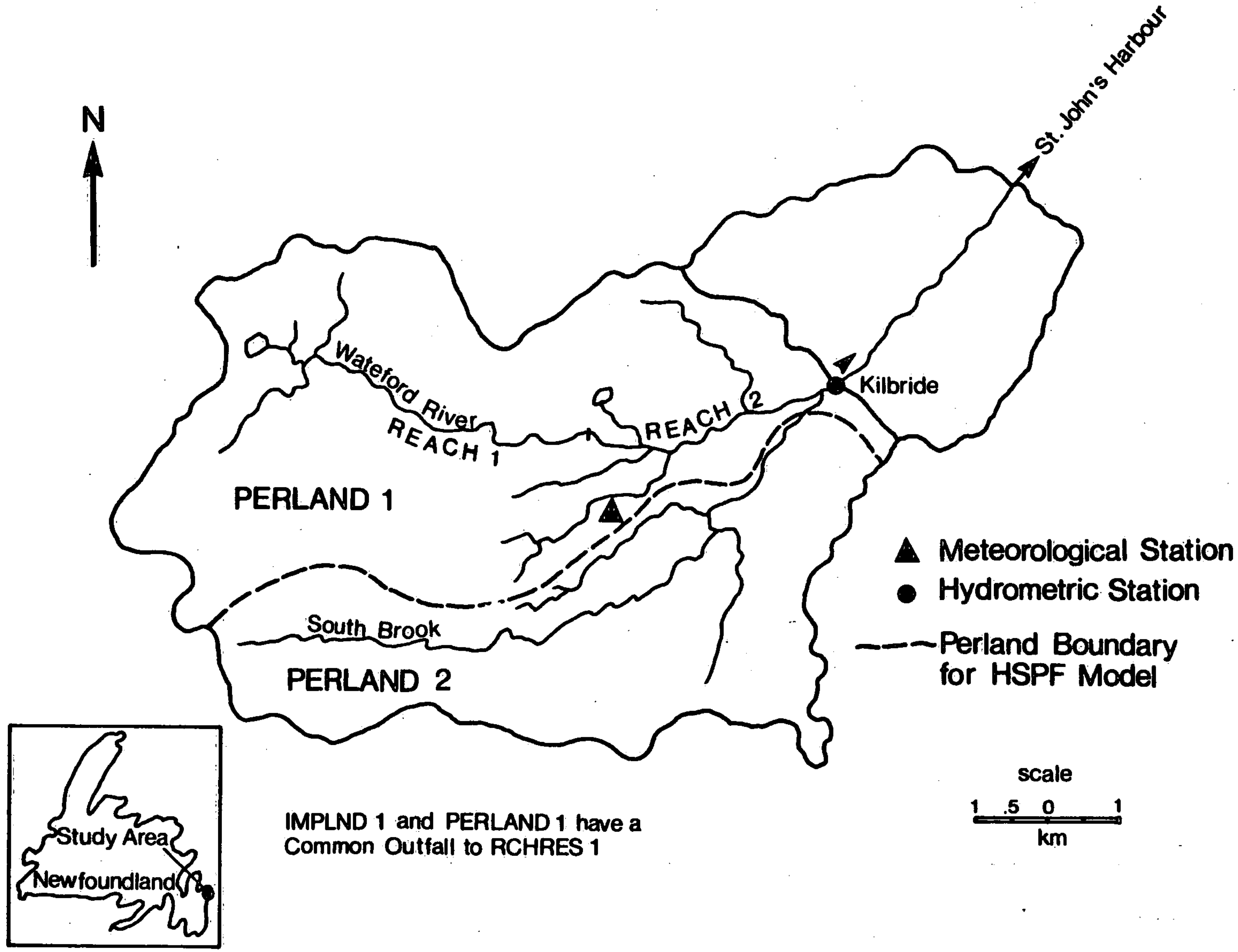


Fig. 1 Map of the HSPF Study Watershed.

