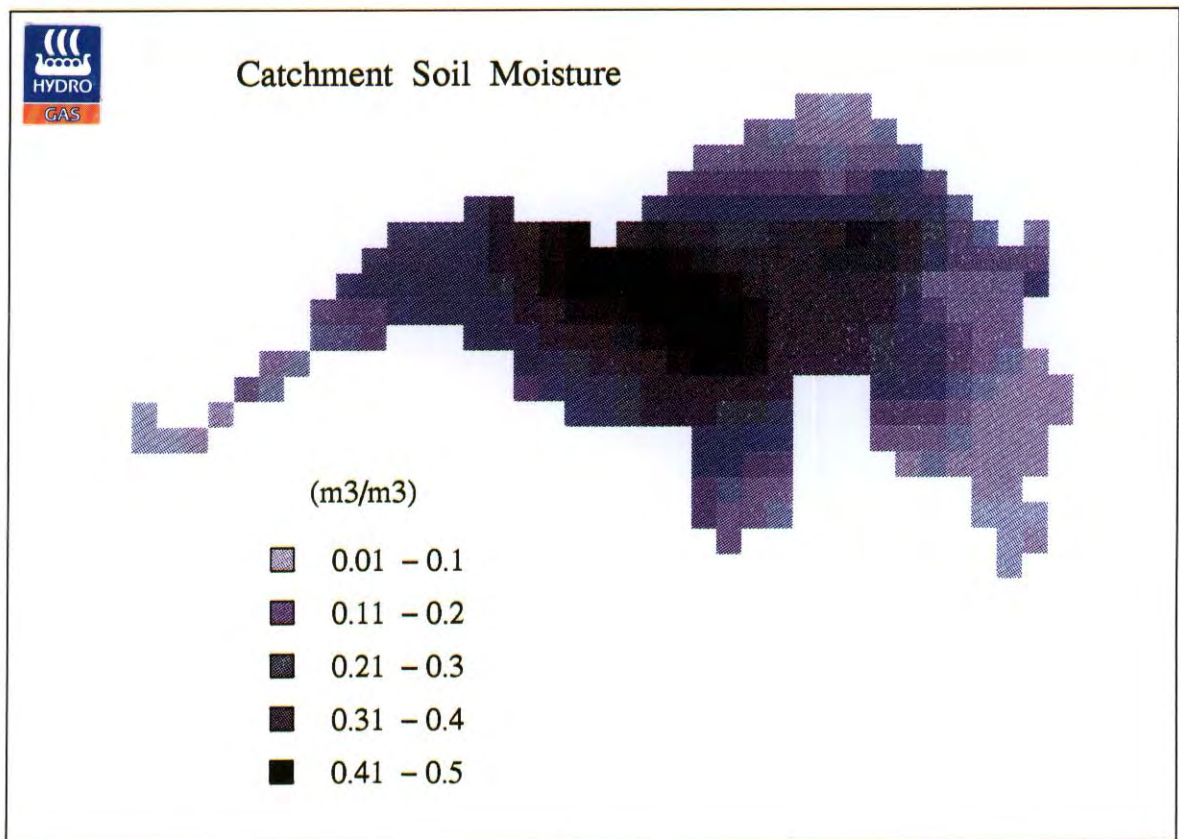


CLIMATE CHANGE RESEARCH

REPORT 8/1996

CLIMEX project:

Soil Moisture Monitoring
and Hydrological Response



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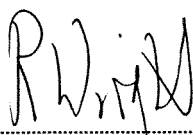
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<p>Abstract</p> <p>This report describes the data obtained from the soil moisture monitoring programme and its application in determining catchment hydrological budgets. The hydrological response of the catchments is evaluated through modelling and hydrochemical tracer experiments.</p>
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CLIMEX PROJECT

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Soil Moisture Monitoring and Instrumentation

The establishment of a soil water monitoring system for the CLIMEX catchments required automated instrumentation with good spatial and temporal resolution, installed at minimum disturbance to the catchment. In view of these requirements, the method of Time Domain Reflectometry (Tdr) was chosen and installed in KIM in July 1993. Measurement of soil water content with Tdr is based upon the attenuation of a voltage pulse passed down a sensor embedded in the soil, the attenuation depends upon the dielectric properties of the soil which are strongly influenced by the degree of moisture. The system in KIM consists of a computer, a cable tester, a multiplexer with coaxial switches and probes connected to the system by lengths of coaxial cable. Thirty four probes, 10, 35 and 50cm in length, were installed throughout KIM catchment during August 1993 (Figure 1), the majority inserted vertically in the soil. Twelve probes are located in the control and 22 in the treatment area. The temporal resolution of readings is determined through control files set up by the operator and the resulting waveforms saved should they be required for further analysis.

The Tdr monitoring is augmented in the area of deepest soil in KIM by measurement of a semi-permanent water table level using a pressure transducer (Figure 1), installed at the soil-rock interface beneath 70cm of soil, the head of water is recorded hourly.

Twenty four probes were installed in EGIL catchment during August 1995, located predominantly in the deeper pockets of soil (Figure 2). Tdr measurements were undertaken for 5 months to determine if soil moisture differs significantly in comparison to KIM and to provide data for hydrological modelling purposes.



