Institute of Hydrology

Natural Environment Research Council

SOME GUIDELINES FOR THE USE OF THE INSTITUTE OF HYDROLOGY DISTRIBUTED MODEL

Ministry of Agriculture, Fisheries and Food Project FD4-AA2 Report

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August 1992

Executive Summary

Ministry of Agriculture, Fisheries and Food research and development project FD4-AA2 has seen the development at the Institute of Hydrology of physically-based rainfall-runoff models. The major model produced is the Institute of Hydrology Distributed Model (IHDM).

The IHDM uses surface and subsurface flow equations, linked in a hydrologically appropriate manner, to model catchment water contents and flows. The main methodologies are numerical approximation techniques; the main parameters are hydraulic and material properties and catchment geometric information.

The last few years have seen the build-up of a body of information on handling this complex model, and this report presents a distillation of this experience with reference to both published and unpublished experience. The aim of so doing is to serve as a concise background for understanding model use and results, and to promote efficient use by new model users.

After a brief setting of the model context, the main classes of information concern:-

- the spatial discretisation of the finite element domain of the variably saturated subsurface Darcian formulation
- the requirement of the model in terms of the early 'run-in', and the related question of establishing model initial conditions from extremely sparse data
- expected processing times
- a discussion of parameters to which the model is most sensitive
- aspects of the effect of uncertainty of parameter values
- the rainfall discretisation for efficient runoff modelling.

Contents

1. Introduction

The River and Coastal Engineering Group, and more recently the Flood Protection Division, of the Ministry of Agriculture, Fisheries and Food has funded the development of physically-based rainfall-runoff modelling at the Institute of Hydrology from the early 1980s. A major model has been developed in the project, together with accompanying techniques. The chief model became known as the Institute of Hydrology Distributed Model (IHDM), the 'distributed' in the title referring to the inclusion of the spatial aspect of runoff generation.

The IHDM is a complex rainfall-runoff model, simulating runoff by the numerical solution of physical equations of surface and subsurface flow in a catchment. This type of work may have been seen, to some degree, as a speculative and innovative MAFF involvement in that it was less an extension of existing flood prediction procedures and more a line of parallel investigation without a tried-and-tested performance record. IH expertise in many aspects of the hydrological cycle has been involved in the research and development.

A number of research papers have been published on the model, following the description of its structure and methodology in an IH publication (Beven, Calver and Morris, 1987). The current report aims to distil the experience gained in the course of this research and development programme into the form of guidelines for handling the model by future users. It draws on the published information and also on unpublished experience of use. This is considered timely in that a body of such information has now accrued, and the project itself is currently scheduled to end in 1994. Model use is, and is likely to continue to be, increasingly undertaken by those new to the details of the model.

The reader, or new user, is still referred to the above reference (Beven, Calver and Morris, 1987) for the basic structure of the model. Only a brief outline will be given here. Recommendations for handling a number of aspects of the model, as defined in the chapter headings, are then considered. These are offered with the aim of efficient and meaningful use of the model.

2. An outline of the structure and methodology of the IHDM

The model solves standard flow equations for surface and subsurface flow which are linked together in a hydrologically appropriate manner. The handling of the linkages is the particular feature, rather than the equations *per se*, that is to say, the research and development has concentrated on the complex context in which the equations are set and solved.

The formulations aimed to be general, accounting for many hydrological circumstances rather than, for example, a site-specific or a steady state model. It is a model able to be run in continuous transient mode under spatially variable circumstances.

Surface flow, whether overland on hillslopes or within a channel network is modelled by a kinematic wave formulation as

$$b_c \frac{\partial Q_c}{\partial t} + c \frac{\partial (b_c Q_c)}{\partial y} - cbi = 0$$

where Q_c is discharge
- y downslope distance
- t time
- b_c flow width
- c kinematic wave velocity ($\partial Q/\partial A$ where A is cross-sectional area of flow)
- i lateral inflow rate per unit downslope length

This is solved in one dimension (the downslope) by a finite difference scheme.

Subsurface flow, of variably saturated nature, is modelled as classic Darcian porous medium flow. Together with considerations of continuity, this gives the standard Richards' equation

$$b_s \frac{\partial \theta}{\partial t} - \frac{\partial}{\partial x}\left[b_s k_x \frac{\partial \phi}{\partial x}\right] - \frac{\partial}{\partial z}\left[b_s k_z \frac{\partial \phi}{\partial z}\right] - Q_s = 0$$

where θ is volumetric soil water content
- ϕ hydraulic potential
- k hydraulic conductivity
- x horizontal distance from drainage divide
- z vertical distance (above an arbitrary datum)
- b_s slope width
- Q_s source/sink term

This is solved by a two-dimensional vertical plane finite element method. Consideration of the third dimension is made by attributing a (variable) width to each part of the two-dimensional plane. It should perhaps be recalled in passing that the reason for numerical solution is the complexity of real world conditions to be met.

A catchment is therefore divided into appropriate hillslope planes and channel components. Calculations are done on each portion separately and are accumulated for inclusion into appropriate down-catchment channel reaches. The nature of the method means that the state of flows, water contents, hydraulic potentials etc. can be viewed for any time and any point.

3. Discretisation

This section deals with the establishment of a suitable finite element mesh for the subsurface flow modelling.

Figure 3.1 shows slope discharge results for simulations which vary only in the mesh structure. The theoretically best result is given by the heavier line (1a on figure) from a fine mesh of aspect ratio 1:1. This ratio is that of the dimensions of the sides of the quadrilateral element: in the IHDM the elements have parallel verticals.

