HYDROLOGIC MODELING WITH REMOTELY SENSED DATA

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INTRODUCTION

Satellite data is seen as the key to further development of distributed hydrologic models. The paper describes the development, on a micro-computer, of a distributed hydrological model, with snow component, using data from satellite as well as conventional ground-based meteorological and hydrological data. The data are combined in a database written specifically for hydrological modeling on micro-computers. Two basins in western Canada with significant snowpack are used, the Kootenay and the Souris. Daily visible and near infra-red data from a NOAA satellite are used, from digital tape and black and white photographs.

The objectives of the study are to investigate the utility of data from satellite in hydrometeorological modeling in different physiographic and climatic areas, to use the models as test-beds for different physically-based components and to develop a land-phase component for climatic general circulation models.

HYDROLOGIC MODELS

A. Selection of Models

There are many different hydrologic models available and almost as many classification schemes. A primary distinction between models is usually based on the degree of understanding of the physics of the catchment incorporated in the model. A deterministic model is one which uses the laws of continuity of energy and momentum and other known (or hypothesized) physical relationships to relate input and output. A stochastic model, on the other hand, simulates the observed variation in the output data without attempting to describe any of the physical processes behind the observations. Frequently, some knowledge of the physical processes is available, so the relationship between input and output is not purely stochastic, but the knowledge may not be sufficiently rigorous to allow use of a deterministic model; the compromise chosen is the parametric model. The parametric approach attempts to find functional relationships between input and output.

A secondary distinction between models may be made on the basis of the input data requirements; between lumped models using basin average data and distributed models that make use of the physiographic data available for the basin. Not all combinations of these two criteria are valid; there would be very little point in having a lumped physical model, the physics necessitates measurements at different points. Also, such a simple classification doesn't include all models; the Tank model (Sugawara, 1984), for example, cannot be placed in either the lumped or the distributed categories; it generates intermediate runoff from each precipitation station (as representing a particular sub-area of the basin) and then combines the runoffs to generate streamflow.

The choice of a hydrological model must depend on the purpose intended. Since, in this case, the intent is to investigate the use of satellite data, to test physical components and to develop a model as a land-phase component for a general circulation model, it was clear that the choice of model must be from within the near-physical lumped category.

Within this category of model, the choice also depends on the time and space scales of the application. Most GCM's operate on a 30 minute time step with a typical experiment integrating the results to monthly data for a period of 5 to 20 years. Hydrologic models, on the other hand, commonly use daily data, and present the simulated results at the same time interval. Clearly, with such a difference in data requirements, the hydrologic model can only provide the GCM with averaged data.

In terms of space scale, GCM's operate on a grid square basis, 5° being a common grid size (say 550 km x 350 km, or 190,000 km^2, in Canada) whereas hydrologic models operate on catchments which might vary from 10 km^2 to 10,000 km^2. A hydrologic component therefore must also use grid squares. This means averaging over different sizes of grid square but, since streamflow is a measure of the time and space integration of precipitation, evaporation and runoff, this also offers the advantage of an independent check of the inputs and outputs of the GCM.

Models using grid-square data have been available for many years (e.g. Solomon et al, 1968). Other examples include the CEQUEAU model (Charbonneau et al, 1977), the EGMO model (Becker & Pfutzer, 1987) which uses a two-level grid square to link the atmosphere with the surface and the surface with the subsurface, and the model of Grove et al (1985) which uses a geographical information system (GIS) to store the large amounts of data needed.

