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HYDROLOGICAL PROCESSES
AND WATER MANAGEMENT
IN URBAN AREAS

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Invited lectures and selected papers
of the Unesco/IHP International Symposium
URBAN WATER '88,
held at Duisburg, Federal Republic of Germany and
at Lelystad, Amsterdam and Rotterdam, The
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Preface

During the last two decades there has been growing interest in many countries in research on urban hydrology. Within the framework of the International Hydrological Programme of Unesco, the activities started with an internationally oriented analysis of problems, followed by inventories of current research and research findings by means of state-of-the-art and progress reports. Moreover several international symposia and workshops have been organized during recent years, mostly on specific topics related to modelling, catchment research, drainage or water resources management. In 1977 a symposium with a wide scope was convened in Amsterdam, including themes on the effects of urbanization and industrialization on water quantity and quality, and their impact on water policy. Today, in our view, the phase of problem inventories in the urban hydrology sphere is over. In an increasing number of cases, design and management of urban water systems are based on hydrological studies. We feel confident that, for the coming years, the integration of know-how on various aspects of urban hydrology, such as water supply and sanitation, town and regional planning, ecology and hygiene, will be crucial. Moreover, the application of advanced technologies and the transfer of knowledge and experiences are the most important items to researchers as well as to planners, managers and decision-makers.

As a contribution to the realization of this long target the international conference URBAN WATER '88 was held in April 1988 at Duisburg, Federal Republic of Germany, followed by a two-day study tour to old cities and new towns in The Netherlands. Research-findings on six themes, experiences with integrated water management and views on the role of water in city planning were presented, and recommendations were made to Unesco, its member-states, WMO and to non-governmental organizations. Due partly to these recommendations, the Intergovernmental Council of IHP recently agreed upon continuation of project-activities on hydrology and water resources management in urban areas during IHP phase IV (1990-1995).

This volume contains an introduction, eight invited lectures and 32 selected papers from the Duisburg-conference. The papers were selected on the basis of general interest, technical innovation, and geographical region. The illustrations on the cover and inside the book were made by the artist Paul Overhaus, Amsterdam. They reflect the topics of the symposium in an artistic way.

Thanks to Hans Hooghart and the IAHS-Bureau for its editorial support.

We hope the contents will be of help to those who are interested in urban water.

Herbert Massing
John Packman
Floris C. Zuidema
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CONCLUSIONS AND RECOMMENDATIONS
INTRODUCTION

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URBANIZATION AND THE HYDROLOGICAL REGIME

For many centuries people have been living together in cities. In many cases their choice of a certain site was based on the presence of water: for navigation and trade, for domestic and craft use, for food production (fish and crops), or even for defence of the inhabitants against enemies.

Although the reasons for establishment of the first historical communities are not clearly understood, urbanization, which is characterized by a clustering of people in relatively small areas, is recognized as an inevitable historical process (Lazaro, 1979). In 1950, about one third of the world population lived in cities. By the end of this century it will be about half of the world population. In the 35 years since 1950, the number of people living in cities almost tripled, increasing by 1 249 million (734 to 1 983 million). In more developed regions about 75% of the population will be concentrated in urban areas (United Nations, 1987). Such trends are reflected in the growth of cities. In the early nineteenth century there was only one city, London, with one million inhabitants. Estimates for 1985 indicated 270 urban areas with more than one million inhabitants and 35 areas with more than five million inhabitants.

Further rapid growth of large cities is expected in the next 15 years: ranking the ten largest cities of the world in 1980 and 2000 shows a range from 20.4 million (New York) to 10.1 million inhabitants (Buenos Aires) in 1980, and a prediction of 31.0 million (Mexico City) to 16.7 million inhabitants (Calcutta) in the year 2000 (Lindh, 1985). These figures underline the dynamic development of urban population and urban areas, especially in developing countries. Some of these areas will see their population double in a short period of 20 years.

High concentrations of population in urban areas bring several implications for the management of water resources. The urban population acts as a driving force which changes the landscape and hydrological cycle of the area, requiring further provisions and certain services. Such services include water supply, flood protection and drainage, wastewater disposal, and water-based recreation. Because of the large population of urban areas, any urban water resources project has a potential to benefit large populations, but design failures may also lead to high damages and even catastrophes. Moreover, the dynamic character of urban areas may cause nonstationary trends in water demands and run-off, and lead to diversity of functions of water resources and water systems. Herewith quality requirements play an increasing role, as water and solid waste pollution problems have increased rapidly. Recently it was reported to the UN-General Assembly that the essential
infrastructure of many Third World cities cannot keep pace with the enormous pressure for shelter and services: a large section of a city's population often has no piped water, storm drainage or roads (United Nations, 1987).