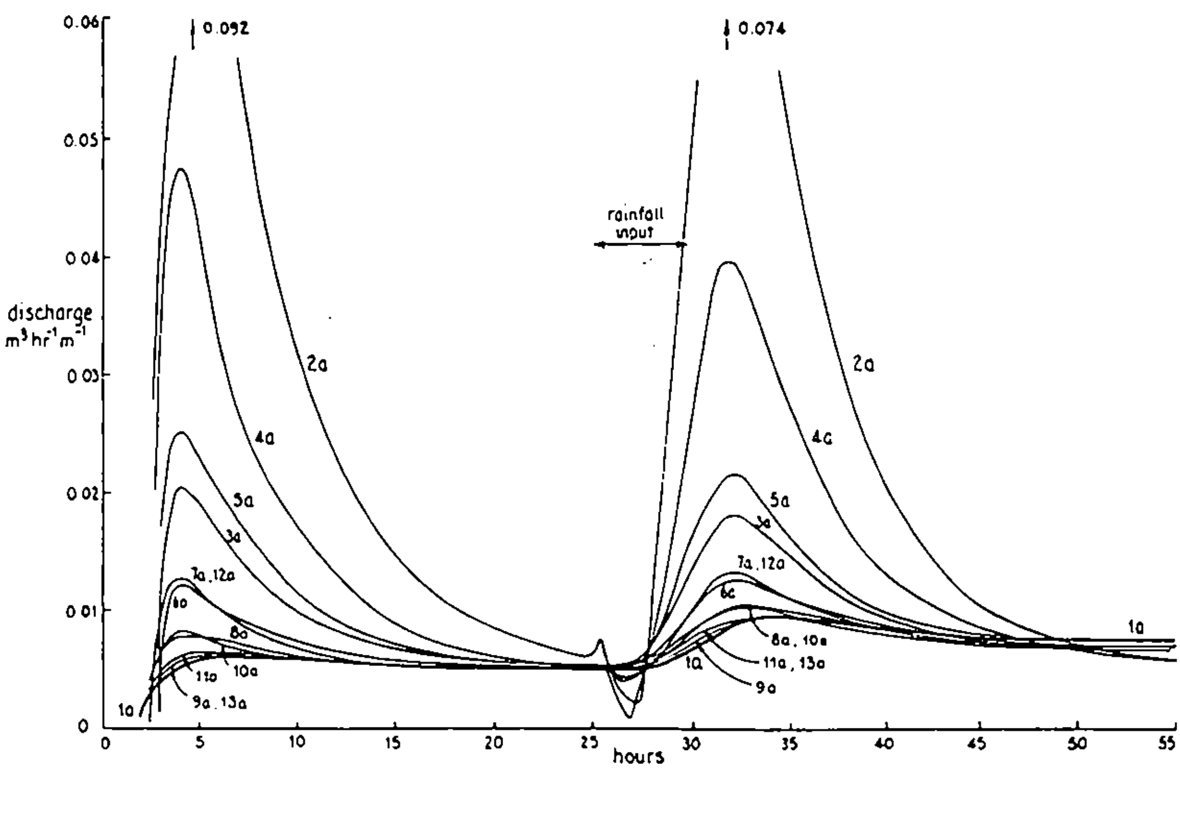

Figure 3.1 *Hillslope discharges for different finite element meshes, covering simulation run-in time and rainfall event.*
(Reproduced, with permission, from Journal of Hydrology, v.110, pp.165-179, 1989).

We aim to avoid using, say, the material parameters of the model to compensate for bad numerical approximation: to do so would defeat the purpose of the physically-based modelling.

One should be aware of the danger of using long, thin elements (i.e. of high aspect ratio) which could appear convenient on a long, thin domain, which is frequently involved in hillslope modelling of a permeable soil over impermeable bedrock.

There is, however, a practical reason not to always use the 1:1 elements, and this is computing time. Figure 3.2 shows some examples, in this case for 55 hours simulated data on a 500 m hillslope (also featured in Figure 3.1 above). Despite technological

