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URBAN HYDROLOGICAL MODELLING AND CATCHMENT RESEARCH IN THE UNITED KINGDOM

by

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ABSTRACT

This Report is a copy of Technical Memorandum No. IHP-4 of the American Society of Civil Engineers Urban Water Resources Research Program, published in July 1976. It is the UK contribution to the state-of-the-art reports submitted to the Subgroup on the Hydrological Effects of Urbanisation set up as part of the UNESCO-sponsored International Hydrological Decade.

TABLE OF CONTENTS

SECTION 1

GENERAL INTRODUCTION

This paper has been prepared at the Institute of Hydrology, following a request from UNESCO for contributions of state-of-the-art reports on urban catchment hydrology relating to catchment based research (IHP Sub-project 7.1) and mathematical models (IHP Sub-project 7.2).

In the United Kingdom as elsewhere, urban hydrology is only now beginning to receive the attention it deserves. Although the Road Research Laboratory (RRL) hydrograph method of sewer design is known internationally, it was until recently the only significant United Kingdom contribution to 'modern' urban hydrology with regard both to data collection and analysis (Section 2 of this report) and to the design method itself (Section 3).

Although the total research effort is increasing, it is still small by comparison, for example, with the U.S.A. However, it is possible that work is more closely co-ordinated in the United Kingdom and that benefit derives from the frequent informal meetings organised by the active researchers in the field. The Department of the Environment/National Water Council Working Party on the Hydraulic Design of Storm Sewers was formed in 1974 and now acts as a focal point for research co-ordination and information exchange.[1] Previously a national colloquium[2] at Bristol University had helped to crystallise the growing dissatisfaction with existing design methods and with the inadequate body of knowledge relating to urban runoff, quantity and quality. Current research at central research stations and universities is concerned with the development of new methods but most results are, as yet, only tentative.

Most of the research is into rainfall-runoff relations and is described in this paper. Economic aspects of sewer design and construction are also under study[3] but are not described here. There is also a growing body of opinion which is interested in total planning rather than sub-division planning. Why not prevent the increased flows rather than design against them? Should we concentrate on standards of maintenance rather than design? There is clearly a significant interdependence between hydraulic design, pollution prevention and maintenance work; and recent re-organisation in the United Kingdom Water Industry has allowed the broader view to be seen at an early stage in planning. But such a view is not the aim of this paper, which is limited to the relatively narrow field of urban hydrology.

Urban hydrology covers a wide range of catchments: the small, totally impervious parking lot draining to inlets; medium sized areas where the dominant process is pipe flow; and larger, mainly natural catchments, with a significant proportion of urban development. The latter case, of a catchment being urbanised but still drained by a natural watercourse, has been studied for several years, but again the pace of research is accelerating as more data are gathered and more workers turn to the topic. The Construction Industry Research and Information Association (CIRIA) has recently initiated a project to provide engineering guidance on the subject, and it is expected that design criteria derived from the recent Flood Studies Report[4] will provide useful input to the project. This five-volume Report represents four years work at the Institute of Hydrology, Meteorological Office, and Hydraulics Research Station. It describes the outcome of an exhaustive study of floods, their magnitude, timing and frequency. Although concentrating on natural catchments, the Report provides a platform of experience and methodology from which to launch further projects in applied hydrology.

As requested by UNESCO, the format of the present paper follows that of the U.S.A. contribution[5] to the UNESCO reports. This paper is much shorter, not only because of the much lower level of activity, but also because some material has been omitted where it is adequately described in the first Technical Memorandum of this special IHP series.[5]

The preparation of this report at the Institute of Hydrology was supported by the United Kingdom Department of the Environment under contract number DGR/480/38.

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SECTION 2

URBAN CATCHMENT RESEARCH IN THE UNITED KINGDOM

Introduction

This section of the report is intended to describe catchment-based research in urban areas in the United Kingdom. Four broad categories are distinguished by the primary objective of the research:

(a). To provide data on rainfall and runoff from urban areas with flow monitored at some convenient point in or at the outfall from a sewer system.

(b). As in (a), but flow monitored at the entry to the sewer system with the specific aim of calibrating an above-ground model of runoff.

(c). Water quality studies.

(d). Studies of the effect on flow in natural watercourses as a catchment is urbanised.

The Map which follows, expanded in detail from an earlier survey,[1] shows the location of all known catchment studies. The accompanying Table gives details of the sewered and urbanising catchments (pages 6 and 7).

Before listing the research in the four areas defined above, the next two subsections deal with methods of flow measurement and rainfall aspects respectively. Described in the final subsection are methods of data collection and processing.

