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Modelling Strategy adopted in MAFF R & D Project FD412

Note to MAFF

Pam Naden
July 1994

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The focus of the MAFF-funded project FD412 is the development of a simple yet spatially-distributed approach to the modelling of large catchments for estimating the effects of climate and land use change on flood frequency. This note reports the outline of the method and the data assembled for applying it to the three large basins of the Severn to Haw Bridge, Trent to North Muskham, and Thames to Teddington.

Outline of method

The general method adopted follows that used for events in Naden (1992). This is based on the digitised river network and a convection-diffusion equation for the river routing, to give a physically-based network response function. This must be coupled with a procedure for generating runoff. On an event basis, Naden (1992) used a unit hydrograph formulation with an assumed percentage runoff and a simple weighting to accommodate differences in rainfall depth across the catchment. In order to address the question of the impact of climate and land use change, this must be replaced by a means of continuously simulating runoff, which is capable of including land use change and which operates within a framework which can include differences in rainfall across the basin.

While differences in runoff response are best defined in terms of differences in soil type and geology, one means of providing distributed rainfall inputs is via a grid system. While it is possible to argue about a suitable grid size, Naden (1993) demonstrated the use of the routing model with time series of observed daily flows from small representative catchments in the Severn. These flows were 'scaled up' to represent the runoff to channels within 40 by 40 km grid squares by multiplying by the ratio of the area of the large basin within the grid square to the area of the small catchment. Using small catchments in this way assumes that, on a daily time scale, river routing within the small catchment is negligible and the flow, therefore, represents the hillslope, or first-order catchment, response. The water balance of the Severn was modelled to within 0.2% giving support to the use of the rather coarse grid and scaling-up procedure.

The requirement now is to produce modelled outflows for these representative small catchments. As the overall model is specific to the Severn, Trent and Thames catchments, models fitted to representative small catchments within different areas of these basins without further generalisation is one approach which, on the basis of the results using observed flows from the Severn, will work. However, in the larger scheme of things it is also worth considering the use of individual small catchments which reflect particular soil and topographic types, rather than simply location within the large basin. For example, in the case of the Thames, there is a mixed geology of chalk or limestone and clay components which need to be represented. Consequently, in addition to the grid square subdivision for the rainfall input, subdivision based on geological/soil properties as represented within the HOST (Hydrology of Soil Types) classification (Boorman *et al.*, 1994) will also be included.

In terms of the flood response, while daily flows are adequate to characterise these large catchments and inadequacies of a simple lumped approach due to differences in rainfall across the catchment (Crooks, 1994) will be addressed within the methodology reported here, the effect of flood plain storage also needs to be included. This will initially be a relatively simple empirical extension of the routing model. If time permits, the question of a more sophisticated model based on digital elevation data will be addressed.

Selection of representative catchments

The three large catchments of the Thames to Teddington, Severn to Haw Bridge and Trent to North Muskham have soil types distributed across HOST classes as shown in Table 1. In selecting representative small catchments, this distribution across HOST classes has been taken into account. The list of small catchments selected is given in Table 2 which also gives the area of the catchment and the proportion of each HOST class. These catchments all have complete or near-complete daily flow data for the period 1985-1992.

Selection of suitable small catchment models

Following on from the work of Houghton-Carr and Arnell (1994) and Spijkers and Naden (1994), the probability distributed model (PDM) of Moore (1985) is a suitable catchment model which could be used in the simulation of small catchment runoff. It uses a simple exponential function of the soil moisture storage in the catchment to convert from potential evapotranspiration (input to the model) to actual evapotranspiration.

An alternative to this model which links in with the idea of a two-component unit hydrograph approach as postulated in Naden (1992) is the IHACRES model (Jakeman, A.J. *et al.*, 1990). This currently assumes a non-linear losses model which is based on temperature and which is used to derive a soil moisture index for the calculation of an effective rainfall. IHACRES then derives a transfer function model for the conversion of this effective rainfall into runoff. The most commonly fitted simple model is two exponential stores in parallel. These can be thought of as providing both quick and slow responses to rainfall which might reasonably be expected to tie up with HOST soil types.

Both these models will be explored as suitable candidates for the small catchment simulation.

Effect of land use change

With regard to the losses models incorporated in both PDM and IHACRES, further work needs to be done on the representation of the effects of land use change. It is assumed that the dominant effect of land use change will be seen in differences of evapotranspiration which then feed through to differences in soil moisture. The evapotranspiration from different land covers, therefore, needs to be explicitly represented within these models, at least in simulation mode, rather than being a calibrated function. It also needs to be capable of representing a mix of different land covers. To this end, two sets of information have been obtained: the digital land cover data from the Institute of Terrestrial Ecology (Fuller, 1993) and daily evapotranspiration data for different land covers as derived in the UK Meteorological Office Rainfall Evaporation Calculation System (MORECS: Thompson *et al.*, 1981).