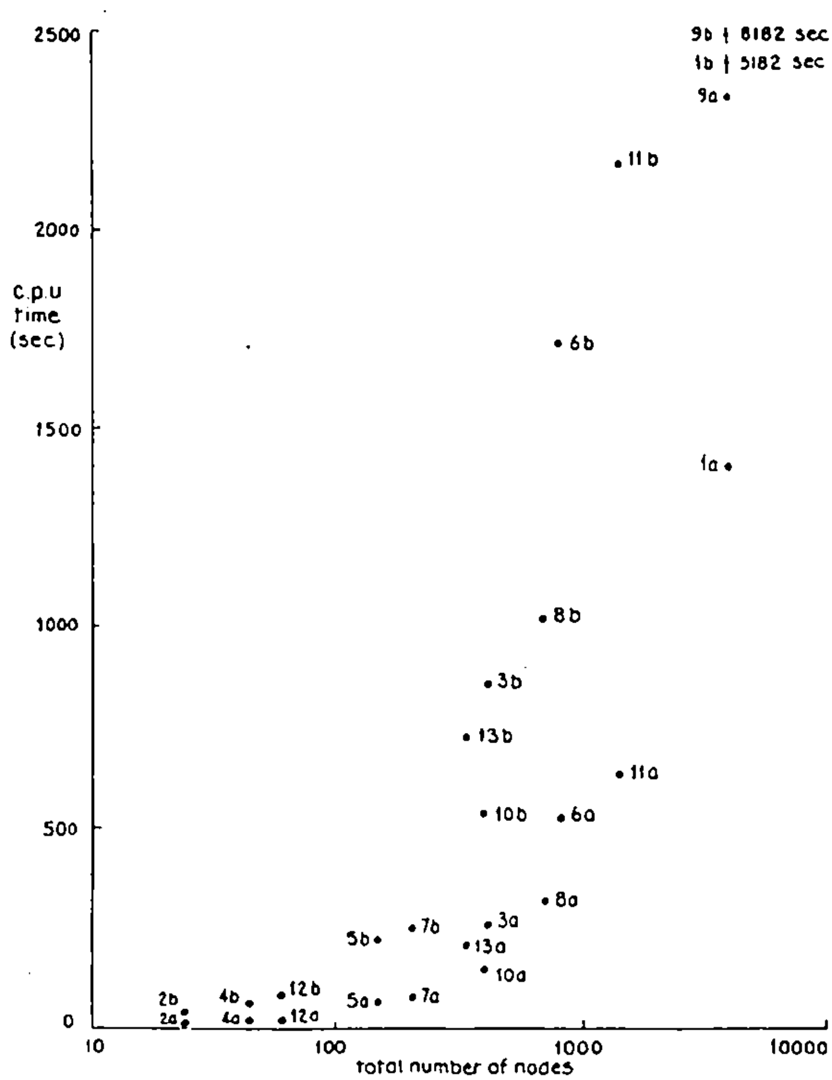

Figure 3.2 *Relationship between computer processing time and number of calculation nodes.*
(Reproduced, with permission, from Journal of Hydrology, v.110, pp.165-179, 1989).

reductions in computing time, the IHDM remains a relatively computationally intensive model, particularly because of its consideration of the unsaturated zone in which water contents, pressures and conductivities are varying in both space and time. It should perhaps be noted in passing that this handling of the unsaturated zone is also one of the model's strengths, particularly since the saturated/unsaturated boundary is an integral part of the model (after initial specification) and is efficiently handled.

Numerical experiments were therefore carried out to determine practical guidelines for suitable finite element meshes with suitable run times: the results are reported in Calver and Wood (1989). The conditions are a little different depending on whether one is primarily concerned with discharge prediction or the prediction of hydraulic or pressure potentials in soil/aquifer materials.

Figure 3.3 sums up accuracy of discharge prediction with respect to c.p.u. time (here on an IBM mainframe). (See Section 4.1 for comparisons of run times with other machines).

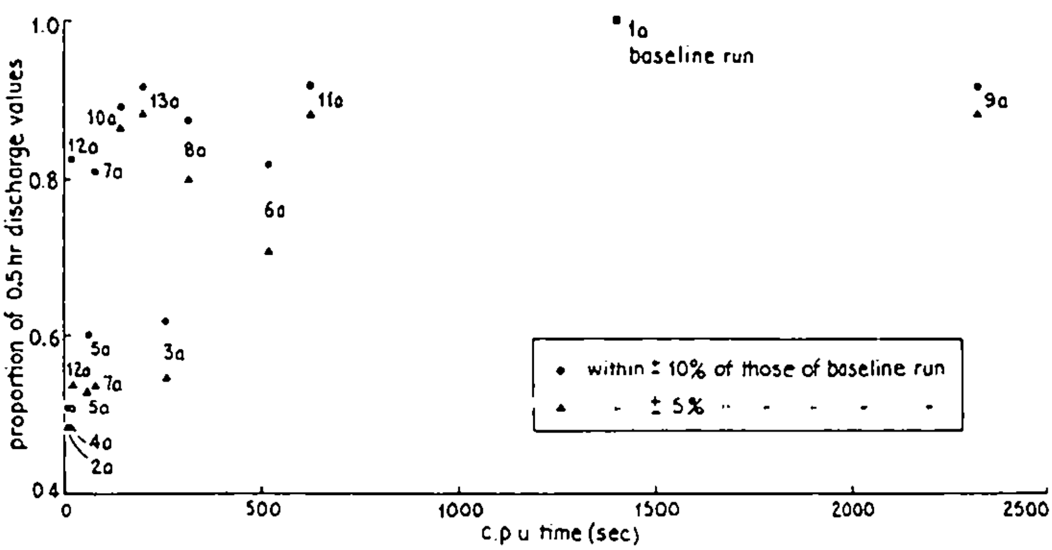

Figure 3.3 *Relationship between processing time and accuracy of discharge prediction.*
(Reproduced, with permission, from Journal of Hydrology, v.110, pp.165-179, 1989).

From Figure 3.3, together with other information derived from the numerical experiments, the main discretisation conclusions are as follows. It should be noted that representative rather than comprehensive conditions were investigated. In practice, too, materials and topographic irregularities need also to be taken into account in spatial discretisation.

- For hydraulic potential prediction smaller elements are preferable with aspect ratios $\leq$ 20, ideally $\leq$ 10.

- For discharge prediction similar regular grids are suitable, though irregular grids fining towards flow boundaries are acceptable.

- Finer grids reduce run-in time (see Section 4 below); lower aspect ratios for a given number of nodes reduce run times.

- Within regard to the trade-off possibilities of Figure 3.3, a higher number of nodes (here, one node per 1-2 m^2 of domain) is appropriate when the emphasis is on accurate prediction; fewer nodes (here, one node per 2-10 m^2) can be used if shorter execution time is the priority.

4. Initial conditions and run-in times

The model initial conditions, in terms of water in the hillslope material, are very significant in terms of event modelling outcomes and, indeed, may persist for some considerable time.