The different functions of water and the various demands for a sometimes limited, sometimes superfluous commodity, easily lead to conflicts. Fortunately, decision makers and politicians recognize more and more the importance of a consistent policy for developing water resources. Moreover, there is a growing plea for an integrated, comprehensive approach to water resources, their interrelation with physical planning, the well-being of the urban population and the ecological values of the adjacent urban areas. Scientific support of the planning process will assist the decisions to be taken. So, it is hoped that perceptive urban planning and urban design will further benefit by considering water-related assets and conditions.

DEVELOPMENTS IN URBAN HYDROLOGY, WITHIN THE INTERNATIONAL FRAMEWORK

The world-wide process of urbanization and industrialization, the deficiencies in the knowledge of urban hydrological processes, and the implications for adequate water resources planning and management have led to international cooperation since about 1970. Within the framework of the International Hydrological Decade (1965-1974) and the International Hydrological Programme (IHP) (since 1975), Unesco took the initiative to promote several activities, as symposia and workshops, and to prepare state-of-the-art reports and manuals. By sponsoring these activities, Unesco has greatly aroused the interest of decision makers, technicians and researchers in many countries of the world for this distinctive branch of hydrology. In the period 1973-1977 one symposium and three workshops were held. A two-volume manual on design of urban drainage systems and data collection and analysis has been published recently (Unesco 1987). And in the IHP-IV Programme (1990-1995) a special project on Urban hydrology and water resources management has been formulated. Besides these IHP-activities, the United States Council on Urban Water Resources Research and especially the late Prof. M.B. McPherson, and subsequently Prof. J. Delleur and Dr. H.C. Torno, organized international workshops to discuss the progress on urban hydrological research (1979, 1983) (Unesco, 1981; American Society of Civil Engineers, 1983). Furthermore the Man and Biosphere Programme of Unesco pays attention to social and ecological aspects of urban development. Since about 1980 other international organizations like the World Meteorological Organization with its World Climate Programme have also been organizing meetings on urban water resources, urban hydrology, urban drainage, etc.; and bilateral workshops and regional seminars are held. Special mention is made of the conferences on Urban Storm Drainage, organized by the Joint Committee of the International Association of Hydraulic Research (IAHR) and the International Association on Water Pollution Research and Control (IAWPRC) (1982, Urbana, US; 1984, Goteborg, Sweden; 1987, Lausanne, Switzerland; 1990, Osaka, Japan). Moreover, many national activities underline the importance of the subject.
THE ROLE OF WATER IN URBAN AREAS

Water in urban areas has several functions for nature and man, as a natural resource as well as providing space for recovery and well-being. The natural hydrological cycle and water balance are very much influenced in urban areas by activities of the population (Lindh, 1983). Water in urban areas is used for many activities, even re-used several times and finally drained into rivers. This leads to strong impacts on the groundwater and the surface water bodies. Budgeting all elements of the urban water system, (from precipitation and water supply import into urban areas up to evapotranspiration and discharge into receiving waters) is imperative. One can speak of an urban water balance (McPherson and Zuidema, 1978).

On the other hand the water regime in its components can be a prerequisite for settlement and industrial activity. This water regime is of great importance for the different functions and uses of water in urbanized areas: e.g. water as a nutrient, water as a factor of health and source of life, water bodies for fishing, shipping and energy source, water as a climatic factor and as a basic condition for ecosystems. All these functions of water may be considered as instruments in town development (Unesco, 1974; Massing, 1977).

This interrelationship and interdependence lead to a more distinct view of the role of water within the urban physical and social system. As today nearly all over the world the urbanization process is moving quickly we have no time to lose in convincing responsible bodies how the role of water in the town of tomorrow needs to be further developed. In order to gather ecological and economical expertise as well as technological experience, an integrated approach to water resources planning is advocated. Moreover, a continuous promotion of integrated water management is needed, with participation from all components of urban activity including the views of the public.

Within the last years there has been a rapid increase of consciousness of the urban population for all sections of the environment. In many cases the public insists upon participating in the planning process.

PURPOSE AND SCOPE OF THE SYMPOSIUM URBAN WATER '88

In view of the developments described, it was the desire of the organizers of the Symposium URBAN WATER '88 to bring together experts on all relevant aspects of the urban sciences. As defined at the Unesco-workshop "Socio-economic aspects of urban hydrology", November 1976 in Lund, Sweden (Unesco, 1979), urban hydrology is "the interdisciplinary science of water and its interrelationship with urban man". Therefore the call went to urban hydrologists as well as to city engineers, to city architects as well as to town planners, to urban economists as well as to town managers, to urban ecologists as well as to town medical officials, to urban sociologists as well as to teachers and artists, and to meteorologists as well as to state planners. The Symposium URBAN WATER '88 has provided a scientific framework to promote the exchange of information. It has forged an integration of expertise and has made the more than 300 participants familiar with the vocabulary, techniques and goals of the other disciplines. Proceedings of the Conference
were pre-published (Hooghart (éd.), 1988).