Fig. 2 **HSPF APPLICATION MODULES FUNCTION**

PERLND
- Snow
- Water
- Sediment
- Quality
- Pesticide
- Nitrogen
- Phosphorus
- Tracer

IMPLND
- Snow
- Water
- Solids
- Quality

RCHRES
- Hydraulics
- Conservative
- Temperature
- Sediment
- Non-Conservative
- DO/BOD
- Nitrogen
- Phosphorus
- Carbon
- Plankton

HSPF UTILITY MODULES FUNCTION

COPY
Data Transfer

PLTGEN
Plot Data

DISPLY
Tabulate and Summarize Data

DURANL
Duration Analysis

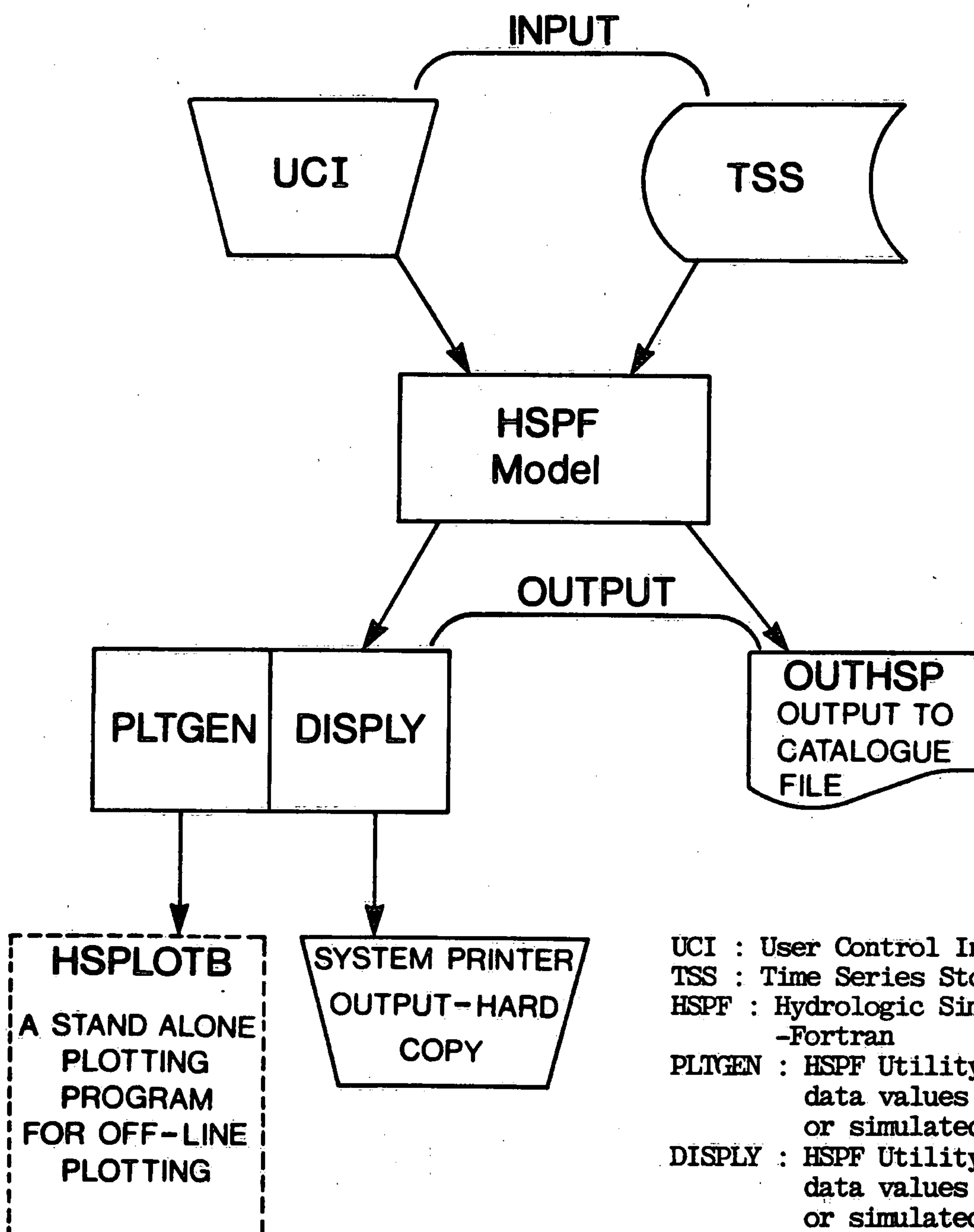
GENER
Transform or Combine Data

NEWTSS

A stand-alone program which creates or copies a time series store (TSS)