Figure 4.1 shows differences in discharges promoted entirely by differing initial pressure potential conditions. Figure 4.2 and Table 4.1 give an idea of the degree of persistence of initial conditions.

The fundamental difficulty is that initial conditions are rarely, if ever, known in practice, particularly in the unsaturated zone. It may in practice prove best to treat the initial condition, particularly if defined by a single or small number of parameters, as the subject of optimisation (see, for example, Calver, 1988). It is, though, not a straightforward process to validate at different degrees of wetness from calibration runs; a range may be required (Calver and Cammeraat, in press).

The question of model run-in times is closely associated with initial condition specification: this is the period of simulation without perturbation by rainfall to allow for any mathematical or hydrological 'settling down'. Mathematically, if one is using a good finite element grid (see Section 3 above) only a few time steps are needed for run-in and the avoidance of early oscillation. Hydrologically, it may take some considerable time to establish, if that indeed is what is required, a steady baseflow, given that one is making an approximation to real-world initial water conditions. This time varies with the initial values, though as a very general rule-of-thumb can be some 100 hours for commonly-used situations running with 0.5-hour time steps.

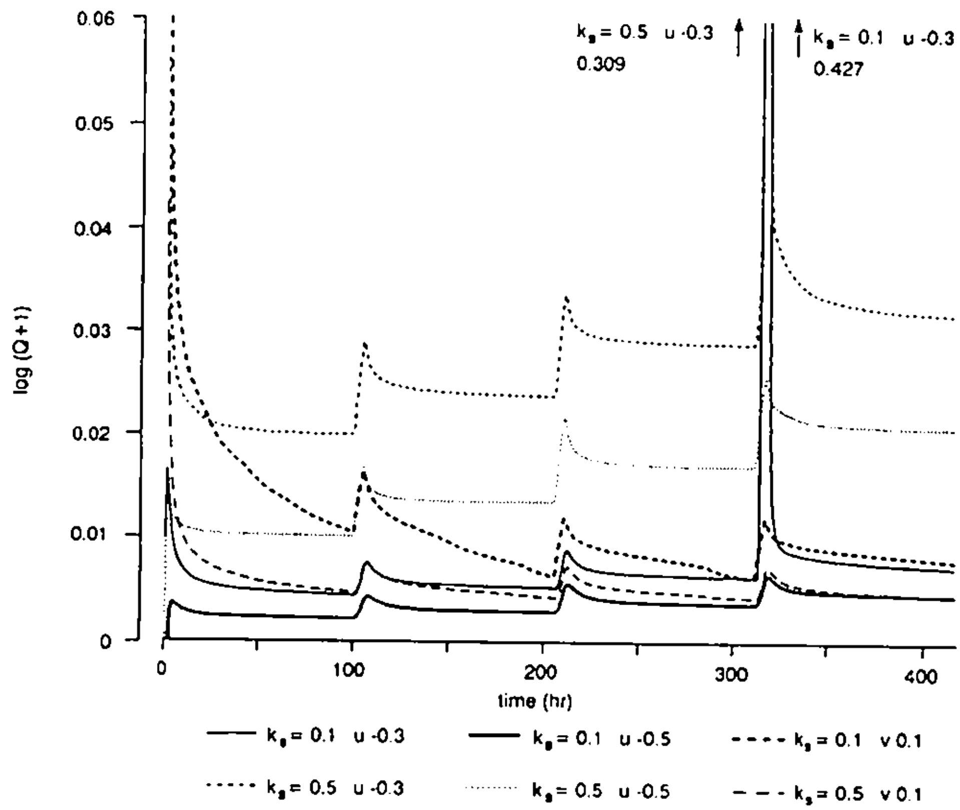

Figure 4.1 *Effects of initial pressure potential differences on hillslope discharge: three identical storm events. Q is discharge (m^3 hr^{-1}) from 1 m slope width; u denotes uniform initial pressure potential at the value (m) indicated; v 0.1 denotes pressure potential at 0.1 of elevation above datum.*
(Reproduced, with permission, from Journal of Hydrology, v.130, pp.379-397, 1992).

Table 4.1 *Slope-base discharges during drainage period for different initial conditions*

ψ_{ui}(m)	k_s(m h^{-1})	Q_{100}	Q_{300}	Q_{1000}
-0.5	0.1	0.00467	0.00225	0.00048
-0.3	0.1	0.00935	0.00270	0.00048
-0.5	0.5	0.00423	0.00164	0.00054
-0.3	0.5	0.00430	0.00165	0.00054

Q in m^3 h^{-1} for unit width (to 5 decimal places); subscript denotes length of drainage period in days. ψ_{ui} is initial pressure potential; k_s saturated hydraulic conductivity.