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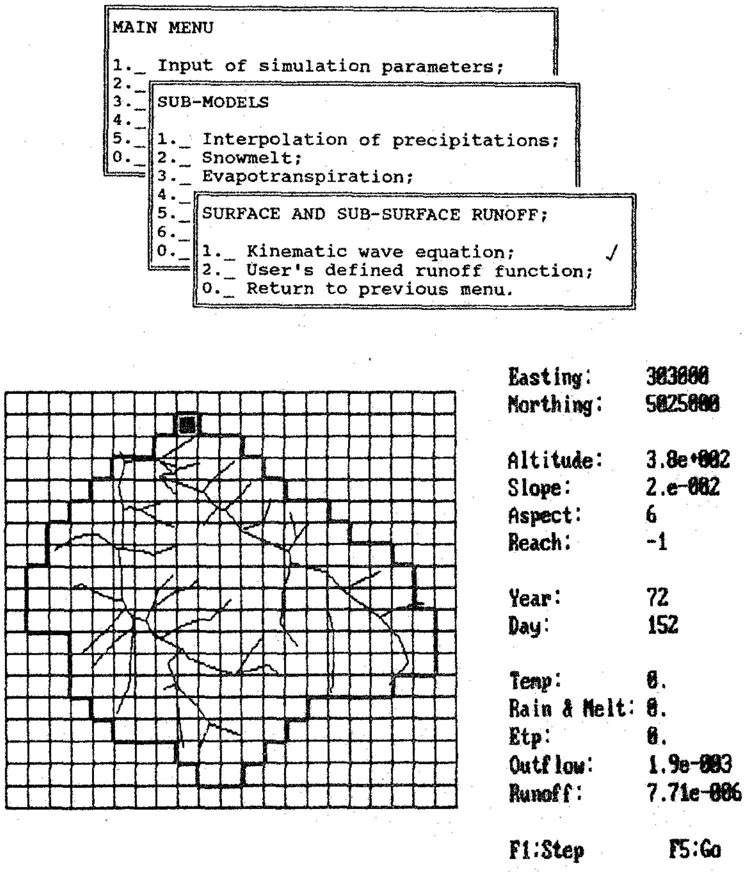
Both from the point of view of research, in this study, and from the practical consideration that ground-based data sources are constantly being cut back, the chosen model must be able to make use of satellite data. A.J. Robinson & Associates Inc. (1986) reviewed the use of remote sensing techniques for streamflow forecasting. This study considered 60 hydrologic forecasting models and 58 types of observed hydrologic data and concluded that the two forecasting models most suitable for remotely sensed data under Canadian conditions were the CEQUEAU (Charbonneau, 1977) and the HSP-F (Johanson, 1981).

The outcome of these steps was the selection of a development of CEQUEAU (known as the Hydrotel model, Fortin et al, 1988) as the main model. A simple lumped model, SLURP, (Kite, 1978) is also used to get a feel for the basin and to detect errors in 'recorded' data.

B. Hydrotel Model

The Hydrotel model was developed by INRS-Eau at the University of Quebec (Fortin et al, 1988) for use on microcomputers. There are seven modules, written in the 'C' language, for data input, physiography, precipitation, evapotranspiration, groundwater hydrology, optimisation and output.

The model operates on a menu system, the user selecting the required operations of the model and specifying the necessary parameters (Figure 1). A basin 'mask' defines the arrangement of grid squares over the basin and further files define the channel reaches and the channel nodes. During a simulation run, the user can display the status of the variables and parameters for any grid square, channel reach or channel node at successive time steps. Figure 1 shows an example for a grid square. After a simulation run, temperatures, rainfall, snowmelt, outflow, surface runoff, and streamflow can all be stored for each grid square for each time interval.



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MAIN MENU

1._ Input of simulation parameters;
2._
3._ SUB-MODELS
4._
5._ 1._ Interpolation of precipitations;
0._ 2._ Snowmelt;
    3._ Evapotranspiration;
    4._
    5._ SURFACE AND SUB-SURFACE RUNOFF;
    6._
    0._ 1._ Kinematic wave equation;      ✓
        2._ User's defined runoff function;
        0._ Return to previous menu.
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```
Easting:       303000
Northing:      5025000

Altitude:      3.8e+002
Slope:         2.e-002
Aspect:        6
Reach:         -1

Year:          72
Day:           152

Temp:          0.
Rain & Melt:   0.
Etp:           0.
Outflow:       1.9e-003
Runoff:        7.71e-006