Methods of Flow Measurement

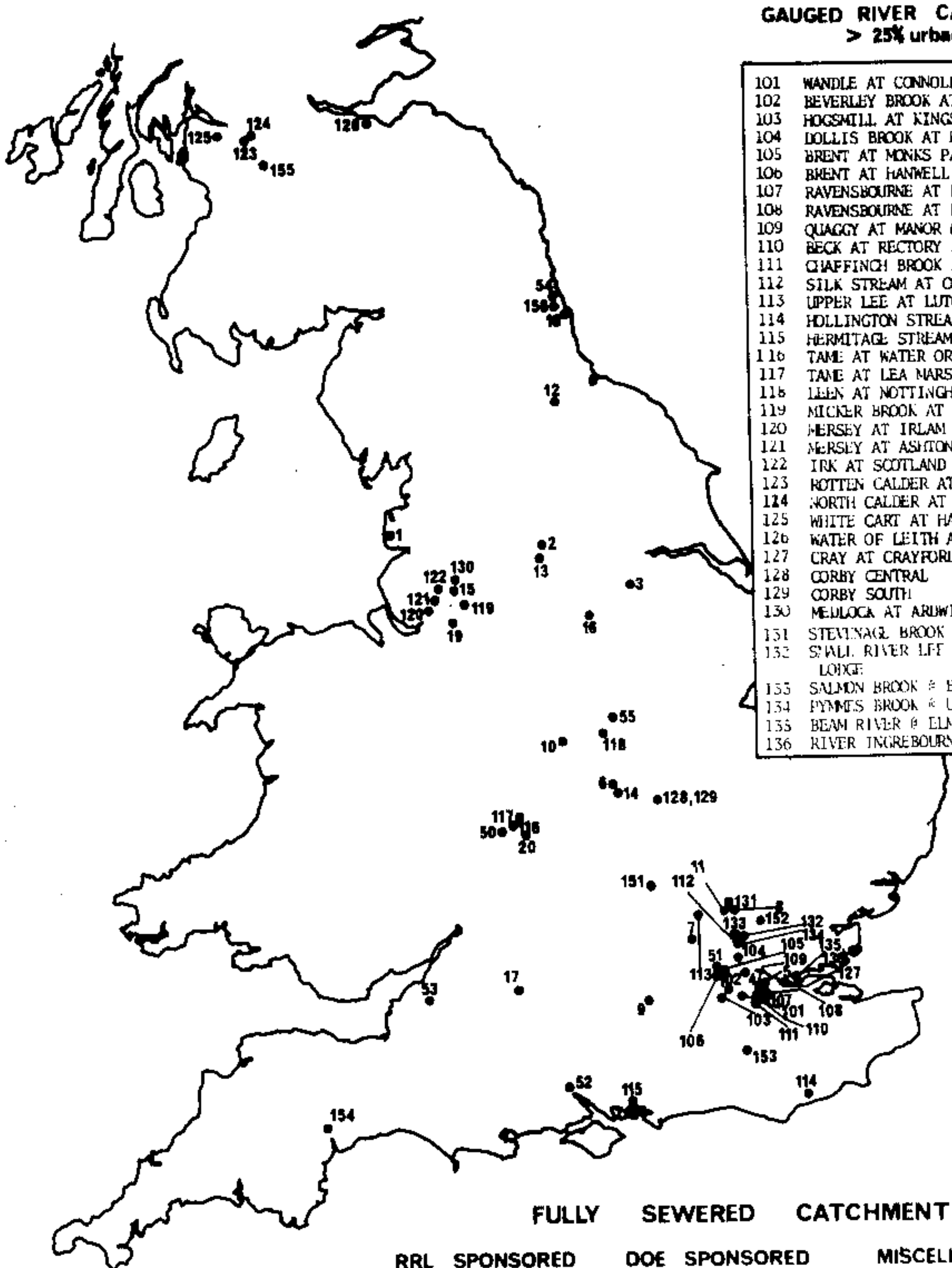
Inlets

There have been several studies[2,3] where a small (< 1-ha) paved area has been gauged, but in each case a significant length of pipe has taken flow from the inlet to the gauging point (V-notch weir or flume). However, an instrument has recently been developed at the Institute of Hydrology[4] which is designed to fit into a road gully and measure inflow to the pipe system. The meter is basically a hinged plate in a vertical, square-section tube through which all flow is forced to pass. Plate rotation is linked to a potentiometer and may be calibrated against discharge.[5] A filtering system and careful design detail minimise the effects of sediment and trash but a high level of maintenance is necessary.