Beside integrating the various disciplines, there were two other considerations: Firstly, world-wide the financial resources, especially of large cities and metropolitan areas, become more and more limited because of the rising costs of public services and of social measures. The costs of providing urban water services are escalating rapidly. It is therefore of vital interest for the urban technician and manager in the field of water to work together in an integrated planning approach with all related urban interests. Secondly, water is one of the renewable natural resources. Protecting water means protecting a natural resource. The increasing use of water, the growing demand for water and the accelerating impact on water often conflict with the protection measures. This happens especially when the urban water system spreads far beyond the borders of the city: e.g. water supply from further upstream with serious ecological consequences in the catchment, sewage discharge into a river with effects on the water system downstream. Therefore interdisciplinary tools are needed to balance the interests and to mitigate the consequences.

SCALE- AND TIME-HORIZONS OF URBANIZATION

The rapid process of urbanization in the world is a challenge for administrators and planners, as well as for technicians and research-workers. As stated before, since 1970 urban hydrology has played an increasing role as a supporting activity to the design and the implementation of urban water systems. A further enlargement of these activities has - in our opinion - to reckon emphatically with the scale- and time-horizons of the urbanization process and its water related aspects. These scale- and time-horizons will affect the approach and the particular action to be taken. We may distinguish:

- (inter)national, (inter)regional, local, river basin related activities. For example: the urbanization of the Rhine-area (river basin and delta), which concerns mainly the North Rhine-Westphalia region of the Federal Republic of Germany and the Netherlands, meets different problems nowadays from e.g. the Paris-Seine area in France or the Tennessee Valley in the USA;
- industrialized countries, developing countries. For example: apart from differences concerning climate and sea-level, flood protection of the fast growing city of Bangkok requires different actions from the Rotterdam-area;
- geographical aspects and climate conditions. Similarities or differences in the hydrological behaviour of various urban areas might be based on physical properties, such as topography and geological and/or soil-conditions; however, historical developments, man’s activities and the socio-economic features of the area (region, delta, river basin) do determine its development. The hydrological impact has also to be considered as part of that process.

TRANSFER OF KNOWLEDGE

From the written contributions to the Symposium URBAN WATER '88 we have learned that there is a considerable amount of experience available, but, spread all over the world, and mostly applicable or applied to one specific situation. There is a strong demand to integrate views and to transfer knowledge and experience at regional, national and
international level, by means of training courses, workshops and symposia. It is advocated that international governmental and non-governmental organizations like Unesco, IFHP (International Federation of Housing and Planning), IAHS (International Association of Hydrological Sciences), IAWPRC (International Association on Water Pollution Research and Control), IAHR (International Association of Hydraulic Research), EC (European Community) and other regional organizations, should support or initiate member-countries to organize such activities. The subjects should preferably not be limited to (urban) water alone. By bringing together experts of various urban and water related disciplines, transfer of knowledge and exchange of views will create a better awareness of good urban planning and design, including water systems, and will promote teamwork for the benefit of the urban population.

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INTRODUCTORY LECTURE

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EXAMPLE DANUBE AREA VIENNA

INTRODUCTION

Water in cities is far too precious and beautiful to be left in the hands of the experts alone. This may have been the reason for allowing a town planner and not a hydrologist to introduce the theme of this colloquium. Historically there are good, legitimate reasons.

Water and towns have been inextricably linked from the early beginnings of 5000-6000 years ago. The first towns developed where an abundance of water and regular floodings resulted in such fertile soils that more was produced than was needed for the livelihood of the farming community. Floods and irrigation made surveys, calendars, and water management necessary, and an appropriate group of experts was appointed to deal with the necessary calculations organizations. Protection from and management of water are therefore at the cradle of town development where society depends on division of labour and public infrastructure; "learned water people" formed the original nucleus of the aristocracy and the expert civil service!

The relationship with and the treatment of water were never based solely on a technical-rational approach but also on mythical-religious thinking. Nymphs and gods lived in rivers and wells; they had to be cared for and honoured and they took revenge for (ecological) misconduct. Later water gained importance as a means of transport. All important European towns originated along waterways. For many the basic layout was determined by a water network - e.g. Amsterdam, Stockholm, Venice. Other towns used the waterway as their tool and turned their backs to it - e.g. Liverpool, Stuttgart, London. Different characteristics of the towns' personalities come to light which are not easily explained. The many religious, cultural, and practical strata determining the relationship of the towns to water were completely changed by the industrial revolution. Science based techniques took over, and tried to dominate the water by instrumentation - with splendid successes, but also with enormous disasters, as was demonstrated by recent major floods. Limits appear which have to be respected and reflected on and to which I would like to contribute some ideas.