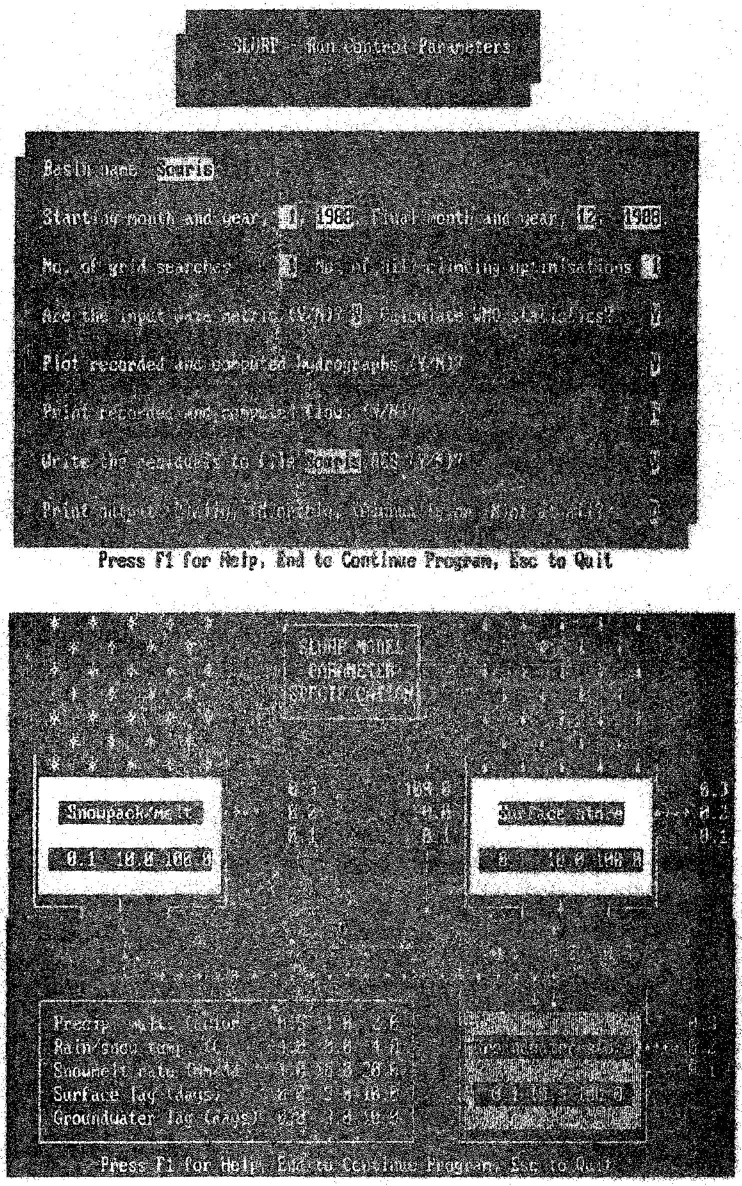
F1:Step          F5:Go
```

FIGURE 1. HYDROTEL MODEL

C. SLURP Model

The SLURP model is a simple lumped basin model which has previously been used in a comparison with the SSARR model (Kite, 1974). The model uses basin-averaged precipitation and mean daily temperature, snowmelt is calculated by the degree-day method and evaporation/evapotranspiration is calculated using the complementary relationship (Morton, 1983).

The user defines 13 parameters via a diagrammatic data-entry screen (Figure 2) and, if optimisation is required, the user sets upper and lower limits for each parameter. The user specifies the type of optimisation required (grid search or hill-climbing) and the type of output required (full WMO statistics, plotted hydrographs, printed hydrographs, residuals to a datafile, daily, monthly, or annual printout of results).



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SLURP - Run Control Parameters

Basin name Souris
Starting month and year, 1, 1988 Final month and year 12, 1988
No. of grid searches [illegible] No. of hill-climbing optimisations [illegible]
Are the input data metric (Y/N)? [illegible] Calculate WMO statistics? [illegible]
Plot recorded and computed hydrographs (Y/N)? [illegible]
Print recorded and computed flows (Y/N)? [illegible]
Write the residuals to file Souris.RES (Y/N)? [illegible]
Print output (D)aily, (M)onthly, (A)nnual, or (N)ot at all? [illegible]
Press F1 for Help, End to Continue Program, Esc to Quit
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SLURP MODEL
PARAMETER
SPECIFICATION

Snowpack/melt
0.1  10.0 100.0

Surface store
[illegible]  10.0 100.0

0.1 [illegible] 100.0

Precip. mult. factor   [illegible]
Rain/snow temp. (C)    [illegible]
Snowmelt rate (mm/C)   [illegible] 20.0
Surface lag (days)     [illegible]
Groundwater lag (days) [illegible]

Press F1 for Help, End to Continue Program, Esc to Quit
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FIGURE 2. SLURP MODEL

DATA

A. Ground-based data

Ground-based data includes standard climatic data such as daily maximum and minimum temperatures, daily precipitation and daily snow on the ground as well as hydrometric and physiographic data. The physiographic data were derived from a digital terrain model.