Practical guidelines to help overcome the lack of knowledge of initial conditions are also presented in Wood and Calver (1992). Possible ways of setting a saturated zone boundary in a hillslope are as follows:-

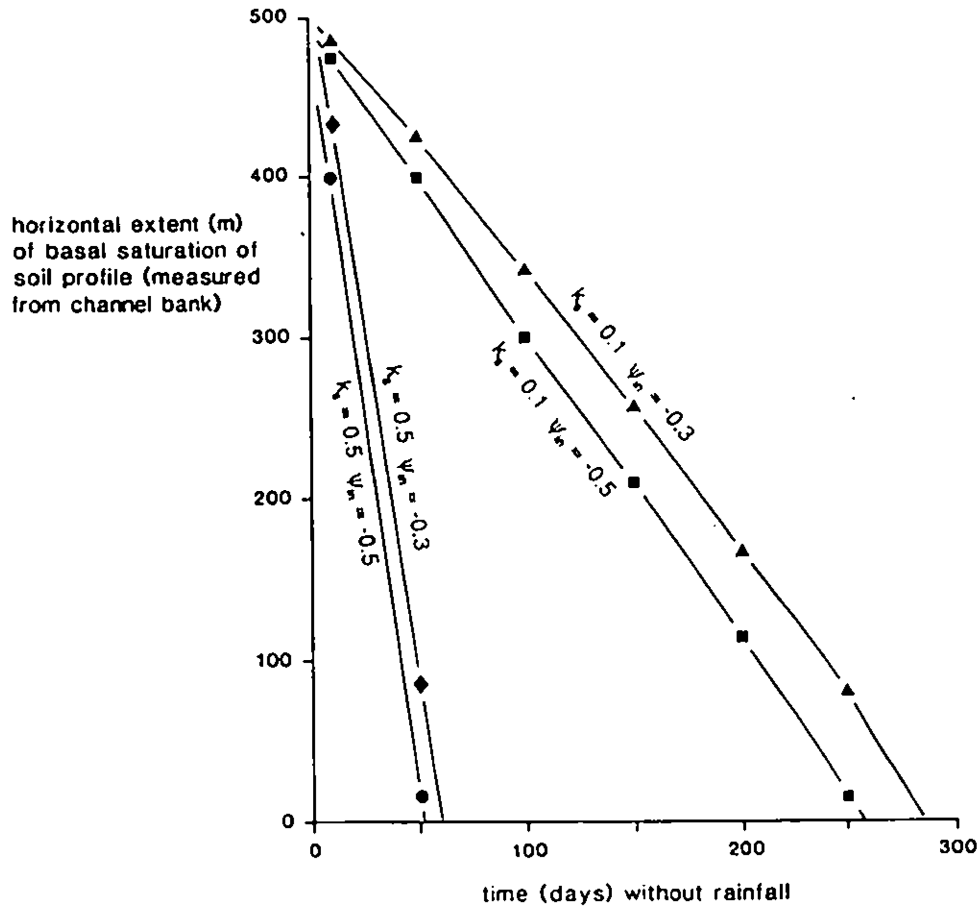

Figure 4.2 *Change in horizontal extent of soil profile saturation over time, without rainfall. ψ_{in} is initial pressure potential in m. (Reproduced, with permission, from Journal of Hydrology, v.130, pp.379-397, 1992).*

- Using a Dupuit parabola approximation based on saturated hydraulic conductivity and unit width discharge, derived by averaging of gauged flow and bankside length.

- Using a similar derivation of discharge per unit width and working back via Lynch's (1984) method to the potentials causing this outflow. This provides only a very local condition.

- The use of Darcy's Law should only be used in a very general way if working from slope-base discharge, since the hydraulic gradient locally departs from that prevailing on the slope as a whole.

- Use of a simple spatially constant or elevation-related distribution of pressure potentials, the characteristics of which have been defined by experiment.

Details further to the above points can be found in Wood and Calver (1992).

With further experience it may become possible to offer an empirical database. For example, work to date suggests that a pressure potential around -0.1 to -0.2 m works well in practice for central Wales upland catchments in winter.

5. Brief hints from field and other modelling examples

This section describes some small points; guidelines are not comprehensive because of various provisos which need to be attached to these points. It is nevertheless felt that there is benefit to be derived from these aspects of user experience.

5.1 RUN TIMES

As a guide to expected computing times, and possibly therefore the formulation of a modelling exercise, some rough indication of run times is given. C.p.u. is problem-specific and the details of machine and (Fortran) compiler specifications are important.

An example catchment of five hillslope and eight channel components, with a total of around 1500 subsurface calculation nodes takes 10-15 minutes c.p.u. on an IBM mainframe for two days predictions at 0.5-hour time steps. Surface flow calculations are short compared with the subsurface. There is not a very great 'overhead' in setting up the model; run time is very roughly determined by the number of nodes and number of time steps.

Very approximately, comparative c.p.u. times of the IHDM on different computers are as follows:-

386 PC with maths co-processor	10 time units
IBM mainframe	1
Silicon Graphics 'Indigo' workstation	0.3
Cray X-MP	0.1

The model run times mean that automatic parameter optimisation, involving many individual runs, is at present rarely undertaken: hydrological reasoning is the key to efficient parameterisation.

5.2 SENSITIVE PARAMETERS

Of the many parameters of the IHDM, some are known *a priori* and others have some expected range from which the value is determined by calibration, or consideration from within that range.

Assuming the topographic configuration and the rainfall time series to be relatively well known, and the time and space discretisation to be properly set up, then the model parameters to which output is most sensitive appear, from practical experience, to be the material saturated hydraulic conductivities, the initial hillslope water condition (see Section 4 above), the surface roughness coefficient (where overland flow is a significant component of discharge) and, to a lesser extent, the material porosities.

Some indication of these sensitivities is given by Figure 5.2.1 based on variation about a manually-optimised parameter set for a Plynlimon catchment. The details are to be found in Calver (1988). ('Overland flow' here represents that in forest drainage ditches which are deemed too small for individual treatment). It is suggested that effort is concentrated on estimation/optimisation of such parameters.

Various other points arise from this type of work and are described below.

The Plynlimon calibrated parameters noted above as being sensitive, transposed well to a neighbouring catchment of similar physiographic type.