ITE land cover data

The ITE land cover data at the 1 km^2 resolution provides proportions of land occupied by 25 classes of land cover. A map showing the dominant class in each kilometre square for the area covering the Thames, Severn and Trent basins is shown in Figure 1. Only 16 of the 25 classes are represented within the three large basins. The distribution across the catchments is shown in Table 3. Furthermore, as the original dataset was derived for ecological purposes, many of the different classes can be amalgamated for the purpose of calculating evapotranspiration losses e.g. grass heath, mown/grazed turf and meadow/verge/semi-natural may all be classified as grass.

In MORECS, fourteen different land use classes are used. However, these mainly reflect differences in crop type i.e. land use rather than land cover. Land use is not provided by the ITE dataset other than by a single class of 'tilled land'. Use of MAFF crop census data would in future enable this to be pursued if it is thought valuable. Here, it is deemed sufficient to move to a simplified six class system as defined in Table 4. Data were, therefore, obtained from the UK Meteorological Office for the land use types of grass, deciduous trees, coniferous trees, upland, and cereals. Information from MORECS on urban was not available but may be calculated using the potential evapotranspiration for grass and a suitable adjustment factor for the actual evapotranspiration.

Evapotranspiration data

Using the six land use types identified above, daily data have been purchased from the UK Meteorological Office to provide potential evapotranspiration (PE), actual evapotranspiration (AE) and soil moisture deficit (SMD) for four sites within the Severn/Trent/Thames area for the years 1985-1992. The sites are Nottingham within the Trent, Ludlow (Preston Wynne for the earlier years) within the Severn, and Lyneham and Stansted on the margins of the Thames. These data have been supplemented by IH data for Plynlimon, Wallingford, and Grendon Underwood.

As actual evapotranspiration depends on the soil type and catchment model used to simulate drainage through the soil, it is envisaged that potential evapotranspiration will form the input series to the models. The MORECS actual evapotranspiration and soil moisture deficit will be used as a baseline comparison. As an indication of the possible influence of different land covers on soil moisture and hence on river flow, Figure 2 shows the MORECS output for the Nottingham site. The much greater soil moisture deficits generated by trees, especially in the drier years of 1989-1992, are clear from this plot.

Monthly MORECS data on a 40 by 40 km grid for both grass and the 'real land use' are more generally available and, if time permits, the project will assess the use of these data in the model. The reason for not using these data initially is that monthly grid values are not available for different land covers individually and, therefore, the impact of land use change could not be readily assessed.

Application of the model

Long-term rainfall data will be assembled for grid squares in order to apply the model to flood frequency estimation. Initially, the 40 by 40 km grid used previously and which matches the MORECS monthly data will be applied. However, it is hoped that the model can be applied to other spatial resolutions in order to assess the maximum degree of coarseness which might be used in the simulation. Scenarios for climate and land use change based on the main controlling variables of rainfall and PE will be derived from the literature and applied to the input time series in order to assess the impact of such changes on flood frequency.