In-Pipe, by Water Level Measurement

All in-pipe monitoring of water level has been at manhole sections with conversion to flow based on assumed friction coefficients. Coefficient values have sometimes been adjusted after calibration, at low flows only, by dilution gauging. The most usual method of water level measurement has been with an air reaction system (Arkon) but a sonar system (Echolot) is being tested in Edinburgh and a water surface following device (Manning Dipper) is under investigation

INSTRUMENTED URBAN CATCHMENTS IN THE UNITED KINGDOM



GAUGED RIVER CATCHMENTS
> 25% urban development

101	WANDLE AT CONNOLLYS MILL
102	BEVERLEY BROOK AT WIMBLEDON
103	HOGSMILL AT KINGSTON
104	DOLLIS BROOK AT HENDON
105	BRENT AT MONKS PARK
106	BRENT AT HANWELL
107	RAVENSBOURNE AT BROMLEY
108	RAVENSBOURNE AT BRANGBOURNE RD
109	QUAGGY AT MANOR HOUSE
110	BECK AT RECTORY RD
111	CHAFFINCH BROOK AT BECKENHAM
112	SILK STREAM AT COLLINDEEP LANE
113	UPPER LEE AT LUTON HOO
114	HOLLINGTON STREAM AT HOLLINGTON
115	HERMITAGE STREAM AT HAVANT
116	TAME AT WATER ORTON
117	TAME AT LEA MARSTON
118	LEEN AT NOTTINGHAM
119	MICKER BROOK AT CHEADLE
120	MERSEY AT IRLAM WEIR
121	MERSEY AT ASHTON WEIR
122	IRK AT SCOTLAND WEIR
123	ROTTEN CALDER AT RED LEES
124	NORTH CALDER AT CALDER PARK
125	WHITE CART AT HAKKHEAD
126	WATER OF LEITH AT MURRAYFIELD
127	CRAY AT CRAYFORD
128	CORBY CENTRAL
129	CORBY SOUTH
130	MEDLOCK AT ARDWICK
131	STEVENAGE BROOK @ BRAGBURY END
132	SMALL RIVER LEE @ ENFIELD LODGE
133	SALMON BROOK @ ENFIELD
134	PYMMES BROOK @ UPPER EDMONTON
135	BEAM RIVER @ ELM PARK
136	RIVER INGREBOURNE @ HAVERING

FULLY SEWERED CATCHMENTS

RRL SPONSORED CATCHMENTS

1	BLACKPOOL
2	BRIGHOUSE
3	DONCASTER
4	KENSINGTON
5	KIDBROOKE
6	LEICESTER
7	OXHEY
8	STEVENAGE

DOE SPONSORED CATCHMENTS

9	BRACKNELL
10	DERBY
11	STEVENAGE
12	DARLINGTON
13	HUDDERSFIELD
14	LEICESTER
15	MANCHESTER
16	SHEFFIELD
17	SWINDON
18	SUNDERLAND
19	WILMSLOW
20	COVENTRY

MISCELLANEOUS CATCHMENTS

50	BIRMINGHAM
51	NORTHOLT
52	SOUTHAMPTON
53	BRISTOL
54	CRAMLINGTON
55	NOTTINGHAM

CATCHMENTS UNDERGOING URBANISATION

151	MILTON KEYNES
152	HARLOW
153	CRAWLEY
154	EXETER
155	STONEHOUSE
156	NEWCASTLE

in Stevenage. Resistance-type gauges (Eurogauge) and pressure bulb types have also been used.

The Construction Industry Research and Information Association is currently sponsoring an evaluation by the Hydraulics Research Station of methods of flow measurement in rivers, open channels and sewers.

Special Structures, by Water Level Measurement

The more reliable data on sewer flows derive from purpose-built flumes either within a specially enlarged sewer section or at the outfall from the system. A good example of the former is at Lodge Farm, Milton Keynes, where a 1.65-m square culvert was heightened to 3.225-m and a trapezoidal flume included during sewer construction. Water level is normally monitored by float in a conventionally separate stilling well, and theoretical stage/discharge relationships are applied.

Dilution Gauging

Most of the U.K. expertise in dilution gauging in sewers was developed in the early 1960's at the Water Pollution Research Laboratory (now Water Research Centre, Stevenage Laboratory) and jointly by the City and University of Newcastle. Lithium chloride was and still is the main tracer employed in sewers. A British Standard describing the constant-rate-of-injection method has been published.(7) Further development of techniques has taken place at the Water Research Association(8) (now the Water Research Centre, Medmenham Laboratory) using sodium dichromate and, more recently, at the Institute of Hydrology using sodium iodide. In both cases, the emphasis has been on gauging in natural streams. Further developments in sewer gauging were reported by Blakey.(9)

The practical application of radioisotope dilution gauging techniques to systems where conduits are flowing full was pioneered by the U.K. Atomic Energy Authority.(38)

Most gauging has been for calibration of pipe stage/discharge relationships and has involved manual techniques which have worked well in wastewater sewers. But in storm sewers it is seldom possible to be on the site and prepared for gauging during a high discharge, and only rarely can similar flows be introduced artificially by pumping. An automatic technique, triggered by a predetermined discharge, is therefore essential to achieve calibration over a wide range of flows. Alternatively, automatic gauging can be thought of as providing direct flow measurement during a storm event. In this context, Tucker(10) has described an apparatus using gulp injection. This method requires a longer sampling time (three minutes in his case) than the constant rate injection and, because the derived flow figure is an average value over the