B. Satellite Data

The types of data which satellites can provide for hydrological models include snow cover, snow water equivalent, cloud cover, precipitation and evapotranspiration data.

The extent of snow cover can be measured from visible bands and cloud cover can be estimated from a combination of visible and infra-red or near infra-red bands (Allen & Mosher, 1986). Snow water equivalent can be estimated from passive microwave data for open agricultural land such as the Canadian prairie region (Goodison, 1986). Moses and Barrett (1986) describe three procedures currently being used to estimate precipitation from satellite; the ERL method using the cloud life history, the Earthsat method which combines satellite estimates with synoptic reports, and the Bristol method of cloud indexing. Regional evapotranspiration may be estimated from the energy balance equations. Remote sensing can assist by measuring the difference between surface and air temperatures (Hatfield et al, 1983).

At this stage of the study, satellite data are used only to supplement ground-based data and so no precipitation rates need be assumed. The only data initially needed from satellite are the percentages of each grid square within the two basins which are covered by snow and/or cloud on each day.

The practical choice of satellites which could provide the necessary data include the polar-orbiting Landsat series using multispectral scanner (MSS) or thematic mapper (TM) data, the sun-synchronous, SPOT satellite, the NOAA series of polar-orbiting satellites and the GOES series of geostationary satellites. SPOT has the highest resolution (10-20 m.) but was rejected on cost grounds. Landsat offered next best resolution (30 m. for TM and 80 m. for MSS) but, again, the data were too expensive to use on a daily basis. GOES, although exceeding the required frequency, was not used because of the problem of distortion at high latitudes.