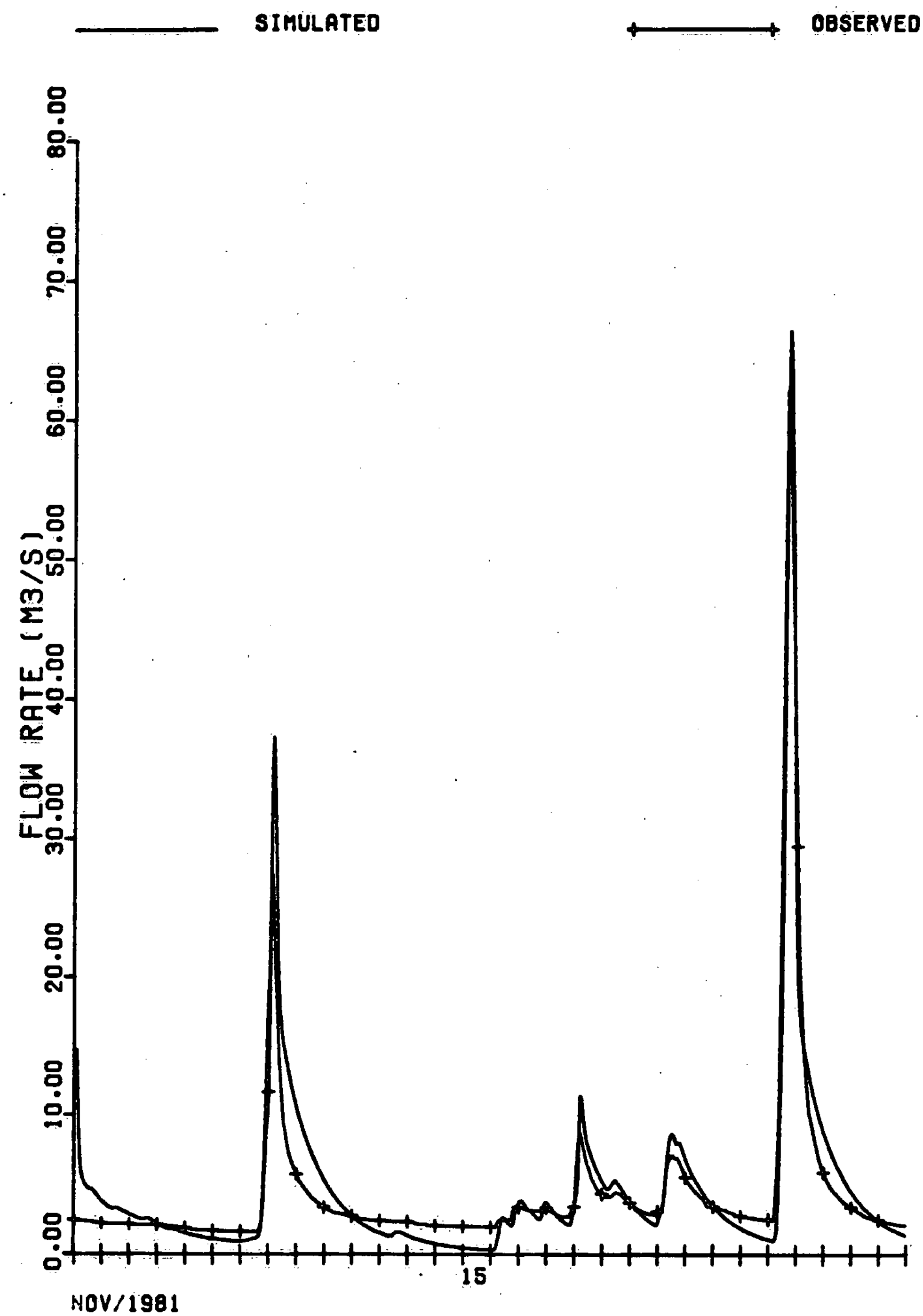
It must be run before a user can perform any HSPF module runs which reguire data to be stored in or retrieved from the TSS