TABLE. SELECTED DETAILS (WHERE KNOWN) OF CATCHMENTS SHOWN ON ACCOMPANYING MAP AS BEING 'FULLY SEWERED' OR 'UNDERGOING URBANISATION'. **(FURTHER INFORMATION AVAILABLE IN REFERENCE 1 OR FROM INSTITUTE OF HYDROLOGY, WALLINGFORD, OXON, U.K.). ALL ARE SEPARATE STORM SEWER SYSTEMS UNLESS STATED OTHERWISE.**

MAP IDENTI-FICATION NUMBER	CATCHMENT NAME	TOTAL AREA, ha	PERCENT IMPERVIOUS	RECORDS FROM	RECORDS TO	METHOD OF FLOW MEASUREMENT	COMMENTS
1	Blackpool	4.81	42	1957	1958	standing wave flume	good quality; incomplete catchment data; combined
2	Brighouse	81	22	1957	1960	depth + a.f.c.*	dubious stage/discharge; no catchment details; combined
3	Doncaster	5.14	30	1956	1958	standing wave flume	
4	Kensington	81	95	1957	1959	depth + a.f.c.*	limited catchment data; combined
5	Kidbrooke	3.42	68	1953	1958	standing wave flume	small factory area
6	Leicester	60	36	1958	1958	standing wave flume	limited record; combined
7	Oxhey (a)	0.47	60	1954	1959	V-notch weir	length of road
	(b)	247	20	1953	1959	standing wave flume	limited catchment data
8	Stevenage (a)	1.39	43	1955	1959	V-notch weir	'WPRL', small industrial site
	(b)	4.8	31	1954	1959	'weir'	'Housing estate 1'; suspected leakage - poor
	(c)	8.0	20	1955	1956	'weir'	'Housing estate 2'; backwater effects, abandoned
9	Bracknell (a)	11.1	45	1974	Date	standing wave flume	'Wildridings'; good quality
	(b)	500	?	1974	Date	standing wave flume	'Easthampstead'; development continuing
	(c)	181	?	1974	Date	standing wave flume	'Great Hollands'
10	Derby	10.38	54	1973	Date	depth + a.f.c.*	two other monitoring points upstream, dilution gauging calibration checks
11	Stevenage	162	35	1973	Date	depth + a.f.c.*	dilution gauging check calibration, new flume under construction
12	Darlington	612	50	1971	1975	depth + a.f.c.*	three sites, all poor; sparse records of older sewer system
13	Huddersfield	325	15	1974	1975	standing wave flume	combined
14	Leicester (a)	10.3	34	1973	1975	depth + a.f.c.*	'Howden Road'; attempted check calibration, dubious
	(b)	8.6	65	1973	1975	depth + a.f.c.*	'Mere Road'; attempted check calibration, dubious

(Continued)

TABLE (CONTINUED)

MAP IDENTI-FICATION NUMBER	CATCHMENT NAME	TOTAL AREA, ha	PERCENT IMPERVIOUS	RECORDS FROM	RECORDS TO	METHOD OF FLOW MEASUREMENT	COMMENTS
15	Manchester	200	35	1971	1973	depth + s.f.c.*	combined; unsuccessful dilution gauging, poor
16	Sheffield	17.5	33	1973	1975	flumes	three sites, all silting up, abandoned
17	Swindon	80	20	1974	1975	depth + s.f.c.*	combined; dubious, no catchment data
18	Sunderland	320	2	1975	1975	Crump weir	not yet developed, really an 'urbanising' catchment
19	Wilmslow	110	40	1971	1975	depth + s.f.c.*	four monitoring points (3 sub-catchments); combined
20	Coventry	45	?	1972	1975	flume	'Canley'; combined; limited catchment data
50	Birmingham	150	50	1975	Date	depth + a.f.c.*	field calibration planned
51	Northolt	0.32	100	1972	1974	V-notch weir	length of road
52	Southampton	0.6	42	1974	Date	Venturi flume	two contiguous catchments
53	Bristol	1210	?	1956	Date	standing wave flume	
54	Nottingham	62	31	1974	1974	dilution gauging	records from a few events only
151	Milton Keynes	202	5	1971	Date	trapezoidal flume	major development on catchment over next few years
152	Harlow	2100	33	1950	Date	standing wave flume	development virtually complete
153	Crawley (a)	4500	25	1954	1973	flume with central notch	'Hazelwick roundabout', developed
	(b)	2200	15	1952	Date	flume	'Woolborough Road', developed
154	Exeter	26	10	1968	Date	V-notch weir	house building continuing
155	Stonehouse	2600	2	1975	Date	flat-vee weir	projected new town
156	Newcastle	320	21	1972	Date	Crump weir	poor data due to silting of weir

*: depth plus assumed friction coefficient.

sampling period, it is likely that constant rate injection and 'grab' sampling is more appropriate for calibration requirements. Development work is continuing at the Water Research Centre (Stevenage Laboratory) and the Institute of Hydrology, with the aim of producing a simple, reliable, and portable package for automatic chemical injection and downstream sampling.