Figure 1. KIM Catchment Instrumentation

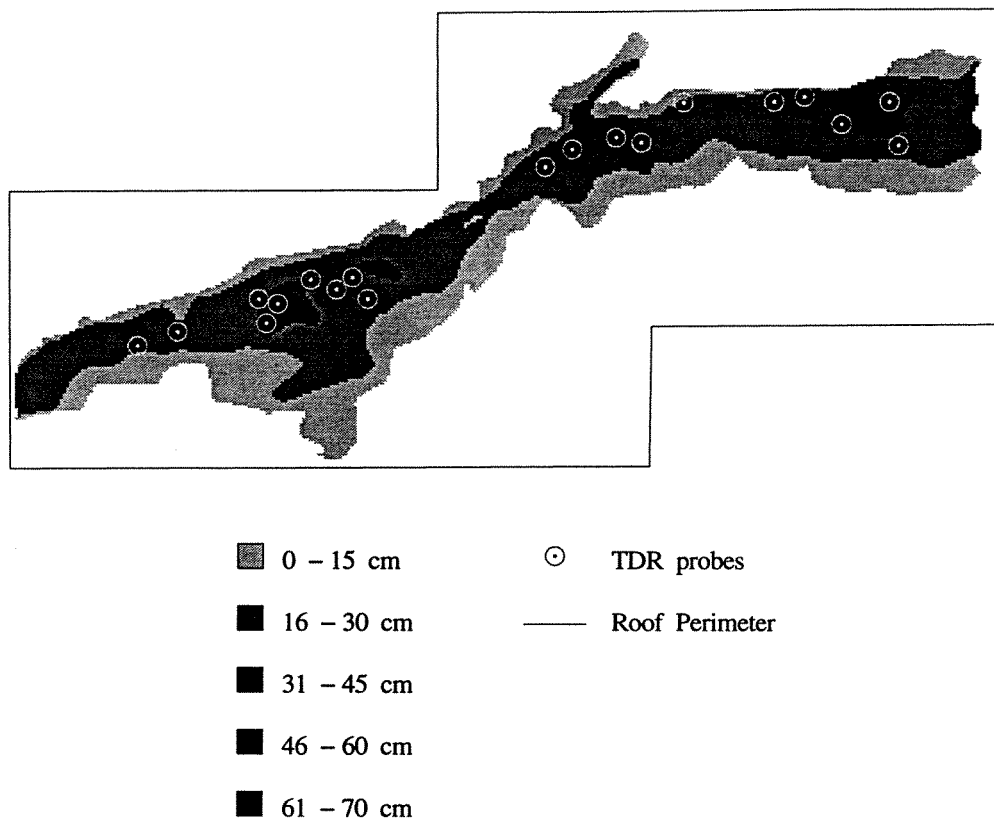


Figure 2. EGIL Catchment, Soil Depth and Tdr Probe Location

Soil Moisture Time Series

The nature of Tdr probe response varies considerably throughout a catchment and is determined by a number of factors, principally, the local soil and vegetation type, probe length, depth and orientation of installation, initial soil moisture and topographical position. This variation is illustrated by daily time series data from three probes of differing length (Figure 3) located in close proximity to one another in the deep soil bowl near the outflow in KIM. Variation between these probes may be as great as $0.45 \text{ m}^3\text{m}^{-3}$ at any given time. However, all three probes clearly illustrate the drying out of the catchment soil to moisture contents as low as $0.03\text{m}^3\text{m}^{-3}$ during early August 1995. Analysis of the time series in Figure 4, reveals the varying response of the soil to regimes of wetting and drying and provides an indication, in conjunction with discharge data, of the degree of soil moisture required to initiate runoff in response to rainfall. The sensitivity of each probe, evident in Figures 3 and 4, highlights the hydrologically dynamic nature of the soil at Risdalsheia principally caused by the shallow and highly porous nature of the soil.

Figure 5 illustrates daily time series data from the pressure transducer. The rapid rise and fall of the water table further illustrates the hydrologically responsive nature of the catchment. The water table lies c. 42cm above the bedrock surface when the catchment is at its wettest, falling to zero during the driest periods. Some malfunction of the instrument has occurred however, at low moisture contents.