Experience of the use of the IHDM suggests that the model's way of handling quick pipe flow/macropore flow in soils involves invoking the fast surface flow equation to match relatively flashy observed channel flows, that is, fast conduits are higher in the modelled profile than in physical reality. This is shown by Plynlimon work (Binley, Beven, Calver and Watts, 1991) and on an experimental Luxembourg slope (Calver and Cammeraat, in press). It would be possible, if this handling were not acceptable, to extract contributions to quick flow lower in the soil profile, but such complexity would only be merited for a very detailed scale. This general point reflects the non-exact operation of Darcy's Law either because of variable unsaturation or because of soil structure: this is a drawback to any model employing the formulation in the unsaturated zone and is not specific to the IHDM.

The channel bank region is a sensitive area. Fixed heads at a (constantly) saturated part of the channel bank, as in the standard formulation, need to be chosen with care, and with reference to the context, whether event or long-term. Complete feedback between channel and hillslope flows is computationally demanding, especially in a whole catchment: a time-varying 'fixed' head based on catchment experience can be an appropriate compromise.

Optimisation of parameters has usually been undertaken against stream discharge because of its comparative availability and usually acceptable accuracy. In Calver and Cammeraat (in press) reference was also made in calibration to the soil water distribution, in particular the local soil saturated/unsaturated zone boundary. Plainly use should be made of material pressure potentials should these exist for a site at a particular time.

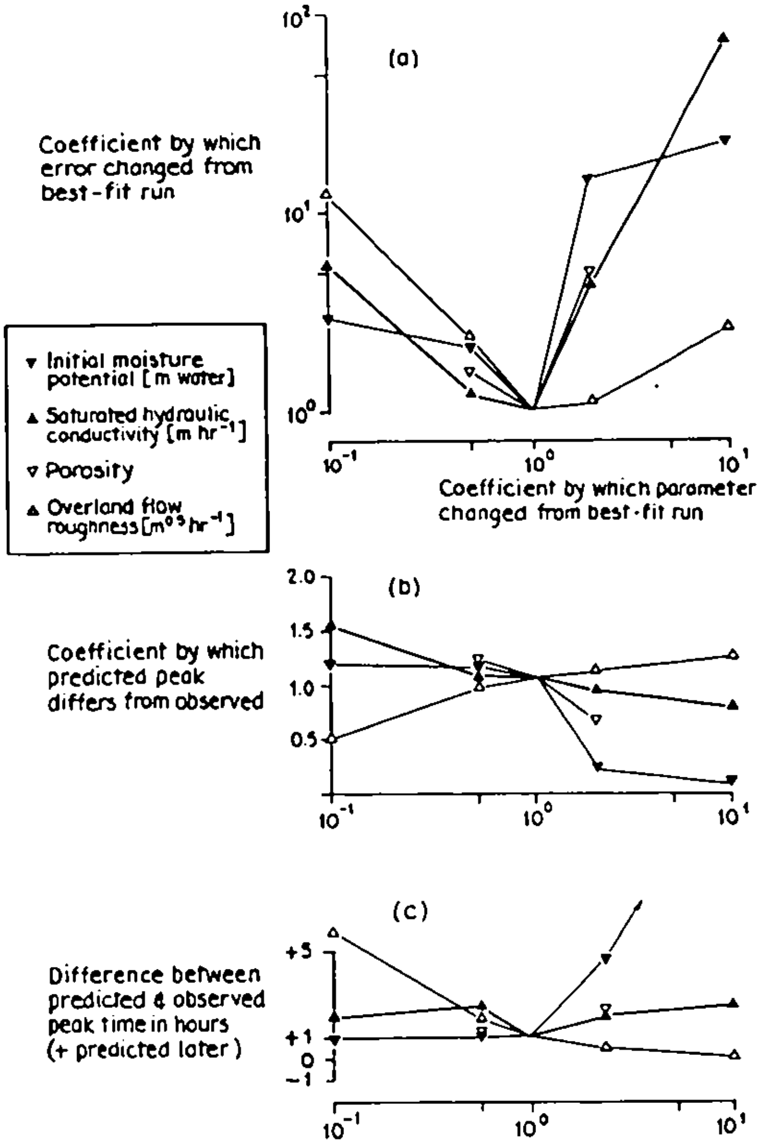

Figure 5.2.1 *Effects of parameter value changes on: (a) sum of squares of differences between observed and predicted flows; (b) magnitude of peak discharge; and (c) time to peak discharge.*
(Reproduced, with permission, from Journal of Hydrology, v.103, pp.103-115, 1988).

An extension to the IHDM of flow path tracking (Calver and Binning, 1990) offers potential scope for calibration against chemical parameters, though it should be pointed out that, because of unsaturated zone inclusion which is indeed the innovative feature of the work, computing requirements are somewhat prohibitive for routine use.

5.3 EFFECTS OF PARAMETER UNCERTAINTY

Results are available on the effect of uncertainty of parameter values on model outcomes from some work jointly undertaken with the University of Lancaster (Binley, Beven, Calver and Watts, 1991). Hydrologically appropriate ranges for four key model parameters (saturated hydraulic conductivity, porosity, initial pressure potentials and surface roughness coefficient) were randomly sampled and the model run to produce a distribution of discharge results for a grassland upland catchment.

Figure 5.3.1 suggests that one should be wary of unqualified predictions of minor catchment changes. A hypothetical change of land use to forest could only be recognised with reasonable certainty if, in addition to vegetation parameters *per se*, account was taken of changes in soil moisture likely over an annual cycle because of vegetation differences.