More and more we move from a one-sided attitude - which treats water in towns from a scientific-engineering standpoint (regarding safety, supply and hygiene) - to a multidisciplinary approach (regarding its creative treatment, "experiencing" the water, using it as an art medium, but recognizing the decisive ecological role it plays in the vividness and variety of our urban environment). Here are some practical examples of my own work. Currently we are working - very close to here - on the restructure of the Rhine embankment and flood protection wall at the city centre of Düsseldorf. We are changing a pleasing but technically onesided structure to a "multipurpose embankment" which apart from flood protection should also serve to give experience of the water and river with
stairs, ramps and cuts. With this work several conflicts have to be overcome between flood protection, form, and sensitivity. I do not want to elaborate further on this project - it is still in the development phase although the plans have been approved in principle. I wish to consider another example, in my view one of the most successful projects of a large urban water development built in recent years, one in which I was involved on the urban planning side from 1971 - 1987: namely the construction of the "New Danube", the "New Danube Islands", and the proposed new retention basin in Vienna. This example demonstrates especially well the change in attitude towards the taming and the usage of water.

**DANUBE AREA VIENNA**

Less than 100 years ago the anarchically unregulated Danube bordering NorthWest Vienna formed a fascinating, braided landscape of rivers, brooks and islands, changing constantly through regular flooding (Figure 1). For Vienna this river landscape was difficult terrain to cross and floods were a constant threat. Between 1812 and 1900, 82 big floods were recorded, and the few wooden bridges were repeatedly destroyed by floods and drifting ice.

![Figure 1. Vienna around 1840.](image)

**The first river improvements and their effects**

In 1864 a commission was formed to study plans for: flood protection; improved navigability; better integration of city and river; construction of a harbour and permanent bridges; and enlargement of the city. After examining a number of plans, the construction of a new, artificial, and canal-like cut was proposed which was to replace the numerous
river channels and remove the water as fast as possible. From 1870-75 Ferdinand von Lesseps, having just completed the Suez-Canal, constructed the new riverbed. There was then already isolated criticism for this solution as being technically forced and not in keeping with the organic whole of the river landscape. This criticism, however, was then rejected as being "romantic" and opposed to technical progress (Figure 2).

The effect of this radical river regulation was that the scenery underwent fundamental changes. The old river channels were almost completely filled in and the meadow character of the landscape disappeared, with the exception of the Prater and Lobau. The groundwatertable sank and the vegetation changed. Where the river channels and meadows had been, within a few decades building works appeared in the chequer board layout typical of the 19th century. The big new railway system and commercial quay were also constructed so that the inner city was separated from the river by barriers. Since this time the Danube has hardly been experienced as a river in the town. The river scenery was gradually dominated by technical constructions of bridges, the railway, and the harbour.

Soon after completion of the river regulation works it became apparent that the measures of 1870-75 still did not provide adequate flood protection and that therefore new plans were required. Between 1900 and 1970 sixteen different proposals were put forward dealing with flood protection.

**The new project and the planning competition**

In 1969 the city decided to dig a "relief channel" parallel to the cut of 1870-75 through the flood area. This would create a 20 km long and 200 m wide island safe from floods.
between the "relief channel" and the Danube. The construction department of the city was commissioned to organize the technical planning and implementation. The first section led in 1972 to vehement protests from the public over its completely shapeless, straight, and constantly sloping channel embankments (Figure 3).

![Figure 3. First section.](image)

Therefore the city decided - despite ongoing construction works - to hold an interdisciplinary planning competition (in 2 phases) aimed at improving the ecological, aesthetic, and effective quality of the flood protection measures. I have been following this project since this time, first as a judge on the competition panel, later in my capacity as townplanner, so that I can report from first hand experience.

With this competition a new fascinating phase has begun, involving new forms of interdisciplinary planning organization and implementation. The jury panel was made up of members from several disciplines: Construction engineers, architects, landscape planners, traffic forecasters, and (representing a new aspect of growing importance) an ecologist.

The results of the competition were deeply stimulating in their attempts to "ecologize" the "relief channel". They included gentle bends and differentiated embankments according to slope, material, and vegetation. They protected existing remnants of the old river network and old trees. Because of pressure on time from the "big diggers" the second phase of the competition was revised. Instead, a new planning organization was set up with the directive to study continuously interdisciplinary alternatives and variants aimed at developing plans for implementation without delay.

**The result of the planning efforts**

This project was in part paradoxical in that the enormous time pressure - which is
Introductory lecture

normally the enemy of good planning - was one of the reasons for its huge success. Because of the short timespan between planning and implementation the participating planners could soon test their joint planning efforts in reality and avoid errors in subsequent sections. Wherever possible the few remaining remnants of the old Danube landscape - old tributaries with old trees - have been carefully conserved and been included in the new plans. The embankments and the many sections of the island have been shaped according to the special needs of varying usage and the "natural" vegetation. The ecological cycle has been supported by generous green bridging spaces (Figures 4 and 5).