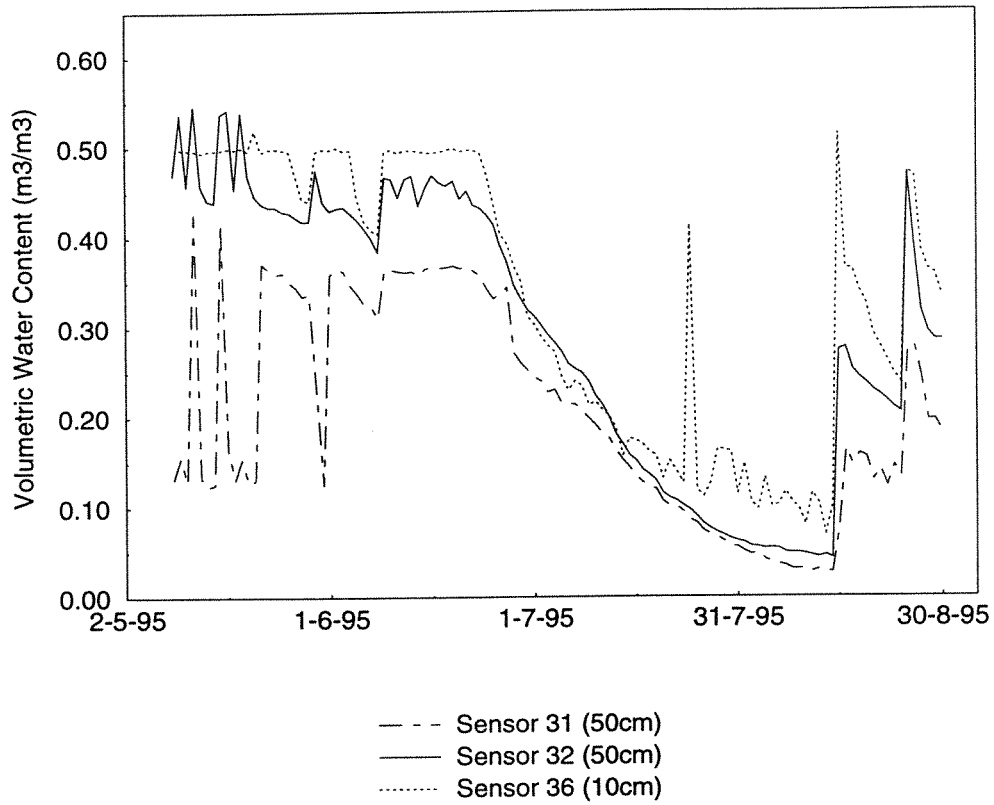


Figure 3. Daily Time Series data for three Tdr probes, KIM catchment

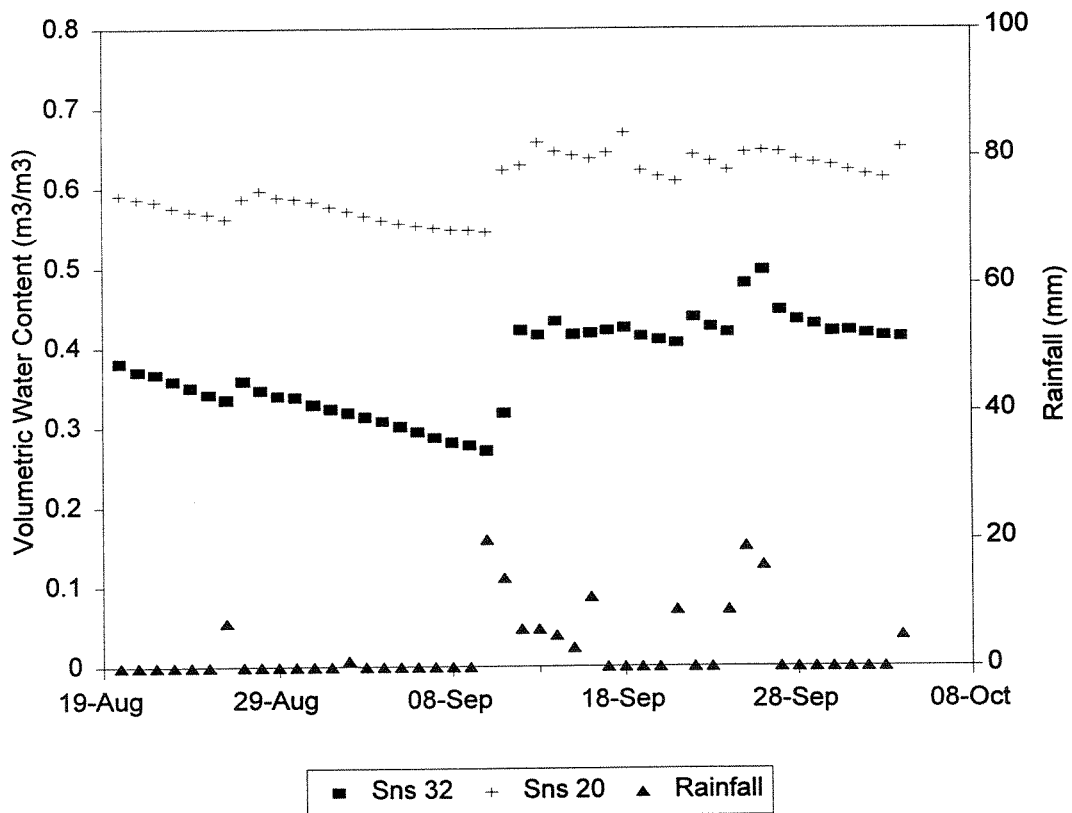


Figure 4. Tdr and Rainfall Time Series Data (1994), KIM Catchment

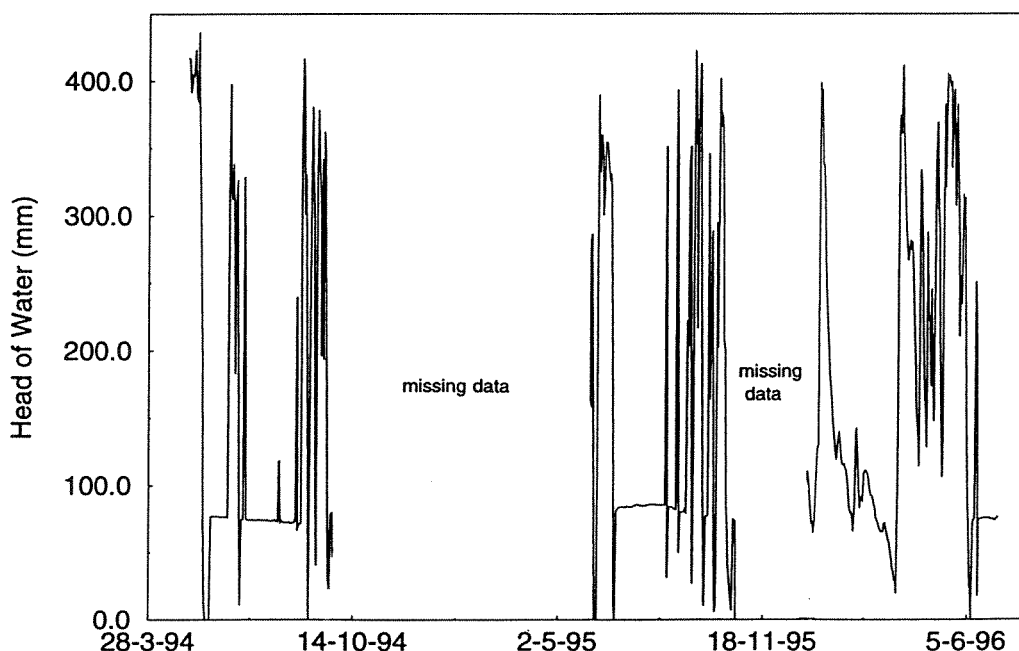


Figure 5. Pressure Transducer, Daily Time Series Data

The data available from the soil moisture monitoring programme in both KIM and EGIL catchments is summarised in Tables 1a and 1b.