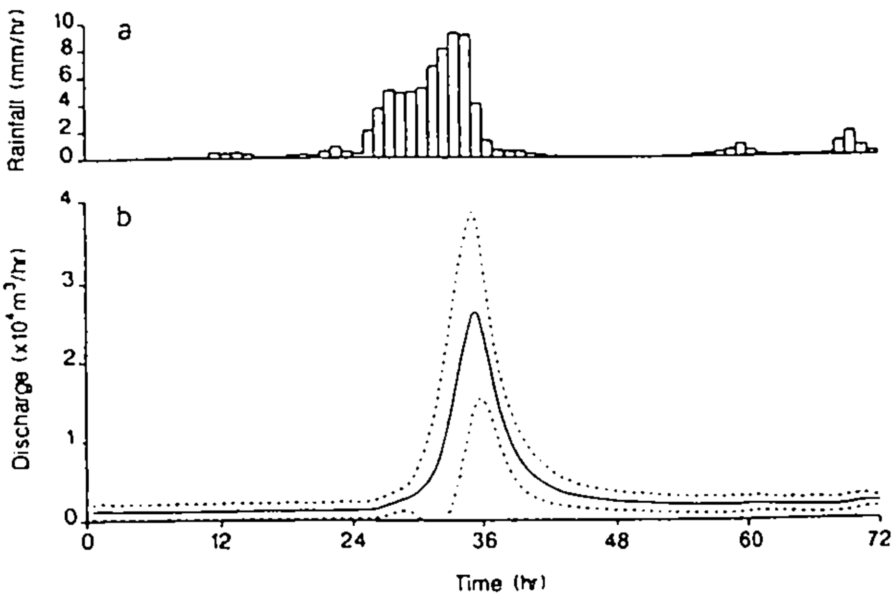

Figure 5.3.1 *(a) Hourly rainfall distribution. (b) Predictive uncertainty using Monte Carlo simulation. Solid line indicates mean flow; dashed lines indicated mean ± 2 standard deviations.*
(Reproduced, with permission, from part of Figure 2 of Binley, Beven, Calver and Watts, Water Resources Research, v.27, pp.1253-1261, 1991, copyright by the American Geophysical Union.)

This methodology is not proposed as routine because of the cumulative run time involved. Normally, use of best and worst cases and the best-estimate seems a sensible compromise. However, it is not always possible to know precisely the best and worst cases in advance in a multi-parameter model. Where the distribution of results is helpful is if there is a strong cost-benefit differential near the ends of the distribution range, whether economic or environmental.

5.4 DISCRETISATION OF MOVING RAINSTORMS

Work has been undertaken on the effect of storm velocities on discharge from a 100 km^2 conceptual catchment (Watts and Calver, 1991). This implicitly covers frontal rather than convective regimes.

For throughflow (rather than overland flow) conditions and a drainage density of 0.5 km^{-1}, directional and speed effects on discharge have been detailed for different rainfall discretisations. Figure 5.4.1 indicates that in these cases a resolution of 2.5 km (4 rainfall 'zones') in rainfall data in the direction of storm movement is an efficient degree of complexity to model, given that finer discretisation raises run time.

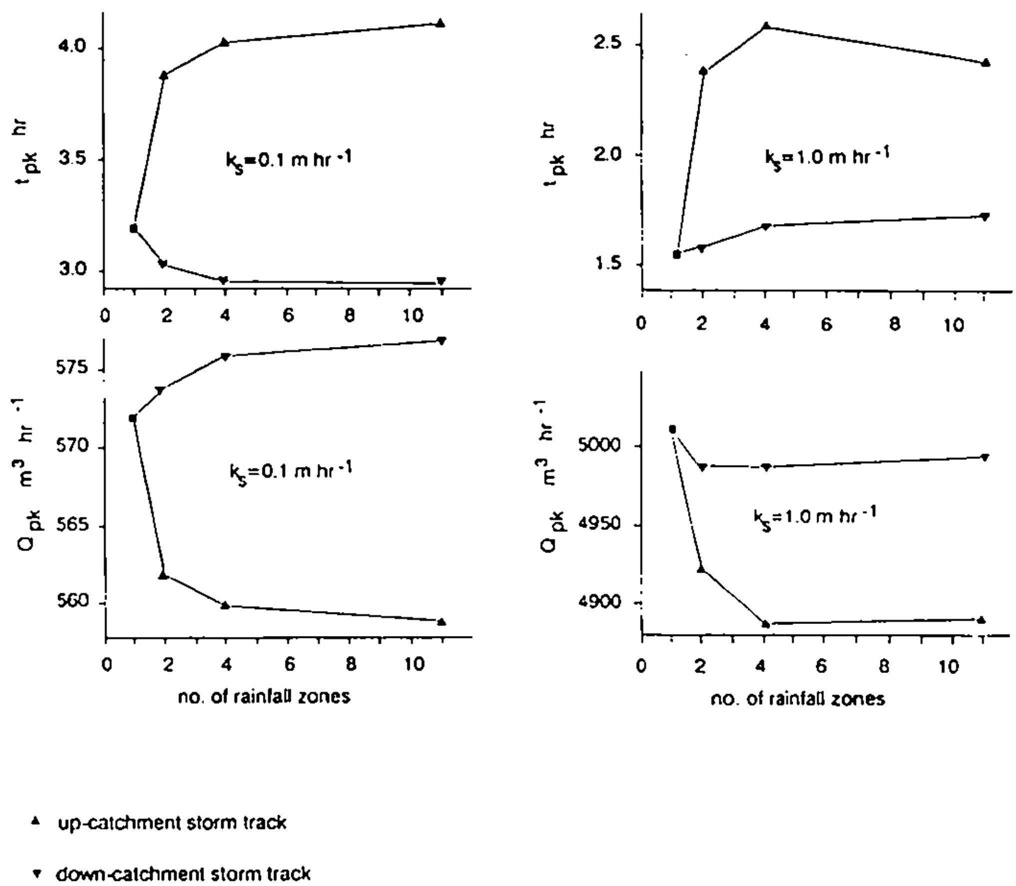

Figure 5.4.1 *Effects of number of rainfall zones on peak discharge and time to peak.*
(Reproduced, with permission, from Nordic Hydrology, v.22, pp.1-14, 1991).