On a cost and availability basis, it was decided to use daily visible and near infra-red data (bands 1 and 2) from a NOAA satellite. Land-use data were derived for each basin from Landsat MSS images using supervised classification.

C. Database

After a review of commercial database packages a microcomputer database with a full-screen data entry system was written in Fortran. The chief advantage of this system over proprietary database languages is that the data are in files which are directly accessible by programs written in Fortran or C. Using a proprietary database would have meant keeping two sets of parallel files, possibly leading to confusion.

The system starts with menu options of displaying, updating or printing data, calculating those data which are distributed over the grid squares of the basin, or adding a new basin to the database (Figure 3). Distributed data include precipitation, temperature, snowdepth, elevation, slope, aspect, and land-use types. If the user is adding or modifying data then the appropriate form will be screened and, if the data already exist, they will be located using direct access files and will be written to screen for viewing or update. Backing up each form is an extensive help, error and validation system to ensure data quality. After filling or correcting the form the user can scroll forward or backward a month at a time or can choose another station or return to the main menu.

BASINS

In selecting basins to test the models on, three criteria were used; the basins should be in different physiographic and climatic zones within Western Canada, they should be large enough to enable use of NOAA images, and they must have routine hydrometeorologic data available.

After considering many basins, the Kootenay and the Souris were selected. The Kootenay basin is situated in the Rocky Mountains in south-eastern British Columbia while the Souris covers parts of south-eastern Saskatchewan, south-western Manitoba and northern North Dakota. Figure 4 shows the locations and 3-dimensional diagrams of the two basins while Table 1 compares some characteristics of the basins. Table 2 shows the numbers of ground-based stations for each basin.

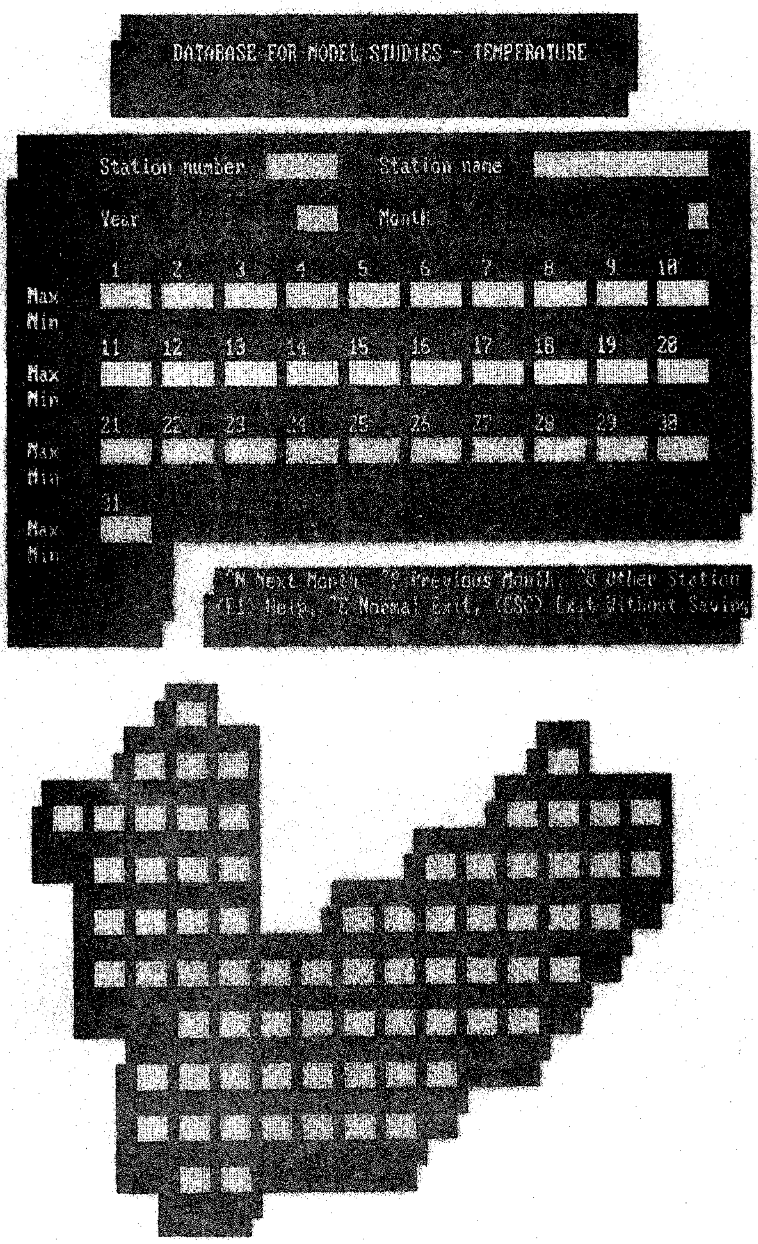