Catchment	Period	Temporal Resolution	Notes
Kim	20/08/93 to 08/10/93	4 hours	sensors 8,14,20,26,32 only
Kim	16/02/94 to 08/03/94 03/05/94 to 08/05/94 13/06/94 to 21/06/94 08/08/94 to 04/09/94	4 hours	
Kim	09/05/95 to 31/08/95	12 hours	sensors 19-29 no data
Egil	01/09/95 to 12/03/96	4 hours	sensor 2 no data
Kim	03/05/96 to present	12 hours	

Table 1a. Tdr data available (Volumetric Water Content (m^3m^{-3}))

Kim	05/05/94 to 24/09/94 02/06/95 to 22/10/95 01/01/96 to present	hourly	Instrument error at low soil moisture
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Table 1b. Pressure Transducer data available (Head of Water (mm))

Catchment Hydrological Budgets

Mathematical interpolation of each Tdr derived point value of soil moisture using the technique of kriging enables soil moisture to be extrapolated over the whole catchment. The resultant soil moisture patterns (Figure 6), illustrate the spatial variability in the soil water available to plants at any given time. The wettest area of soil in KIM at any given time corresponds to a region of deep soil (c.60cm) in the centre of the largest soil pit (Figure 6). These kriged soil moisture surfaces enable water storage for the whole catchment over a given time period to be calculated. Since soil moisture is determined by Tdr, and rainfall inputs and runoff outputs are automatically logged, evapotranspiration (Et) is then the only remaining variable in the catchment water balance;

$$\text{Rainfall} = \text{Runoff} \pm \text{Change in Soil Moisture} + \text{Et}$$

Such whole catchment estimates of Et avoid the errors associated with Et estimates from micro lysimetry caused by, for example, changes in the hydrological boundary conditions, disturbance of soil, and lumping up from the lysimeter to the whole catchment scale. In addition, production of the kriged moisture surfaces at a suitable temporal scale during periods without rainfall and runoff may potentially discriminate relative spatial differences in Et rates throughout a catchment and aid in the interpretation of soil-plant responses to the experimental treatments.

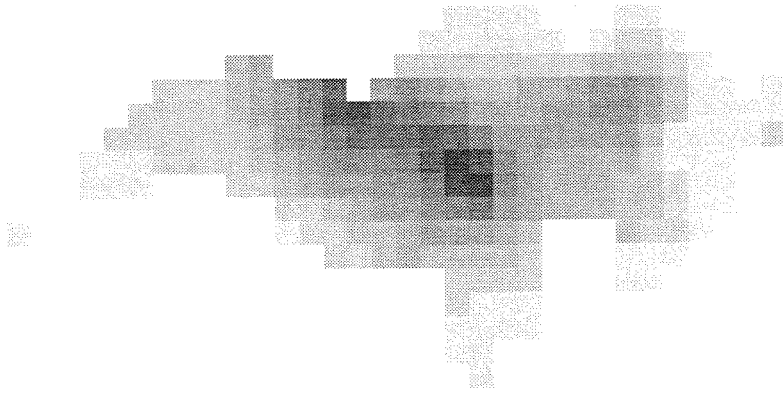
Estimates of whole catchment Et for Kim over time periods varying between 24 hours to c. 6 months are illustrated in Table 2. The values vary from 25.2 to 78.8%, suggesting that considerable errors may be associated with the methodology. Estimates for the two longest time periods (25.2% and 32.4% over 104 and 160 days respectively) are similar to values of 25-30% derived by calculating Et as the difference between rainfall and runoff on an annual basis and assuming soil moisture change to be negligible. The implication of these results is that the kriging process leads to an inaccurate estimation of whole catchment soil moisture. Estimates of Et made over longer time periods, using this method, are able to dampen the effect of errors in calculating the change in soil moisture and consequently produce more realistic results.

Time Period	Et Estimate (%)
11/08/94 to 01/09/94	43.8
25/08/94 to 01/09/94	60.3
17/06/94 to 25/08/94	78.8
04/03/94 to 16/06/94	25.2
04/03/94 to 25/08/94	32.4
30/08/95 to 31/08/95 (No rainfall or runoff)	0.0021m over 24 hours

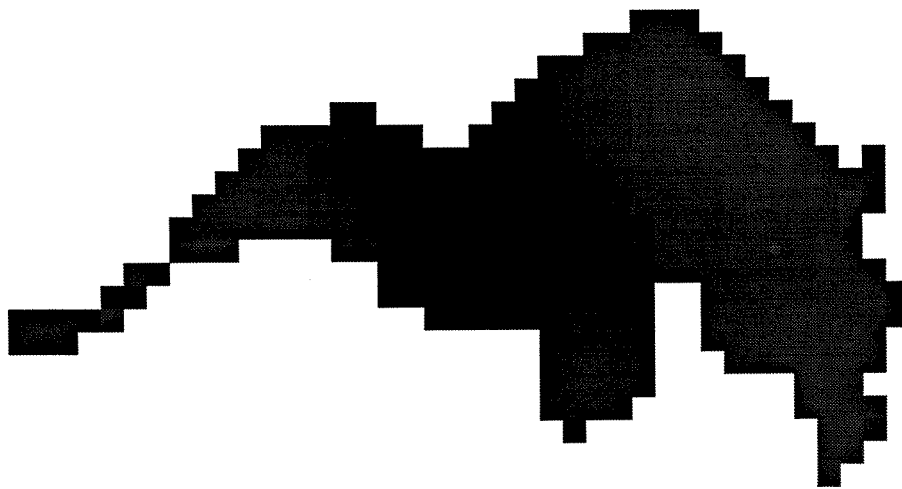
Table 2. Estimates of whole catchment Et for KIM

Figure 6. Kriged soil moisture surfaces for KIM.
(a) 13/06/94; low moisture status. (b) 16/06/94; near saturation

(a)



(b)



Volumetric Soil Moisture Content
(m³/m³)

- 0.01 – 0.120
- ▒ 0.121 – 0.240
- 0.241 – 0.360
- 0.361 – 0.480
- 0.481 – 0.600

Soil Moisture Variability

The inherent variability in the physical and chemical properties of the soil at Risdalsheia causes a large spatial variation in soil moisture, both laterally and vertically. The vertical installation of most Tdr probes results in soil moisture values integrated over two or three soil horizons, this lumped value is derived from soil that may differ considerably in structure and porosity, and hence moisture content. Consequently, the error associated with estimates of whole catchment soil moisture can be attributed, in part, to the insensitivity of the Tdr probes to vertical variation in soil moisture.