Other Methods of Flow Measurement

Both ultrasonic and electromagnetic methods of flow measurement have been applied to natural watercourses(11) and to pipes that are completely filled. Commercial instruments of either type are available. The difficulty of using either method to gauge flow in conduits flowing partly full has so far prevented their exploitation in sewers, although they could be used where there is an inverted siphon.

Rainfall Aspects

The requirements of urban hydrology are such that recording raingauges are needed for determination of rainfall in time periods as short as one minute. A recently published catalogue(12) of such gauges shows that there are about 1200 of them in the U.K. and that they are predominantly in urban areas. Nevertheless, it is unusual for an existing gauge to be in a suitable location when an urban catchment study is begun, and new gauges are usually deployed. The Dines tilting siphon gauge is the commonest instrument but increasing use is being made of tipping bucket gauges connected directly to magnetic tape data loggers.

In some studies, the recording raingauge is the sole source of rain data but in others it is used only to distribute in time an average catchment rainfall derived from a larger number of daily gauges. In some cases, gauges are installed with the orifice at ground level in a surrounding anti-splash configuration. Despite the greater accuracy of data from a ground level installation, it is debateable whether they should be used to produce rainfall-runoff relationships for subsequent design applications using rainfall statistics based on the regular network.

Studies of storm movement require dense networks of gauges and/or a radar. The South London/Surrey area is well endowed with gauges and a number of these have had their entire period of record digitised to form an archive of data from which to extract the statistics of storm velocity and direction. This work forms part of current research at the Meteorological Office(13) where methods of analysis are based on the work of Marshall(14) at the University of Bristol. The use of radar to study storm movement in urban areas is being actively pursued at Birmingham University.(15)

The possibility of urban development inducing convective rainfall is under study at Queen Mary College, London.(16)

Gauged Urban Catchments

The most significant contribution to urban hydrology in the U.K. has been the programme of data collection initiated by the Road Research Laboratory in the early 1950's.(2) Twelve catchments (see Map, page 4) of various sizes and types were gauged for up to five years to provide the data upon which the Laboratory's hydrograph method of sewer design was based. (The RRL Model is described in Section 3). Some of the data have now been digitised at the Institute of Hydrology and are available for testing with alternative models.

A more recent exercise was commissioned by the Department of the Environment. A number of local authorities collected rainfall and runoff data for a few years starting in 1972. Unfortunately, when the scheme was later scrutinised by hydrologists, most of the catchments were found to suffer in one way or another from problems of calibration, siting, or supervision. Subsequently, the emphasis was changed to study a few catchments in more detail and with improved instrumentation and procedures. The Hydraulics Research Station and the Institute of Hydrology are now responsible for data processing and general supervision on sewer catchments in three towns (Derby, Bracknell, Stevenage); and thirteen catchments in nine towns were dropped from the scheme (Nos. 12-20 inclusive on the Map, page 4). Other data have been collected by researchers in Southampton,(3) Birmingham,(17) and Nottingham.(10) All these catchments are gauged in or at the outfall from a pipe sewer system.

Other catchments, equally 'urban' in character, are gauged in an open watercourse receiving discharge from several sewer systems. Most of those which are more than 60% developed are in the Greater London area. All gauged catchments with more than 25% development are shown on the Map, page 4.

Small Sub-Catchments Gauged at Inlet Point to Pipe System

It is generally recognised that a further advance in knowledge of urban runoff processes requires that the above-ground and below-ground phases be considered separately.(18) As stated previously, some small areas have been studied but the gauging has always been made at the downstream end of a short length of pipe. In order to gauge exactly at the phase boundary, the Institute of Hydrology is installing gully meters (see "Inlets," above) at eleven sites within three catchments that are already gauged downstream (Bracknell, Stevenage, Southampton). It is intended to collect data throughout the summers of 1976 and 1977. Additional sites, with different slopes and surfaces, might be gauged in later years. In the meantime, it is planned to commission a complementary study on the laboratory catchment at Imperial College, London,(19) where the effects of catchment and storm characteristics can be studied under controlled conditions.

From 1960 to 1965 the Road Research Laboratory turned its attention to motorway drainage and instrumented eight sites on three motorways. Runoff was monitored by flumes in the outfall pipe to each length of road. Imperial College undertook analysis of the data.[20]

Water Quality Studies

Some catchment studies are primarily directed to problems of water quality but they invariably require the same effort applied to the measurement of quantity as do rainfall-runoff studies.

The first published account of a storm runoff quality investigation based on systematic analysis of recorded data seems to be the work of Wilkinson[21] who took advantage of the gauged catchment at Oxhey (No. 7 in the Map) set up by the Road Research Laboratory in 1953. He found that first flushes were not much more polluting than subsequent flows except after long dry periods.