In a prairie watershed, such as the Souris, not all runoff reaches the main stream. Because of the topography, some runoff is caught in depressions or sloughs with internal drainage. The effective real drainage area varies with antecedent conditions and with precipitation in a complex manner but, in order to deal with this in a model, the effective drainage area is defined as that area of a basin which might be expected to contribute runoff with a probability of 50%. The effective drainage areas for Alberta, Saskatchewan and Manitoba have been mapped (PFRA, 1983) and have been used to delineated for each grid square in the basin.

DATA ANALYSIS

A. Satellite Data on Magnetic Tape

NOAA satellite data are received from the Atmospheric Environment Service station in Edmonton, Alberta, on magnetic tape. The image is transferred from a 1600/6250 bpi 9-track tape drive, via a windowing routine, to a 70 Mb hard disk on a 386 microcomputer.

Initially, a particularly clear image for each basin was geographically corrected to the basin topographic map, and all subsequent images are registered to these base images. The cloud-covered and snow-covered areas within the basins are identified using a supervised classification technique and the percent of each grid square covered by cloud, snow, both or neither is calculated (Kite, 1988). At any stage in the image analysis process 35mm slides and 8.5 x 10.8 cm. colour prints can be obtained using an on-line image capture device. A series of computer programs were written to automate the process but a high degree of manual intervention is still needed for registration and classification of the image.



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DATABASE FOR MODEL STUDIES - TEMPERATURE

    Station number          Station name

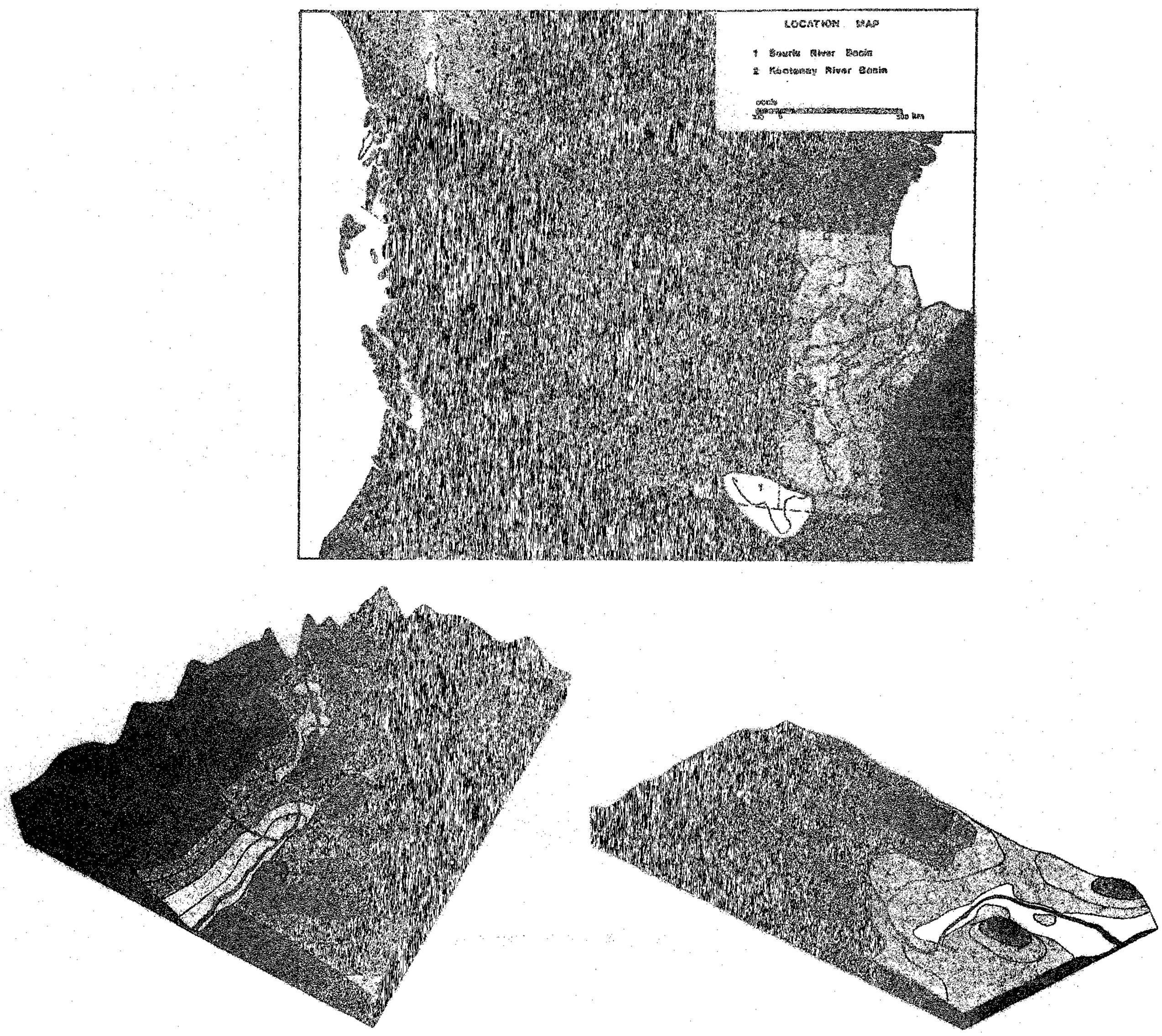
    Year                    Month

     1    2    3    4    5    6    7    8    9    10
Max
Min
     11   12   13   14   15   16   17   18   19   20
Max
Min
     21   22   23   24   25   26   27   28   29   30
Max
Min
     31
Max
Min
           ^N Next Month, ^P Previous Month, ^O Other Station
          (F1) Help, ^E Normal Exit, (ESC) Exit Without Saving
```