In order to quantify the degree of lateral variation in soil moisture, an experiment was undertaken in a soil pit close to the study catchments. Tdr readings were taken from 92 probes installed vertically in the 19.25m² rectangular pit, at 25cm intervals along transects 25cm apart. Total soil moisture for the pit was calculated by kriging 10 tdr readings, chosen randomly from the 92 possibilities, for each of 20 estimates undertaken. This process was then repeated, incrementing the number of randomly chosen probes by 5 each time 20 estimates were obtained. ANOVA was then undertaken comparing each set of 20 estimates with the 20 obtained by using 90 of the 92 readings. (Two probe readings were discarded to provide a minimal variance for purposes of analysis). For comparative purposes it was assumed that estimates using the 90 probes represented the true soil moisture content of the pit. The analysis enabled discrimination of the minimum number of randomly chosen probes (S_{min}) that are required such that no significant difference exists between soil moisture estimates using all 90 readings and those estimated using S_{min} . Table 3 illustrates that S_{min} lies between 50 and 55 probe readings, confirming that lateral variability in soil moisture is high and that a probe density of less than that of S_{min} (c. 2.7 probes m⁻²) introduces significant inaccuracies into the estimation of total soil moisture. Fifteen randomly chosen probes from the pit represents a relatively high probe density (0.78 probes m⁻²) for whole catchment studies (KIM has a density of 0.043 probes m⁻²) however, estimates of soil moisture differ to those using 90 probes by upto 30%, resulting in calculated differences in soil moisture content of the pit which are significant at the 99% level.

These estimates using randomly located probes are however, likely to represent a worse case scenario. Probe location in the study catchments has been undertaken with respect to soil depth, topography and vegetation, enabling the broad variations in soil moisture to be discriminated and estimation of catchment soil moisture to be optimised for a given number of probes.

	55 probes	50 probes	45 probes	15 probes
90 probes	NS	90%	95%	99%

Table 3. Significance (%) levels of the ANOVA test for soil moisture estimates using a varying number of randomly chosen probes against estimates using 90 probes. NS indicates significance is below the 90% level.

Hydrological Modelling

The Institute of Hydrology distributed model (IHDM), a physically based distributed hillslope hydrology model has been applied to the CLIMEX catchments and used to predict changes in soil moisture through time as driven by rainfall input. The resultant values of soil suction derived from the model describe the 'strength' at which the moisture is held in the soil matrix against the force of gravity and thus the susceptibility of soil water to downward and lateral movement. In addition, values of soil suction describe the available moisture for uptake by vegetation, defined as the water held between field capacity and the permanent wilting point. The model is calibrated using a number of soil physical characteristics, rainfall, runoff and meteorological parameters from each site. The model is validated through a comparison of observed and predicted runoff. In addition, a more qualitative assessment of model performance may be made through comparison of the predicted values of soil tension with Tdr derived soil moisture data. The modelled soil water data is necessary to provide estimates from 2 of the 3 study catchments at any one time, since only one Tdr system is available.

Model Calibration

(i) Representation of hillslope topography

The two dimensional nature of IHDM necessitates a simplification of the topography within the CLIMEX catchments. The four isolated soil pits separated by granite outcrops in Kim are represented as one continuous soil block, 40m long, of varying width and depth. In Egil, a uniform strip of soil extends down through the centre of the catchment, bounded on each side by granite bedrock of a higher elevation. It is assumed that rainfall, falling upon the granite, flows immediately down the rock face and into the soil. This enables the catchment to be modelled without the inclusion of rock within the topography, which would require, for example, representing the rock as soil with a porosity of zero. Limitations of IHDM with respect to the topographical representation are apparent; The soil depth of each width strip must remain constant, hence a compromise is required between representation of the soil depth in the deepest bowl areas and the thin soil at the edge of each soil pocket. In both catchments, the hillslope finite element mesh consists of 1 metre spaced vertical elements, six nodal points located down each element are thought to be sufficient in number to represent vertical variations in soil matric potential.

(ii) Vegetation

Vegetation is represented in both catchments as a continuous cover of heather and trees with a root depth of 12cm. The root depth and density distribution are used to weight evapotranspiration at each vertical element.

(iii) Saturated Hydraulic Conductivity (Ksat)

Ksat values derived in the field using double ring infiltration suggest 0.2m hr^{-1} for the organic rich surface layers and 0.004m hr^{-1} for the deeper mineral horizons. Incorporation of these

figures within the model provides a reasonably close match between predicted and observed discharge. However, such infiltration ring derived Ksat values probably do not adequately reflect the extent of non-Darcian macropore flow along, for example, root channels. This may explain the slight improvement in predicted discharge derived by increasing Ksat in the mineral layers to 0.04m hr^{-1} .

(iv) Pf Curves

Pf curves for the soil at Risdalsheiea have been provided by Wageningen Agricultural University. These relationships illustrate the variation of soil moisture with soil tension, and describe both the porosity and moisture retention properties of the soil. Curves have been provided for the organic rich top 15cm of soil and the deeper mineral layers and suggest a porosity of c.75% and 50% respectively. These values correlate closely with Tdr derived volumetric water contents recorded at saturation. A number of parameters that describe these Pf curves, including porosity, are required by the model to derive soil tension at each nodal point.

(v) Antecedent Soil Moisture

The initial soil moisture status for a model simulation is derived from Tdr data and utilised to read a corresponding value of soil tension from the Pf curves. One lumped value is then applied to the whole catchment.

(vi) Meteorological Data

Extensive meteorological data and canopy characteristics are required for the IHDM preprograms in order to derive the effective rainfall for a simulation. In the absence of some of the required data, manipulation and simplification of the preprograms has been necessary, for example, during simulations with continuous rainfall, Et is assumed to be negligible and canopy interception is estimated from vegetation maps.