![Planning efforts](image.png)

**Figure 4. Planning efforts.**

Before planning began, a market research institute estimated 40 000 people would visit the island on fine days. However, the Viennese have adopted it with enthusiasm; on sunny summerdays around 500 000 Viennese visit the islands! This intensive use requires careful and continuous management because - as can be imagined - such numbers attract many commercial utilities and enterprises which must be controlled carefully so as not to damage the long term recreational and scenic character.

**The next planning phase**

Renewal and further development of the whole former river landscape - "Danube area Vienna". The positive experience of the above mentioned planning organization led to two (at least) equally ambitious projects. Firstly the organization of the 'southern belt and western approach' which includes reshaping the bed of the river Wien and at the same time providing flood protection from the Wienerwald. Secondly the renewal of the whole urban Danube area concerning the future role of the nature park, the central station and major international events like world exhibitions.
Figure 5. Embankment types.
Again a large hydro-technical infrastructure project should serve as pacemaker for the whole of the development: namely the construction downstream of Vienna of a power station with retarding basin necessary for water management and ecological reasons. With this project the character of the river will change at Vienna; the current will be reduced and will be similar to before the original regulation; the water level will rise by 7 m at the basin and by 2-4 m in the city area.

When first published, this plan met fierce opposition from the ecologists. However, further studies convinced this group too, that the plan corrected part of the on-going ecological damage, caused by the continued lowering of the Danube riverbed following the regulation of 100 years ago. Raising the water level of the river will also raise the ground water, and old brooks which are threatened from drying out can be supplied with water again. At the same time the lowering of the Danube riverbed will be stopped in the Vienna area in both the "New" and "Old" Danube where swimming areas are threatened. A second main aim connected with changing the character of the river is to reshape the part of the city on the northern embankment (presently occupied by little used harbour and railway installations) into an attractive urban part of the river. Raising the river level will again make the Danube into an "experience" and bring it closer to the town.

Based on the previously described experience, the tried and tested type of planning organization for the "New Danube" has received the following additional directives;

- Interdisciplinary cooperation from the beginning of the planning stage
- More consideration for ecology and the social sciences
- Integrated public participation in extended form
- Systematic compatibility checks of all technical measures
- Opening up of competitions to students and young graduates as well as to scientists of disciplines other than engineering.

The experience I have described, with a new planning organization aimed at interdisciplinary innovation in the broadest sense has been and is an intellectual adventure. It is increasingly understood by the public and is accompanied by a very active publicity campaign by the city, with exhibitions, films, and school competitions as well as public debates. Thus the future of the Danube area has become a central theme of public discussion in Vienna.

**FINAL CONCLUSIONS FOR THE THEME OF THE SYMPOSIUM**

For the theme of your symposium - Hydrological processes and water management in urban areas - in my capacity as town planner and with my experience especially of the Danube area of Vienna I consider the questions developed below as most important:

A The frightening but fascinating interrelationships between hydrological processes and town development are based on the inextricable entwinement of all processes. After all, the hydrological problems which we tried to solve at Vienna were caused by a method of removing floodwater by canal-cuts which had led to further problems: deepening of the river bed; lowering of the ground water level; moving floods downstream, etc. Our recommendations probably "cure" and relieve some of the
heavy damage but also cause new problems. The water quality in the "New Danube" suffers from "hypertrophy". Diversion for recharge of the meadow areas requires amongst other things channels and shafts which represent possible dangers to groundwater pollution. Thus recharging the surface water forces us to "play god" by regulating artificially the water level changes, which used to happen naturally and which were so typical for the formation of the meadow scenery.

Comparable problems apply to the level of groundwater under built-up areas. The double wall-boxsystem of keeping groundwater at certain levels requires constant control and continuous human balancing intervention through pumps. Who decides the groundwater levels politically?

Above all the dangerous deepening of the river bed is only shifted to another section further downstream of Vienna, where sooner or later another retention basin would be necessary; the ghosts, once called, will only be put to rest again when the whole hydro-system has been brought under human control (with all the dangers of political misuse and misunderstandings of the system as a whole).

To what extent may we and should we interfere technically, and to what degree do new cybernetic approaches and control systems allow us a return to a new "naturalness" of self regulation which could help to limit human interference to a minimum?