Hedley and King,[22] investigating a combined drainage system in the Haunch Valley, Birmingham, emphasised the importance of the highly polluted initial runoff and discussed means of providing temporary storage. They also drew attention to the need to identify the separate sources of pollution and their relative significance. Their techniques of data collection were described separately.[23] More recently,[24] runoff from an urban motorway has been gauged and analysed. Motorway runoff quality was studied at Lancaster University for several years prior to December 1974. Three sites on the M6 motorway were monitored with particular emphasis on salt dispersal, and Patrick[36] reported on the nature of sediment collected in settling tanks elsewhere on the same motorway. A further extensive study of motorway runoff quality is under way at Imperial College using new sites on the M1 motorway. This study is partly sponsored by the Transport and Road Research Laboratory, which has a particular interest in the deposition of oil on the road surface and its ultimate fate.

Tucker[25] used dilution gauging for flow measurement at Nottingham and analysed the samples to give not only the discharge hydrograph but also the concentration-time curve of polluting constituents. He also emphasised the importance of 'first flush' pollution.

The changes in sediment production resulting from building activity have been studied on a 0.26-km^2 catchment near Exeter.[26,27] This is clearly a highly significant source of sediment; and some of the large sewers in Birmingham, for example, have up to a 0.5-m depth of building debris in the invert.

The Water Research Centre is working on the Shephall catchment in Stevenage (also being studied by Institute of Hydrology and Hydraulics Research Station teams) and are collecting data with the aim of devising and calibrating a mathematical model of the storm-water pollution process. They are looking at the ways in which pollutants accumulate on and are freed from urban surfaces. Also, they are studying the effects of intermittent discharges of polluted surface water on water quality and the contamination of sediments and biota in receiving streams.

A team at Middlesex Polytechnic have begun a programme[28] of data collection, chemical analysis and urban land use surveying related to storm-water pollution in the catchments of the River Brent and Silk Stream in North London. Here they will be installing some new instrumentation to complement river gauging stations operated by the Greater London Council. (Nos. 105, 106, 112 in the Map, page 4).

Catchments Undergoing Urbanisation

This subsection describes active or recent work involving the collection and/or analysis of data with the aim of learning more about the hydrological consequences of urbanisation.

The Gloucester Joint Surface Water Study[29] was established in 1969 with the aim of assessing the magnitude-frequency relationships of flows in North Gloucestershire rivers and how these relationships would be affected by the anticipated development of the region. A network of gauging stations and autographic rainfall recorders was established.

Gregory[30] has analysed over 600 storm events occurring in four years, during which the subject small catchment near Exeter was progressively built over. The study continues.[31]

At Milton Keynes, the Institute of Hydrology is studying two catchments: one is to remain rural for several years and the other is to be completely developed. Rainfall and runoff gaugings started in 1972 and, on the catchment being urbanised, flow is presently being gauged both in the original natural stream and in the parallel main storm sewer (see "Special Structures," above).

The Scottish Development Department is gauging the 26-km^2 Calder Water (No. 155 in the Map) with the aim of studying the effects of a projected new town on runoff distribution and water quality. The University of Newcastle and Northumbrian Water Authority are studying runoff from a developing industrial estate at Cramlington.

The above studies have each been designed specifically for the purpose in hand, but other workers have used data from established gauging stations and drawn conclusions about the effects of urbanisation on high flows, low flows, and hydrograph shape.

Hollis has made an extensive study of the flow regime of the 21-km^2 Canons Brook catchment which changed from a rural state in 1951 to a fully developed state in 1970. He has shown[32] that while the frequency of winter flood peaks has remained unchanged, the frequency of summer floods has increased markedly.

Urbanisation of this clay catchment does not seem to have altered the magnitude-frequency relationship at return periods greater than 20 years. Hollis has subsequently[33] reported on the effects on the low flow regime.

Hall[34] studied the change in shape of the derived unit hydrographs for both urban and rural catchment areas in the headwaters of the River Mole near Crawley (No. 153 in the Map). Whilst confirming the expected trend for lag times to decrease with urbanisation, he concluded that a simple measure of 'percentage impervious' was inadequate and that changes in the channel system and the distribution of impervious surface within the catchment should be considered. Packman[37] followed Hall's techniques in analysing unit hydrographs in two urbanising catchments in North London. He found that non-linear effects tended to obscure the changes in lag time due to urbanisation. While the expected reduction in lag time could be observed in the initial stages of urbanisation, including the establishment of the basic sewer system, later infilling had little extra effect.

Data Collection and Processing Systems

Compared with the U.S.A., the expenditure on gauging of urban runoff in the U.K. has been small. There have been so few data that sophisticated methods of handling and processing have not been required. Records have been obtained on charts and extracted manually. Only recently has the use of analogue-to-digital conversion equipment been justified, and magnetic tape logging systems are being used in urban hydrology for the first time this year (1976).