FIGURE 3. DATABASE

TABLE 1
COMPARISON OF BASINS SELECTED

	KOOTENAY	SOURIS
Average elevation, m.	1,860	570
Average slope, %	.36	.0073
Average aspect, degrees clockwise	176	155
Land use - primary	coniferous	grass
- secondary	bare ground	crop
- tertiary	crop	bare ground
Drainage area, km**2	7,100	58,700
Effective drainage area, km**2	7,100	20,500
Mean annual precipitation, mm.	600	450
Mean annual runoff, m**3/s	120	30
Mean annual runoff, mm.	520	40



Kootenay River Basin

Souris River Basin

FIGURE 4. STUDY BASINS

TABLE 2
DATA AVAILABILITY

	KOOTENAY	SOURIS
No. of streamflow stations	5	15
No. of meteorological stations	18	54
No. of snowcourses	8	17

B. Satellite Data as Photographic Images

In an attempt to speed up the image analysis process, black and white photographs of NOAA visible and IR images are used to interpolate between the digital images. The method has been described by Johnstone and Ishida (1984) and was originally used for flood forecasting on the St John River, New Brunswick. The equipment consists of a dedicated microcomputer, a video camera and copy stand and a density slicing unit.

The image is navigated to a pre-digitised basin outline containing geographical reference points by moving the photograph and zooming the video camera. The image is videodigitised and the digital data are analysed using density slicing to select suitable thresholds for cloud and snow cover. Finally, a program calculates the percent of each grid square covered by cloud, snow, both or neither. Usually, the visible image is used for snow on the ground and the IR is used to measure cloud. Again, a high degree of manual intervention is needed, but the average time needed to analyse an image is only 20 minutes compared to 2 hours using the totally digital system.

Table 3 shows some statistics for the NOAA black and white images used. It can be seen that for the Kootenay basin, over 90% of the images expected were received and over 97% of those received were usable. Of the usable images, only 36% were for non-100%-cloud days (that is, days for which snow-cover could be measured). Comparable statistics for the Souris basin are 93%, 97% and 48%. Reasons for images being unuseable include poor alignment (missing part or all of the basin) and streaky images resulting from software problems at the satellite reception station. The software problems are associated with a major changeover in the satellite reception system.

TABLE 3
SATELLITE DATA AVAILABILITY

	KOOTENAY	SOURIS
Total no. of images expected (Jan. 1, 1988 - Feb. 28, 1989)	425	425
Total no. of images received	388	397
Total no. of useable images	378	387
No. of images < 100% cloud	135	184

C. Combining Satellite and Ground-based Data

The database contains an option for combining satellite and ground-based data in which temperature data are distributed to each grid square using data from the three closest climate stations, adjusted for elevation and weighted according to inverse distance. Precipitation is distributed similarly and is then adjusted using the satellite cloud cover information. Snow cover distribution uses the additional information from satellite snow cover data and from snowcourse water equivalent data. Temperature and precipitation lapse rates are variables and the user can also manually adjust any of the distributed data.

DISCUSSION

It seems clear that some of the more important areas in hydrology are currently the design of better physically-based catchment models, the design of techniques to use satellite data in models and the development of better land-phase components for global circulation models.

At this stage in the study, the basins and the models have been selected and a PC database has been built to combine ground-based data with satellite data. Data for the two basins for 1988 has been collected and the first model has been calibrated for the basins. The daily satellite data have been analysed for cloudcover and snowcover for both basins for 1988. The availability rate of data from the selected satellite source is high and encourages the view that such data would be useful for developing research models for practical water resources engineering.

The next stage is to calibrate the Hydrotel model for the two basins, investigate the utility of the present satellite data and expand the satellite data to other parameters.

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