The riverbed of the "Wien" - which I have not discussed here - was also channelled 100 years ago and does not satisfy current demands. It demonstrates a second question clearly: Two systems of flood transportation are under discussion, either by a long underground tunnel or by a change of the riverbed in such a way that the character of a "natural" river is recreated "artificially". This can be done using new retention basins to even out flood flows and guiding additional flood waters from urban areas into a separate channel below the visible riverbed. If the first solution is adopted, the river which gives the city its name, would be piped and would disappear from view, in the second solution a new "naturalness" is attempted and the experience of changing water levels of a mountain stream is preserved even though controlled in part artificially. I cast my vote for the second solution, but have considered the question which I had been pursuing during the planning phase of the Danube area:

How can we succeed in "refining" and shaping the necessary technical treatment of water in such a way that it becomes an act of culture - or perhaps even art?

In the last resort the examples which I quoted lead to the question of responsibility when dealing with water. In the context of our theme of hydrological processes and water management in urban areas we are mainly appealing to the responsibility of each individual citizen. The modern town dweller experiences his drinking water only from the tap to the sink, what happens before and after is lost from sight. That is the reason why today in everyday life we are still using water as if the supply of good quality was limitless. Town people do not realize the efforts and costs, the enormous technical installations and the increasingly more difficult problems and consequences which are associated with the supply, treatment, transport, and waste removal of water.
Hydrology and town development must cooperate so that the city dweller experiences with his senses the preciousness of water in the miracle of the water cycle. Only then will he finally change his attitude when dealing with water. This cooperation effects all themes of your symposium: The adverse effects of soil sealing on reductions in groundwater and on floods, the senseless but growing water consumption, the waste of water in combined sewage and the pollution from poisonous substances which makes swimming in rivers and lakes an exception rather than a rule.

How can the multiple techniques of water treatment - from the source through filtration to sewerage - be made visible to town dwellers that they learn to develop a feeling of responsibility when dealing with water?

These are important interdisciplinary issues; why should it not be possible to integrate large waterworks or old sewerage from the 19th century or a modern treatment plant into the urban environment thus making it into an experience for the town dweller so that he "learns" and "understands" one of the most important principles of our civilization?

A different, sensible approach to water requires not only greater understanding with the mind but also an experience with the senses. The natural seepage of water can be demonstrated by different types of vegetation; the effect of very high water consumption on e.g. remote water supply areas must be reported by the media; division of water cycles into rain, water supply service, and sewage must give noticeable financial relief, but must also become visible in town, in brooks, wells, cisterns, natural sewage plants. Perhaps public gauging stations should be installed where the level of the "environmental gauge" has its place in the daily news just like the weather forecast and the share index!

The living experience of the water as well as the concern about it must contribute to a new respect without which our common efforts will have little effect. My own professional experience of which I have told you a little leaves me in an optimistic mood. There still remain many untapped possibilities for the cooperation between skilful town planners and water experts!
THEME A

URBAN HYDROLOGICAL CYCLE
WATER BALANCES OF URBAN AREAS

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ABSTRACT

Metropolitan water balances provide valuable information for designing and operating an integrated urban water management system. Although often used e.g. for assessing the effect of urbanization, field observations of the urban budget are rarely available. Water quality aspects generally require another schematization of the pathways than used in terms of the quantity. The field data show interesting gaps over the assumptions used in some water balance models. The role of the urban groundwater and evapotranspiration are regularly underestimated. For drainage of urban areas these pathways could be exploited more than they are now. Balancing the water budget of an area requires large amounts of high quality data; but still errors of 10% or more are easily made.

INTRODUCTION

Water balance studies essentially are the initial stage of a hydrological systems analysis of a metropolitan area (McPherson, 1973). They provide an overview of the water flows along the pathways of the system and of the importance of the different hydrological parameters. Because balances are generally made up for periods exceeding the time constants of the system, short-term variability is smoothed out, along with the stochastic measuring errors. The water budget should be balanced; analysis of residual terms provides a means to detect systematic errors, either in the measurements or calculations, or in the schematization of the pathways. A major problem in water balance studies remains the assessment of evapotranspiration. A well-known technique for assessing balances was developed by Thornthwaite and Mather (1955, 1957) but it is hardly applicable in urban areas because of its assumptions.

Water balance studies have proven to be both flexible and understandable. By taking the balance over different periods of time, longer-term variations can be studied, e.g. month-to-month or annual variations. Even the effect of slow climatological changes can be studied this way.

The assessment of a water balance asks for large amounts of data. Data on precipitation, runoff, evapotranspiration, groundwater levels, open water levels, etc. have to be collected over a long period, accurately and with a high spatial resolution. The efforts required, in terms of labour and finances is therefore extensive. This probably explains why so many (urban) water balance studies are limited to model studies (Streit, 1974; Zvi, 1977; Giambelluca, 1986). Grimmond and Oke refer to six of them.