Model Simulations

Figure 7 illustrates a simulation of a rainfall event in Kim during October 1994. A hydrochemical tracer experiment was conducted during this period resulting in 44 hours of rainfall, this was modelled for Kim as $c.2.2\text{m}^3 \text{hr}^{-1}$ of rain applied to a soil block of 290m^2 . Predicted runoff closely matches observed using $K_{\text{sat}} = 0.2 \text{ m hr}^{-1}$ and 0.04 m hr^{-1} in the surface and deeper layers respectively, and an initial lumped catchment soil tension of -0.45m . The sensitivity of the model to the initial soil moisture conditions is illustrated in Figure 8. Wetter initial conditions of -0.25m tension significantly increase discharge in the first few hours. Alteration of initial soil moisture conditions by $+ \text{ or } - 0.2\text{m}$ requires 15 hours of rainfall to fully remove the effect of the initial conditions from predicted runoff.

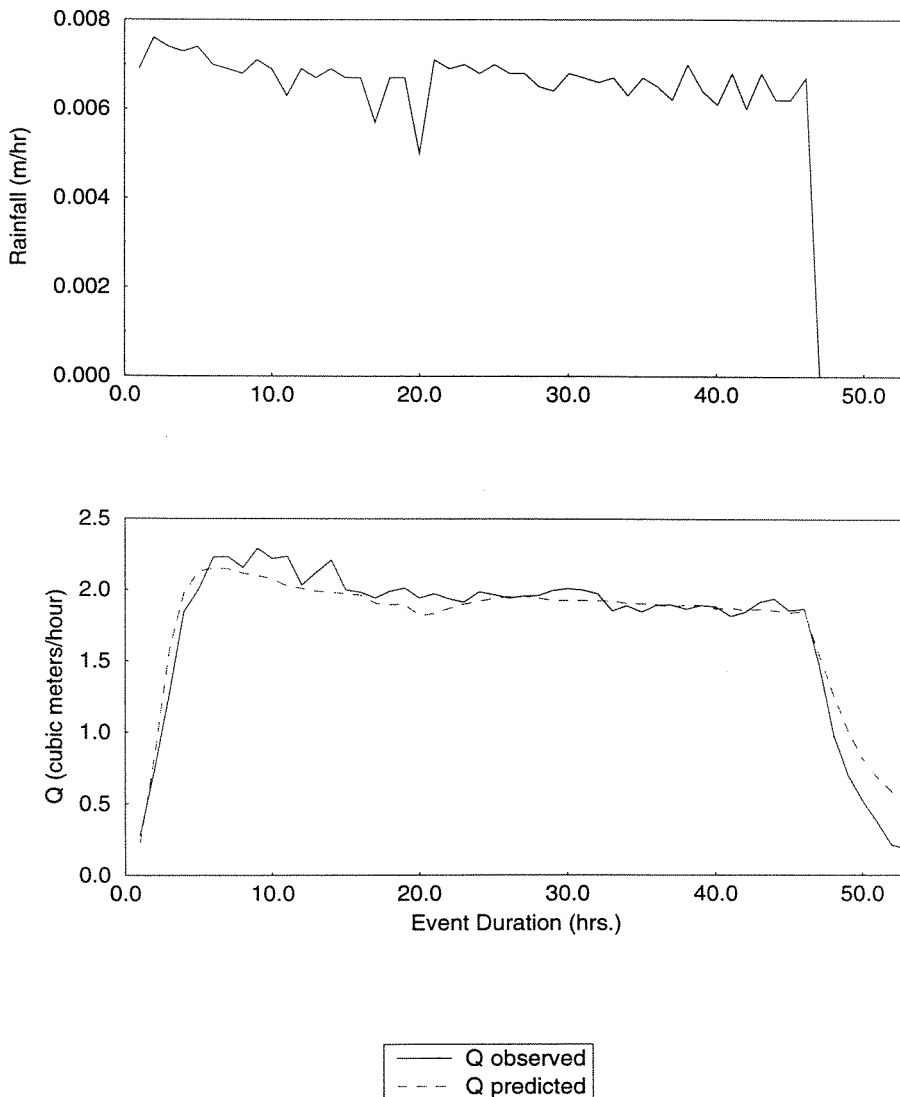


Figure 7. Rainfall, Observed and Predicted Runoff for a model simulation in KIM

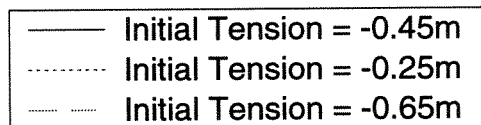
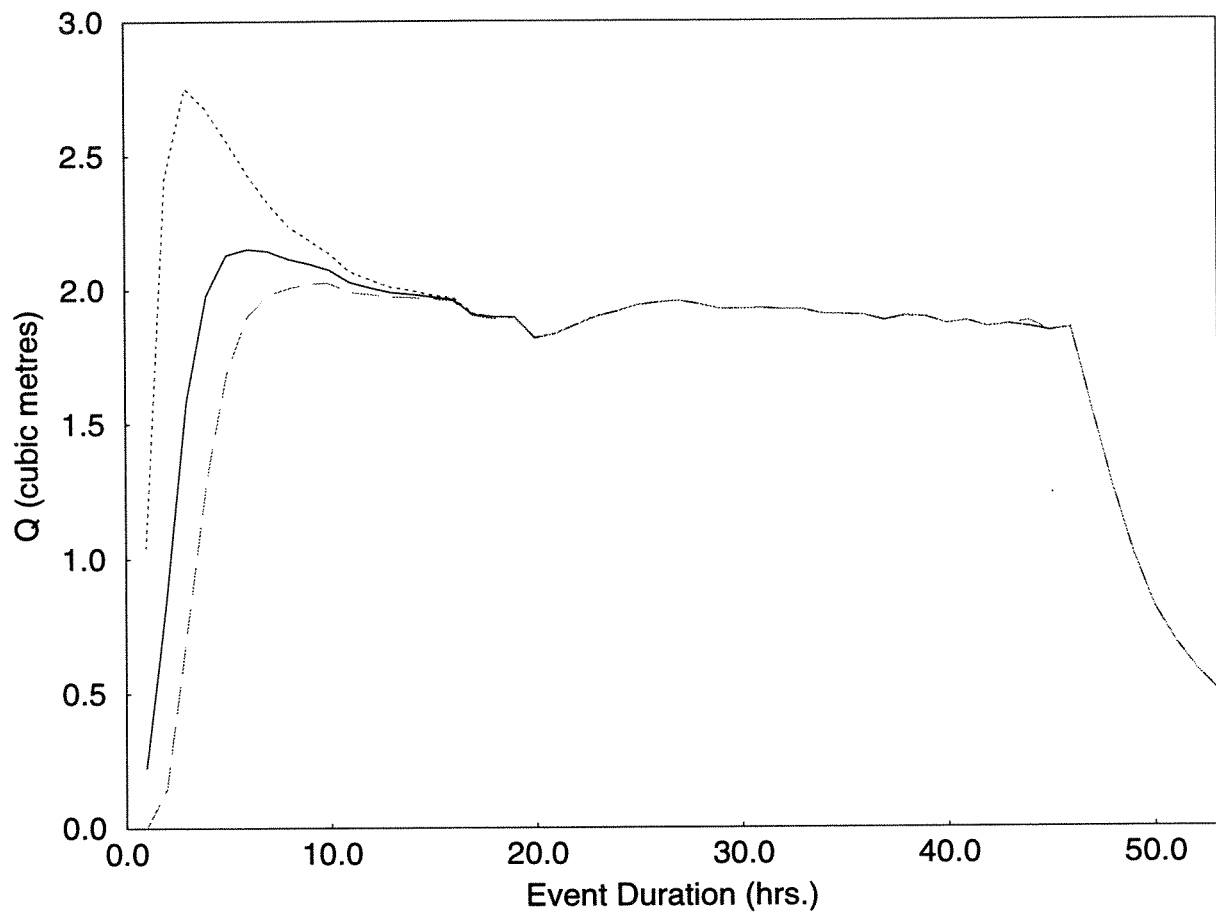


Figure 8. Model Sensitivity (Runoff) to initial soil moisture conditions

A schematic representation of soil tension simulated for a rainfall event in Kim in August 1995 is illustrated in Figure 9. After 12 hours of continuous rainfall, the catchment has become saturated with positive pore water pressures evident. Only the surface layer of soil at the top of the catchment and the mid depth soil layers exhibit a negative tension. Hydrochemical tracer experiments indicate dominant flowpathways in the soil surface layers and at the soil-rock interface supporting this simulated response. After 96 hours (rainfall finished at $t=20$) the upper catchment has dried considerably and large negative tensions are evident. However, vertical infiltration and lateral drainage maintain high soil moisture contents downslope and the deeper soil pockets remain at, or close to, saturation. This modelled hydrological behaviour is supported by both Tdr and pressure transducer time series data which indicate that the deepest soil pockets may take a substantial period of time to dry.