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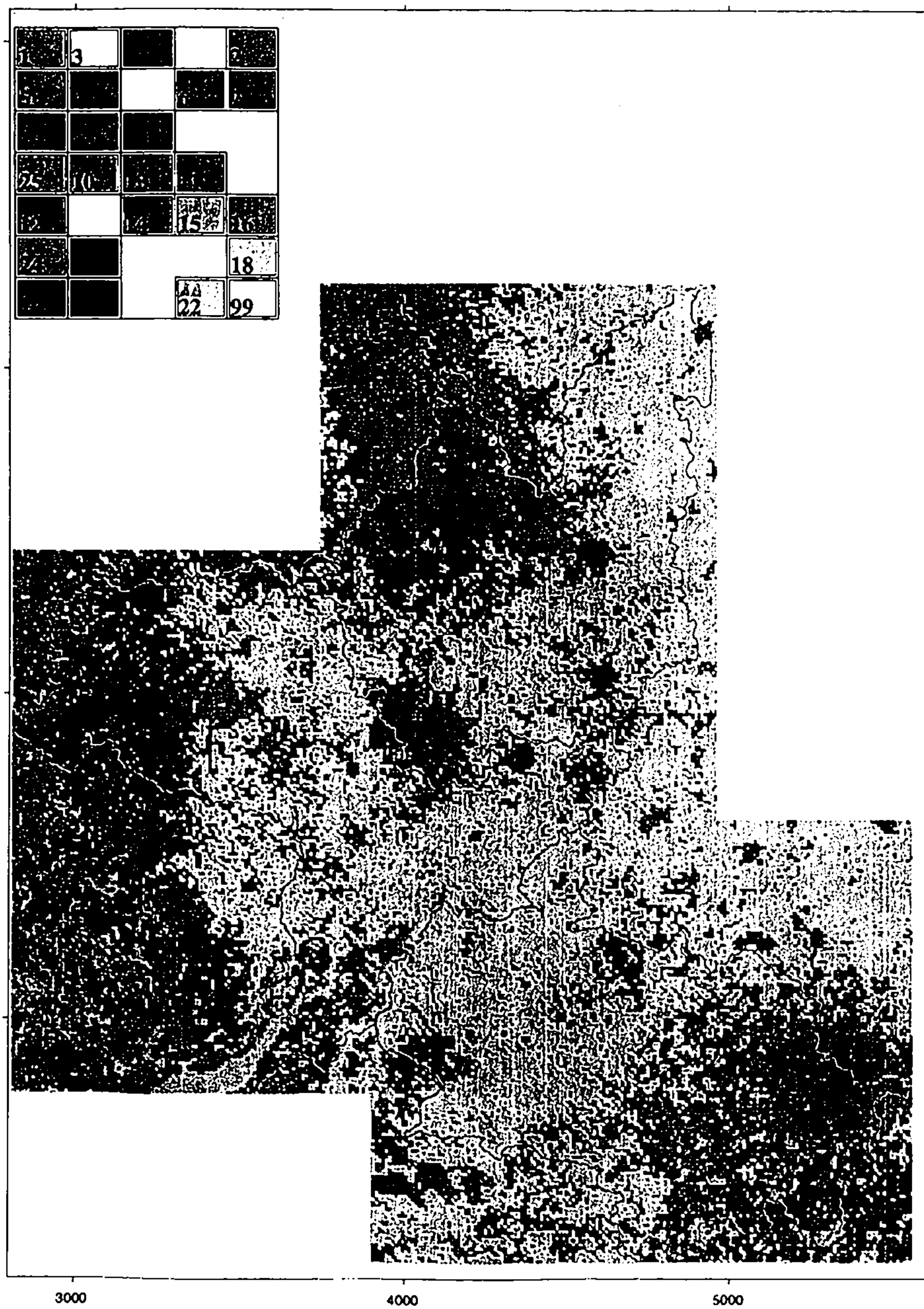
Table 1 HOST classes for large basins

HOST class	Severn at Haw Bridge (km^2)	Trent at North Muskham (km^2)	Thames at Teddington (km^2)
1	-	-	1791
2	99	82	1393
3	495	494	497
4	693	741	-
5	792	412	696
6	99	-	298
7	198	245	99
8	297	247	199
9	297	412	398
10	99	247	398
11	99	-	-
12	-	-	-
13	-	82	99
14	-	-	-
15	99	165	-
16	-	-	99
17	693	-	-
18	1286	741	895
19	99	-	-
20	99	82	298
21	693	1235	-
22	99	-	-
23	396	82	398
24	2078	2552	199
25	693	247	2089
26	198	82	-
27	-	-	-
28	-	-	-
29	198	82	-