These model studies are not suited for studying the pathways of the water, because of the
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risk of making self-fulfilling prophecies. However, for studying the effects of urbanization the method seems acceptable, provided that the parameters can be identified. This is the most disputable part of these studies. Unfortunately a sensitivity analysis is lacking in most cases.

This paper will be limited to the results of balance studies based on actual data. Problems with transferability and representativeness of the model parameters are avoided this way. Neither will I discuss the differences between the rural and the urban water balance; literature on the effect of urbanization can be found elsewhere, e.g. Streit (1974), IAHS (1977), Hollis (1979), Wohlrab (1982), Giambelluca (1986).

OBJECTIVES OF BALANCE STUDIES

The objectives of a water balance study can be manifold. The main reasons for carrying out such a study are:

a. verifying the pathways in the system;
b. assessing the amount of flow along the (or certain) pathways;
c. assessing the pollutant loads along the (or certain) pathways;
d. assessing period-to-period or long-term variations;
e. assessing the impact of changes in the geography of an area;
f. parameter assessment.

The assessment of pollutant loads (c) is a tricky objective. If we are in the lucky position to be dealing with a conservative constituent, we still have to cope with the correct assessment of the concentration. Moreover, low flow - high concentration pathways tend to be disregarded in the water balance, causing large errors in the material budget. Despite the interesting features that can be derived from water-plus-constituent balances, balanced budgets are hardly available (Malmqvist, 1982; Hopkinson and Day, 1980; Hogland and Niemczynowicz, 1980; Uunk and Van de Ven, 1984; Ellis, 1986). Certainly for balances of this type we rely on model calculations instead of field observations.

What makes the water balance interesting in the framework of integral urban water management? Above all the amounts of flow and loads along certain pathways, as these data give insight into the urban water system, into the effects of urbanization and into the methods to mitigate these effects. It is from this integral water management point of view that I want to look at the results of the balance studies.

PATHWAYS

Although the urban hydrological system differs from city to city - especially when comparing cities with a different degree of development, or with a different climate - it is characterized by two water sources and two major pathways. The sources are the atmosphere and the public water supply. The rapid surface/sewer water pathway is quite different from the groundwater path. The system is represented in Figure 1.

To highlight a few details (I) water flows unpaved to paved areas and vice versa, (II) brick
and tile pavements are fairly permeable; to call this impermeable area would be misleading, (III) for a separated sewerage system the sewer block is split up, (IV) leakage of water supply mains can be an important groundwater source, (V) interaction with an aquifer underneath the phreatic groundwater influences the drainage extensively.

Figure 1. The urban hydrological system (in term of water quantity).

For considering water quality aspects, we ought to make a different schematization. Although the system depends on local circumstances, Figure 2 is intended to represent the pathways being studied by environmental engineers. Mostly they pay attention to factors influencing oxygen management, nutrients, micropollutants and bacterial pollution.
Figure 2. The urban hydrological system in terms of water quality.

Notice the differences with Figure 1. New elements and pathways show up. In future water balance studies this gap between the system description in terms of water quantity and in terms of water quality is to be closed, in order to achieve a more integrated view of the urban water management system.

**BALANCE PERIOD AND TIME CONSTANTS**

Balances are meant for studying longer periods. Short-term variations are smoothed out deliberately by integrating and/or averaging. This is to avoid process dynamics blurring the data. To that end the time constants that govern the processes have to be known. An impression of their magnitude is given in Figure 3.

For the surface/sewer water pathway the largest constants are of the order of one or two weeks. For the groundwater flow this is several months or years. In balance studies therefore the dynamics in the groundwater stock cannot be neglected, unless the balance is taken over a period of several years. This applies to eutrophication and sediment quality as well.
Figure 3. Some time constants involved in the urban runoff process.

THE WATER BUDGET

Measured data on water budget of urban areas are scarce. Only two extensive studies could be retrieved; one for the city of Lund, Sweden (Hogland and Niemczynowicz, 1979, 1980) and one for two small basins in Lelystad, the Netherlands (Van de Ven and Voortman, 1985; Uunk and Van de Ven, 1984; Oldenkamp, 1988). The three annual water budgets involved are illustrated in Figure 4. Details of the characteristics of the area are given in Table 1.

Both cities are located in a temperate maritime climate. Use of water from the public supply system for irrigation is negligible, unlike the situation in many other towns. Significant input by dew or by cloud droplets is absent (Grimmond and Oke, 1986; Giambelluca, 1986). Losses from the public supply system are not mentionable as a source of water in Lelystad; data for Lund are not available.

In all the balances, the amount of stormwater discharged directly into the receiving water is only a fraction of the input, even with a separate sewerage system. The major part of the urban runoff either flows off through the sewage treatment plant or percolates to the groundwater. In view of the results of Lelystad, it is not unlikely that the groundwater leakage to the sewer system in Lund has to be explained by (more) percolation.
Table 1. Characteristics of the basins in Lund and Lelystad.