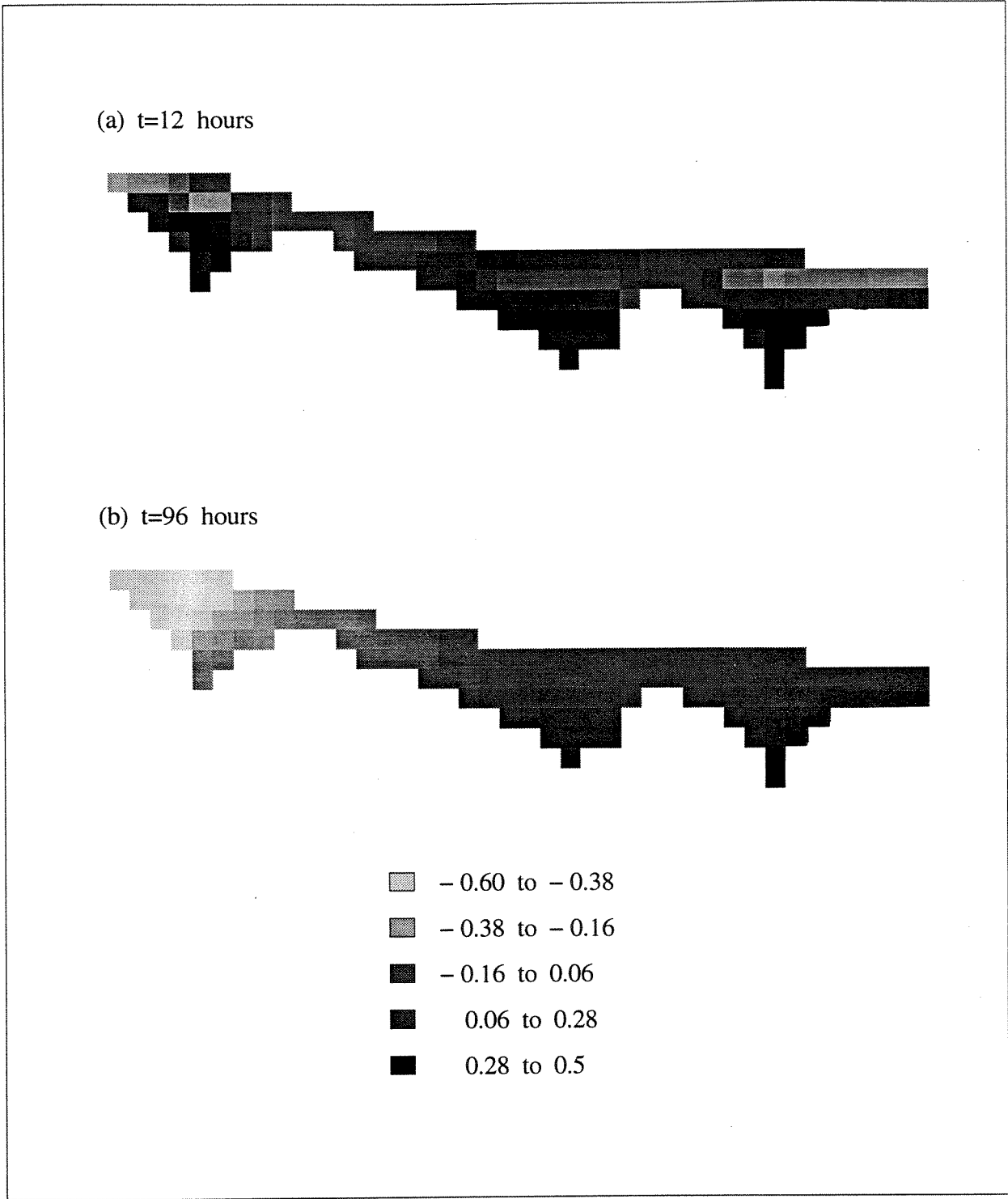


Figure 9. Soil Water Tension (metres) in KIM as predicted by IHDM. Positive tensions indicate saturation, negative values indicate undersaturation

Hydrochemical Tracer Experiments

A series of hydrochemical tracer experiments have been undertaken in KIM. Rainfall dosed with a known concentration of Lithium Bromide is sprayed onto the catchment that is in hydrological steady state with respect to inputs and outputs. The recovery of bromide in runoff and soil solution enables assessment of the flow contribution from pre event (old) soil water and (new) rain water. In addition, dominant flowpathways are identified and soil water residence times determined. Initially runoff is dominated by old water (Figure 10), but mixing of new and old water in the soil surface layers results in an increasing new water contribution with time, such that after 15 hours of tracer injection, new water contributes c.60% to the flow. Analysis of soil water recovered from surface lysimeters indicates that the organic soil surface layers act as a dominant flowpathway for rain water through the catchment. Deep soil lysimeters indicate that a significant pathway also exists at the soil-rock interface for water that has infiltrated slowly down through the soil matrix.

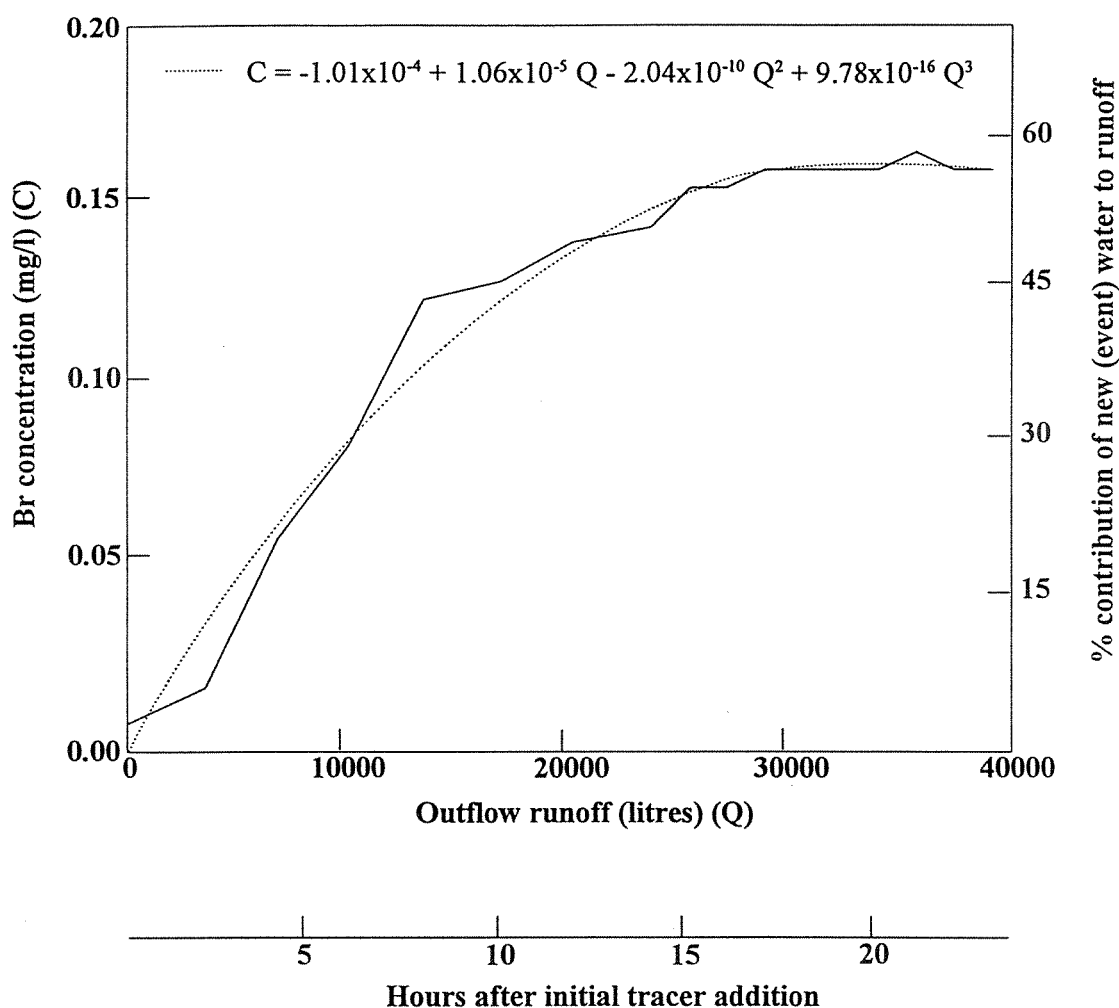


Figure 10. Bromide Trace, Kim Catchment - August 1995

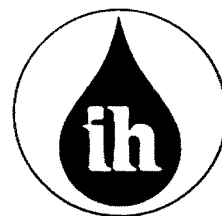
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