As part of the data gathering exercise commissioned by the Department of the Environment (see "Gauged Urban Catchments," above), Coventry City developed a system[35] of processing and archiving data using a digitiser. Rainfall increments, water levels, or flows from any number of recorders, can be extracted for any specified time interval and stored on magnetic tape for retrieval in various formats for different purposes. One of the main users of the system has been the Gloucester Joint Surface Water Study (see the preceding subsection). A similar system is in use at the Institute of Hydrology and has recently been extended to cope with data received from magnetic tape data loggers.[4] The Microdata logging system is used, which can record analogue voltage inputs on up to 12 channels in digital form on compact cassettes. Input may be from a raingauge, a gully meter (see "Inlets," above), or a water level recorder, either float type or Manning dipper (see "In-Pipe," above).

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SECTION 3

URBAN HYDROLOGICAL MODELING IN THE UNITED KINGDOM

Introduction

This section contains a brief account of urban hydrolgical modeling in the U.K. Answers to a recent questionnaire[1] revealed that the overwhelming majority of sewer designers used either the rational or TRRL (Transport and Road Research Laboratory) methods or both. The TRRL method (formerly called the RRL method) was developed by the Road Research Laboratory (now TRRL) and is the best known British contribution to post-war urban hydrology. A brief history of the evolution of the TRRL method is given in the next subsection. Despite its U.K. origins, all but one of the several independent and published studies of comparative evaluation have been performed in other countries. Studies in the U.S.A. have been listed,[2] and these and others are also described in a recent literature review[3] produced at the Hydraulics Research Station, which also reproduces published data on the performance of the various methods.

Despite the lack of formal evaluation in the U.K., there has been a fair amount of published criticism founded on theoretical objections to the basis of the model. This has prompted the development of alternative design models, but the RRL method's simplicity and orientation to design have been recognised as important attributes and any new developments will inevitably be measured against it. The newer models are described in a later subsection.

As noted in Section 2, water quality modeling is being actively pursued in the U.K. but has not yet been included in a hydrological model.

Also noted in Section 2, the hydrological effects of urbanisation have been studied in the U.K. Most of the work has concerned single catchments and, although unit hydrographs and regression equations have been used to illustrate trends, the studies have not been concerned with model calibration. In one case, however, positive recommendations are made for application to an urbanised and ungauged catchment and this is given a brief mention in a later subsection.

The TRRL Method

The TRRL method of sewer design can be categorized as a design/analysis model in the sense used in the first of the special IHP Technical Memoranda series.[2] It was developed at the Road Research Laboratory using data collected from 1952 to 1960 (see Section 2) and was described in detail in 1962,[4] with a scientific paper[5] and engineers' guide[6] in 1963.

These early descriptions of the model are recognised by hydrologists as being similar to the Clark-Johnstone method of unit hydrograph synthesis, except that the area-time curve is routed through a non-linear storage rather than a linear storage. Later, the concept of routing through a single storage was replaced[7,8] by a method whereby a separate routing was applied at every pipe length. By thus emphasising that the storage allowance was linked to storage in the pipes, the model's designers left themselves open to criticism regarding the need for storage routing at all. It is argued[9,10,11] that the pipe storage is implicitly allowed for in the area-time diagram construction and need not be considered again. The reply to this is that, whatever the cause, there is clearly an effect of reservoir-type storage and the TRRL model matches this effect in practice. But several workers have queried the philosophy of 'two wrongs make a right', not only in the matter of storage but also with regard to percentage runoff assumptions (i.e., 100% from paved surfaces, 0% from the rest), the assumed relationship between rainfall and runoff frequencies, and the neglect of surcharging.

These criticisms raise the general point of whether or not it is necessary to understand the hydrological processes at work in sewered catchments. It is likely that the majority of engineers are satisfied with an empirical method, such as the TRRL method, despite the general awareness that, when used with the recommended design rainstorm, it over-estimates the discharge for the specified return period.[12] In recognising that it is the specification of a design rainfall input which is at least as important as the rainfall-runoff model itself, the Transport and Road Research Laboratory is in the process of issuing a revised guide[13] on the use of the method. This incorporates some of the new information on rainfall statistics and design profiles which has become available following publication of the Flood Studies Report.[14]

Using the same assumptions as for the TRRL method, King[15] substituted simple functional relationships for the design storm profile, area-time diagram, and flow-retention relationship. He was thus able to give a functional form for the design hydrograph and to produce a set of design curves for quick evaluation of peak discharge.

Other Methods Developed in the U.K.

Sarginson[10] has focussed attention on the problem of identifying the source of the storage which the TRRL method models so convincingly, and he proposed that the above-ground and below-ground storages be treated as two separate linear reservoirs in series (compared with the TRRL method, which represents them together by a linear channel and non-linear reservoir in series). He has subsequently suggested[16] that the assumption of 100% runoff from impervious surfaces with no contribution from pervious areas is an over-simplification, and that depression storage and infiltration should be more realistically modeled. Further work[17] has led to a prediction equation for percentage runoff in terms of catchment slope; and the two conceptual reservoirs, originally unequal, are now taken to be equal.