Fig. 3 HSPF OVERVIEW



UCI : User Control Input
TSS : Time Series Storage(data base)
HSPF : Hydrologic Simulation Program -Fortran
PLTGEN : HSPF Utility Module for plotting data values of either observed or simulated or both on a graph
DISPLY : HSPF Utility Module for displaying data values of either observed or simulated or both in tabulated form.
OUTHSP & HSPLOTB are file names.

Figure 4. SIMULATED AND OBSERVED FLOWS



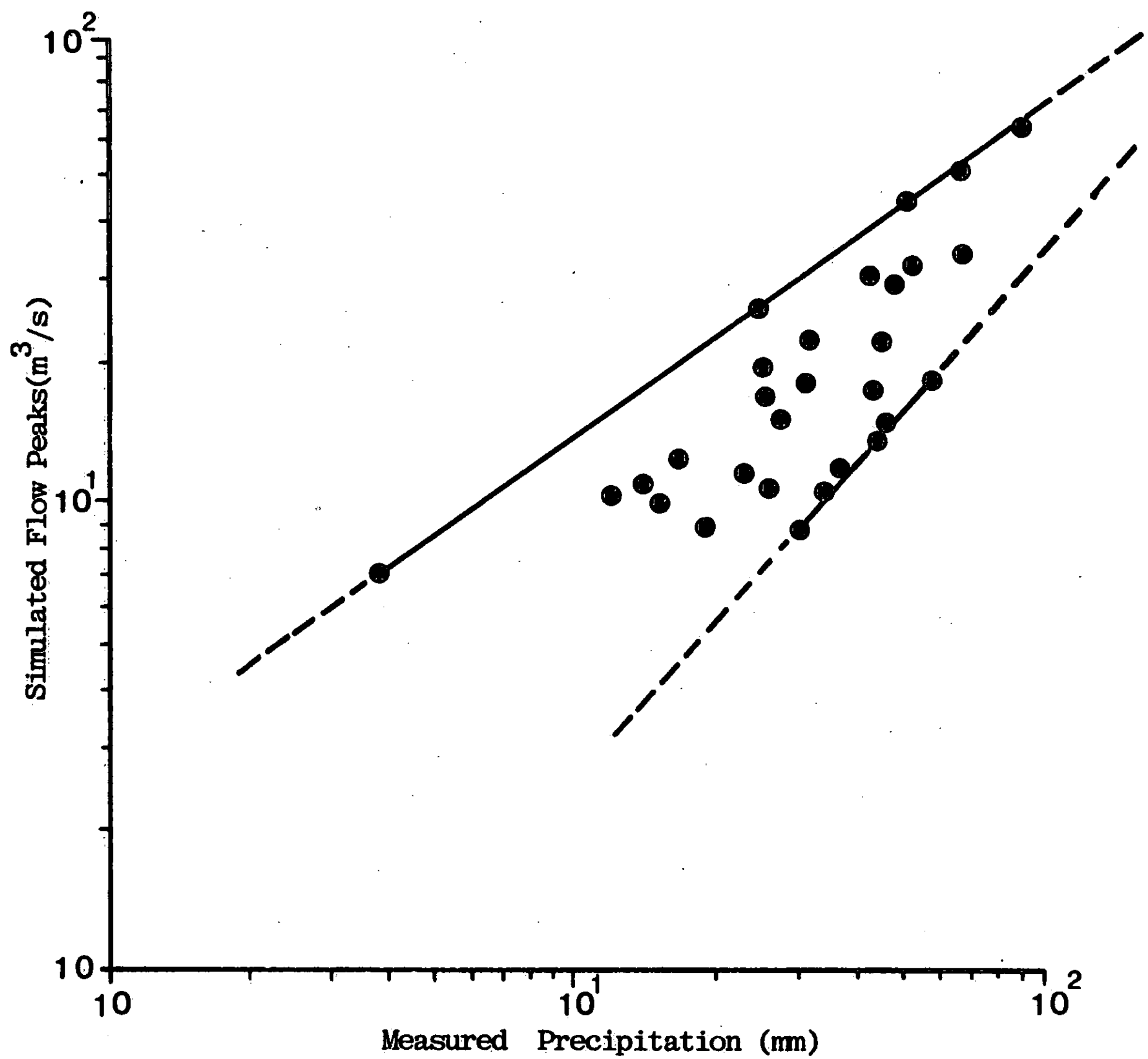
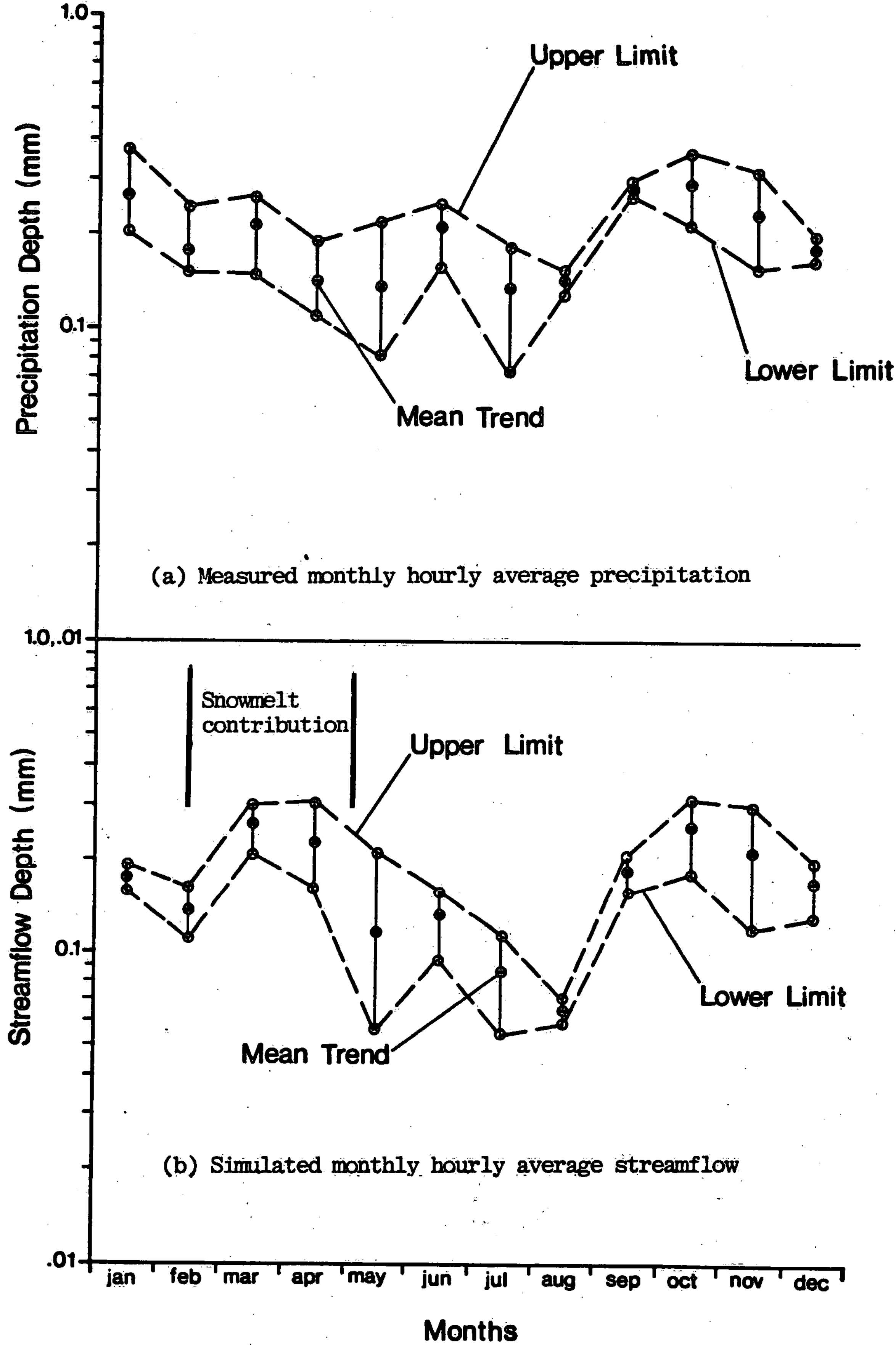