Table 2 Selected small catchments for modelling: proportions of HOST classes

CATCH	Area	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Lake
28031	148.5	0	0	0	30	0	0	0	0	1	1	0	0	1	0	4	0	0	0	0	0	4	0	0	33	1	23	0	0	1	0
28039	74.0	0	0	8	1	5	0	0	0	12	7	0	0	2	0	0	0	0	19	0	0	7	0	0	38	0	0	0	0	1	1
28046	83.0	0	0	0	68	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	4	0	0	11	0	2	0	0	1	0
28048	139.0	0	1	0	25	0	1	0	0	2	0	0	0	3	0	0	0	0	0	0	0	6	0	0	61	0	1	0	0	0	1
28056	94.0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	10	2	0	32	0	0	54	0	0	0	0	0	0
28060	69.0	0	0	38	0	24	0	0	0	1	1	1	0	3	0	0	0	0	16	0	0	15	0	0	1	0	0	0	0	0	0
28066	130.0	0	0	0	0	3	0	7	1	5	2	0	0	0	0	0	0	0	1	0	0	12	0	0	70	0	0	0	0	0	0
28079	86.3	0	0	29	2	7	0	2	2	3	6	1	0	0	0	0	0	0	5	0	0	19	0	0	24	0	0	0	0	0	0
39012	69.1	36	0	2	0	1	2	2	2	3	11	0	0	0	0	0	0	0	5	0	0	0	0	1	0	35	0	0	0	0	0
39015	44.5	81	0	0	0	0	10	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0
39026	199.4	0	17	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	17	2	0	9	5	46	0	0	0	0	0
39033	49.2	51	0	1	0	1	4	0	0	0	1	0	0	0	0	0	0	0	36	0	0	0	0	0	0	5	0	0	0	0	0
39036	16.0	0	0	97	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
39042	76.9	0	77	0	0	4	0	1	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	14	0	1	0	0	0	0	0
39052	50.2	0	0	9	0	2	0	0	0	0	8	0	0	4	0	0	0	0	12	0	0	0	0	0	0	66	0	0	0	0	0
39054	31.8	0	0	17	0	0	0	0	0	2	0	0	0	0	0	0	6	0	11	0	7	0	0	2	13	41	0	0	0	0	0
39055	17.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	95	0	0	0	0	0
39065	13.4	85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0
39073	84.0	0	79	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0
39077	59.2	88	0	0	0	0	8	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39101	53.1	88	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
54018	178.0	0	0	0	20	4	0	0	1	3	0	1	0	0	0	0	0	4	16	2	0	0	1	0	46	0	0	0	0	0	0
54020	180.8	0	0	2	0	33	1	4	0	1	3	11	0	0	0	0	0	1	9	0	0	2	0	0	33	0	0	0	0	0	0
54022	8.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	58	0	1	0	0	0	0	0	0	0	0	14	0	0	26	0
54025	52.7	0	0	0	0	0	0	0	0	0	1	0	0	0	0	4	0	45	1	0	0	0	6	0	24	0	16	0	0	3	0
54034	40.8	0	0	0	58	0	0	0	0	0	0	0	0	1	0	0	0	0	13	0	0	12	0	0	15	0	0	0	0	0	0
54044	92.6	0	0	34	6	15	0	5	1	0	4	1	0	0	0	0	0	0	7	0	0	9	0	0	17	0	0	0	0	0	0
54048	102.0	0	8	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	2	0	7	3	0	30	6	41	0	0	0	0	0
54087	4.7	0	0	70	0	6	0	1	0	0	6	4	0	0	0	0	0	0	2	0	0	3	0	0	9	0	0	0	0	0	0

Figure 1 Dominant ITE land cover classes



Land Cover data are provided by the Institute of Terrestrial Ecology from its Land Cover Map of Great Britain. For more information, contact Sue Wallis or Robin Fuller (Telephone: 04873 381).

This map was produced at the Institute of Hydrology, Wallingford, OX10 8BB, on Feb 1 1994

Table 3 ITE land cover classes represented in the Severn, Trent and Thames

ITE No.	ITE class	Severn at Haw Bridge (%)	Trent at North Muskham (%)	Thames at Teddington (%)
5	Grass heath	2	3	1
6	Mown/grazed turf	19	21	14
7	Meadow/verge/semi-natural	21	17	21
8	Rough/marsh grass	1	-	1
9	Moorland grass	1	2	-
10	Open shrub moor	1	-	-
12	Bracken	1	-	-
15	Deciduous woodland	7	4	9
16	Coniferous woodland	1	1	2
18	Tilled land	29	28	35
19	Ruderal weed	-	-	1
20	Suburban/rural development	8	14	10
21	Continuous urban	1	4	1
22	Inland bare ground	1	1	1
25	Open shrub heath	2	-	-
	Unclassified	5	4	4

Table 4 Simplified land cover classes for evapotranspiration

ITE No.	ITE class	Simplified class
5	Grass heath	Grass
6	Mown/grazed turf	Grass
7	Meadow/verge/semi-natural	Grass
8	Rough/marsh grass	Grass
9	Moorland grass	Grass
10	Open shrub moor	Upland
12	Bracken	Upland
15	Deciduous woodland	Deciduous woodland
16	Coniferous woodland	Coniferous woodland
18	Tilled land	Winter/spring cereals
19	Ruderal weed	Grass
20	Suburban/rural development	Urban/bare ground
21	Continuous urban	Urban/bare ground
22	Inland bare ground	Urban/bare ground
25	Open shrub heath	Upland

Figure 2 Soil moisture deficit for Nottingham
(MORECS calculation)