Workers at Birmingham University have applied automatic optimisation techniques[18] in refining the TRRL method by consideration of above-ground storage and by an iterative approach to find a 'true' mean pipe velocity rather than the use of a pipe-full velocity.[19]

Kidd[20] has further emphasised the importance of separating the above-ground and below-ground phases of runoff. In his model, depression storage is deducted and a loss rate is applied to the total rainfall to give the rainfall excess. This is then routed to the sewer inlet through a single reservoir. Linear and non-linear reservoirs are compared and the superiority of the latter is clearly demonstrated.

A single linear reservoir is used by the Transport and Road Research Laboratory[21] to modify the rainfall excess hyetograph generated on pervious surfaces only, when applying their method in areas of tropical rainfall.

Models of motorway drainage may be considered as special cases of the above-ground runoff model. With their regular geometry and single surface type, motorways are more susceptible to deterministic modeling of physical processes than to the lumped parameter approach used in the models described above. It is interesting therefore that, even in this situation, workers at Imperial College preferred to base their proposed method firmly on empiricism. They developed a dimensionless hydrograph design method,[22] for single peaked hydrographs only, with scaling factors determined from prediction equations whose coefficients had been determined by multiple linear regression on catchment and storm characteristics. They also describe[23] a conceptual model using a single linear reservoir for the impervious areas only. The storage constant takes one value if it is raining and another if it is not raining; furthermore, the values depend on storm rainfall and site characteristics so the model is more accurately described as quasi-linear.

Current work at the Hydraulics Research Station and Institute of Hydrology is designed to produce a recommended set of design methods for use in different situations. The rational method and TRRL method will probably continue to be the most suitable in preliminary design of small and large schemes, respectively, but for high accuracy and large schemes in particular, it is likely that a new design method incorporating economic design criteria will be proposed. The Hydraulics Research Station is studying various methods of pipe flow routing and ways of allowing for surcharging. The Institute of Hydrology is concentrating on the above-ground phase, extending the work of Kidd,[20] seeking prediction equations for runoff volume taking account of depression storage and unpaved areas.[24]

Progress in hydrological modeling inevitably appears to involve more complicated procedures for the designer to implement and more information to be gathered. It is vital for the researcher to be aware of this and to ensure that recommended improvements are truly beneficial. For example, the present use of TRRL is probabilistically unsound and too simple in terms of scientific hydrology. But unless a new method can be shown to give more accurately sized pipes and less costly protection against surface flooding, no amount of technical elegance will persuade the engineering profession to adopt it. It is this reluctance to accept anything which appears more complicated than is considered necessary that is sometimes responsible for recommendations that we return to simpler techniques. The most notable of recent calls to that effect was by Hepworth,[25] who pursued the claim that the storage routing correction in the TRRL method was spurious and needed only to counteract overestimation of flow rates during the first half of the storm. He suggested that a simple time-area calculation should be applied just to the part of the rainfall profile occurring after the peak intensity.

The Urbanised Catchment

It is sometimes difficult to make a neat separation between the hydrological modeling of urban catchments (by which we tend to mean sewered catchments) and that of natural catchments either undergoing progressive urbanisation or already substantially urbanised. In practice, however, the distinction is whether or not any attempt is made to simulate flow through pipe systems. If not, and if the extent of sewered areas is represented simply by one or two catchment characteristics, then we have an 'urbanised catchment model'. The characteristics can be included as independent variables in regression equations to predict model parameters. This approach has been used frequently in the U.S.A. with the simple unit hydrograph model[2] but only one such study has reached a similar stage in the U.K. Hall[26] studied unit hydrographs for several urban and rural catchments near Crawley, and also the changing shape of the unit hydrograph during progressive urbanisation of three of the catchments. He developed a dimensionless unit hydrograph scaled by only one parameter and related this parameter to basin ratio ($L/\sqrt{S}$; where L = main channel length, S = main channel slope) and degree of urbanisation. Packman,[27] applying the same techniques to catchments in North London, obtained reasonably consistent values of lag time, and his dimensionless unit hydrograph is similar to that subsequently published in the Flood Studies Report.[14]

In response to queries arising since publication of the Flood Studies Report,[14] the Institute of Hydrology re-examined basic data and produced recommendations[28] for adjusting estimates of the mean annual flood, the T-year flood and hydrograph shape for urbanising catchments.

Conclusions

Urban hydrological modeling in the U.K. continues to be geared primarily to the improvement of sewer design methods. The common aim is to seek a compromise between the mainly old, established, easily applied but theoretically unattractive methods, and the highly complex analytical models based on physical laws.

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