Figure 5. Flow Peaks Simulated for Measured Precipitation

Figure 6. Simulated Monthly Hourly Streamflow for Measured Monthly Hourly Precipitation



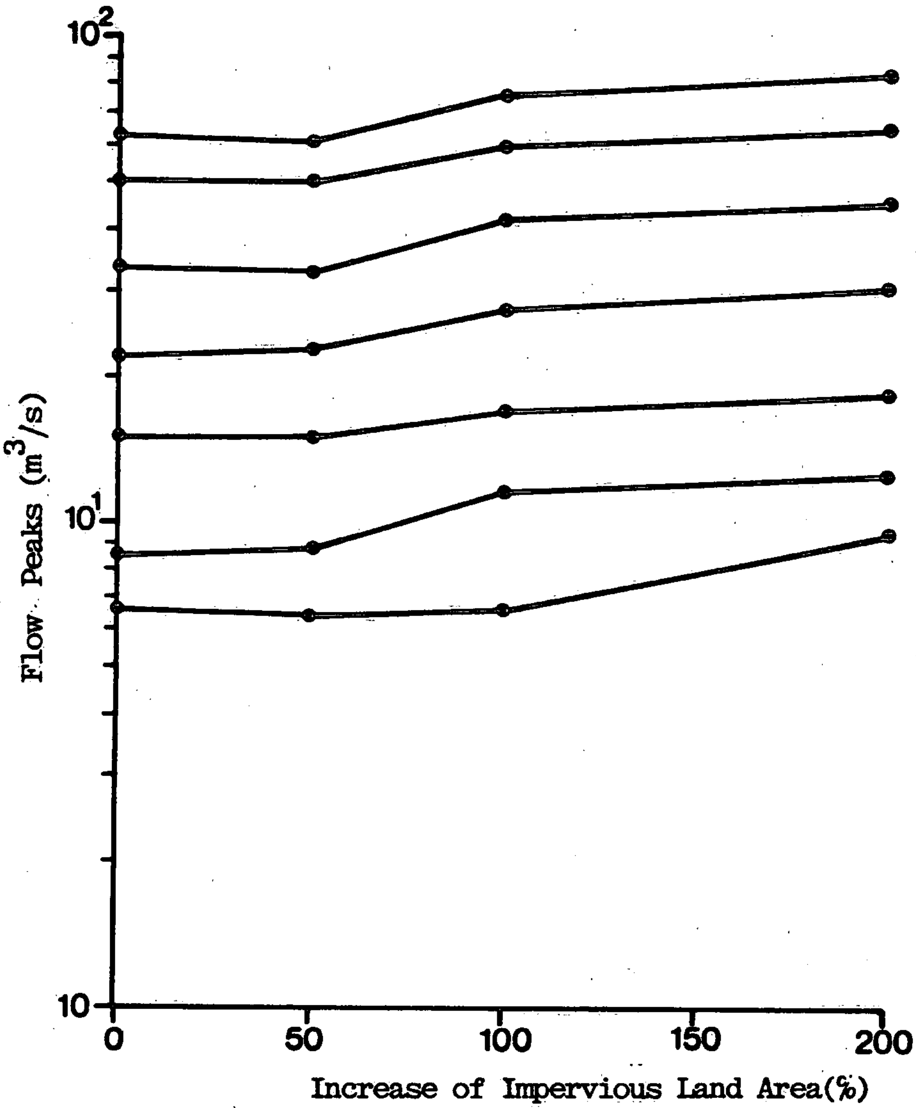


Figure 7. Simulated Flow Peaks by HSPF Model for Progressive Land Development Scenarios of the Waterford River Basin.