Figure 5.4.2 indicates that the use of catchment-lumped precipitation data under these circumstances introduces an error which increases as storm speed decreases. The direction of error is likely to be an underprediction of peak discharge and an over-

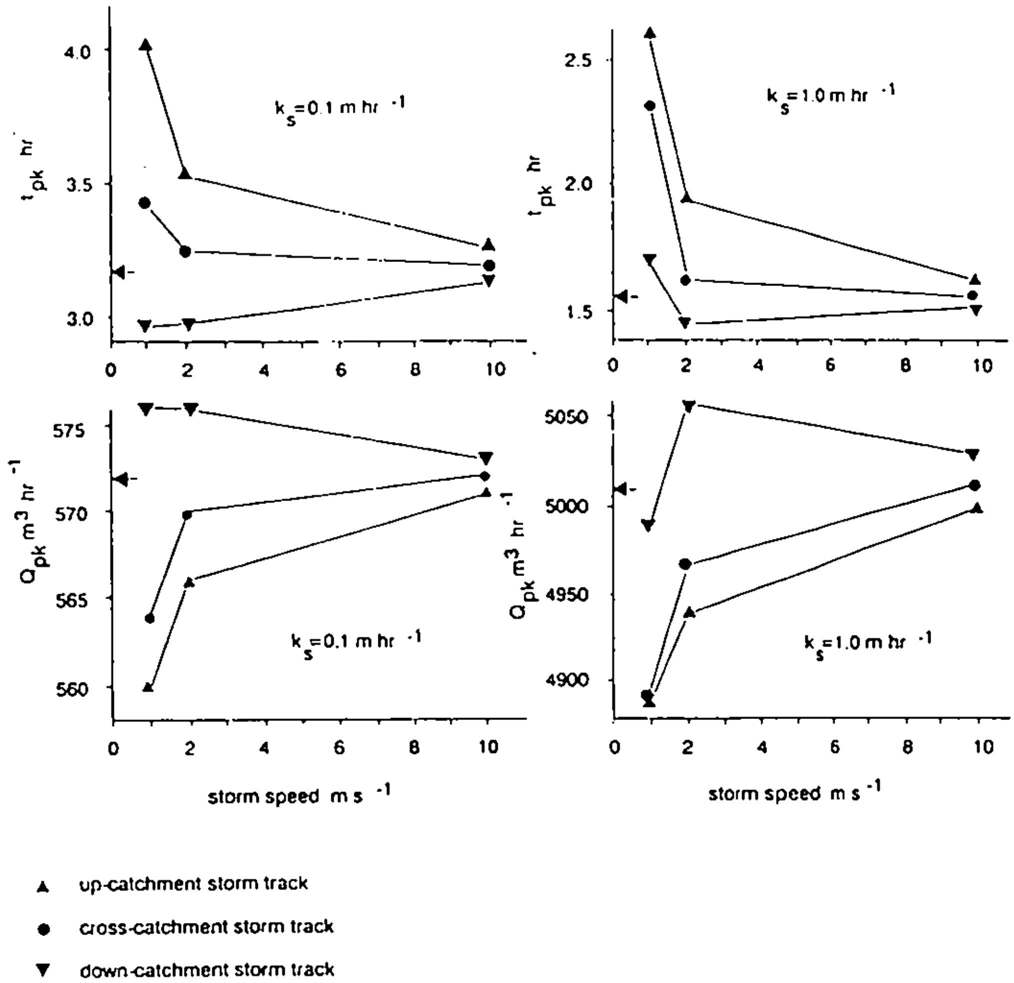

Figure 5.4.2 *Effects of storm velocity on peak discharge and time to peak. Arrows against vertical axes indicate lumped rainfall results. (Reproduced, with permission, from Nordic Hydrology, v.22, pp.1-14, 1991).*

prediction of time to peak in the case of storms moving downcatchment, and an overprediction of peak discharge and underprediction of time to peak for upstream or cross-catchment storm directions.

6. Concluding remarks

It will be appreciated that specific points concerning the use of the IHDM have been dealt with in the chapters where the particular context has been discussed, indeed such is necessarily the case in a report dealing with guidelines for a complex procedure.

A general comment is that investigations that relate to the numerical procedures can to some extent be more readily explored and concluded upon; those guidelines which, in contrast or in addition, relate to practical modelling experience and comparison with field data can take longer to produce. A document such as this is believed timely because of the accumulation of IHDM experience to date, but it is to be borne in mind that some aspects represent the current state of the modelling art and future emphases could change: findings of investigations of the more systematic type should expect to hold.

Acknowledgements

A number of past and present IH staff have contributed greatly to this project, as has Dr W Wood of Reading University. We are grateful to the Ministry for funding this research and development programme.

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