<table>
<thead>
<tr>
<th>Total area</th>
<th>Lund city 19.4 km²</th>
<th>Lelystad housing ar. .02 km²</th>
<th>Lelystad parking lot .0076 km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>0-4 % ?</td>
<td>&lt;0.5 %</td>
<td>&lt;0.5 %</td>
</tr>
<tr>
<td>Paved area and roofs</td>
<td>37 %</td>
<td>41 %</td>
<td>93 %</td>
</tr>
<tr>
<td>Permeable pavement (a)</td>
<td>?</td>
<td>11 %</td>
<td>51</td>
</tr>
<tr>
<td>Combined sewerage (b)</td>
<td>3.25 km²</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Separate sewerage (b)</td>
<td>4.0 km²</td>
<td>.0082 km²</td>
<td>.0070 km²</td>
</tr>
<tr>
<td>Inhabitants</td>
<td>60.000</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>Hydrological basis</td>
<td>sand + clay</td>
<td>clay</td>
<td>clay</td>
</tr>
</tbody>
</table>

(a) brick and tile pavement
(b) paved and roof surface connected to the sewer
Figure 4. Annual water budgets of the basins in Lelystad and Lund. Amounts in mm. (Unk and Van de Ven, 1984; Oldenkamp, 1988; Hogland and Niemczynowicz, 1980)

Note the high discharge of the subsurface drainage on the parking lot in Lelystad; it is clear evidence for the permeability of brick and tile pavement. The large amount of percolating water is also caused by the very limited evapotranspiration from these surfaces. The pavement acts as an evaporation-blocker for infiltrated water and loss of percolation water by transpiration does not occur. Increased groundwater recharge can also result from runoff from impervious to pervious surfaces (Mather, 1978). By use of brick and tile pavement or porous asphalt and by stimulating runoff to pervious areas, the possible negative effects of urbanization on the groundwater recharge can be converted into an
increase. Ultimately this could result in problems with groundwater tables too high in metropolitan areas.

The public water supply is a major source of water, certainly in dry periods and drier areas. In developed cities all this water is treated after use, before being discharged. As is shown by the balance of Lund, a leaky sewer system can cause a large additional hydraulic load to the treatment plant. This could influence the treatment efficiency in a negative way. Moreover, the costs for transport and treatment of this groundwater are certainly not negligible.

The weakest point in the balances remains the estimation of the évapotranspiration. The urban microclimate is highly variable and shows an oasis-type of advection. The transpiration of different types of vegetation is unclear. The evaporation from pavements is hard to assess because the subsurface heat flux remains unknown and the availability of water on the pavement surface is an uncertain factor. Although progress has been made in the development of the theory (Grimmond, Oke and Steyn, 1986), the operational applicability is hampered by lack of calibrated parameters and the proper measurements. A lot of (field)work still has to be done. In the meantime, the évapotranspiration is estimated using rough assumptions.

As an example of a monthly water balance, the average water balance of the housing area in Lelystad is shown in Figure 5. It indicates precipitation plus seepage (P+K), discharge by the stormwater drains (Qs) and subsurface drainage (Qd) and évapotranspiration from the unpaved area (Ea), the paved area (Ec) and from some solitary trees (Eb) (Uunk and Van de Ven, 1984; Oldenkamp, 1988).

Figure 5. Monthly water balance for the housing area Lelystad; average of 1970-1980.
The difference between the sum of the inputs and the outputs is only 6%. The changes of the water stock in the unsaturated and saturated zone are clearly illustrated by the difference between the sum of the inputs and the sum of the outputs during the year. In the autumn the recharge of the unsaturated zone precedes the increase in the discharge of the subsurface drains. Notice the small amounts of storm sewer runoff compared to the evapotranspiration and the subsurface drainage runoff.

**ACCURACY OF THE COMPONENTS**

Accurate measurement is extremely difficult in an urban environment. A small, well-defined, well-controlled, experimental basin is better suited for water balance calculations than a large urban area; problems with spatial variability are avoided and the flow along the different pathways can be monitored accurately. However, the inaccuracy of the measurements can hamper a proper assessment of the balance.

The accuracy of precipitation measurement strongly depends on the type of instrument used, the level of the orifice and the location. Underestimations of 10-15% are not exceptional. E.g. raingauges on top of garage roofs make the results questionable.

In general the input by the public water supply system is well-known; the leakage is derived by comparing the water flow leaving the production or stocking site with the sum of the known uses. The output of the treatment plant is generally monitored in a decent way. The error is estimated at about 5% or less.

Difficulties occur with the more diffuse flowpaths. The discharge of stormwater drains is still measurable if the number of outlets is limited to a few. Weirs tend to have an accuracy of 5-10%, but deviations can be larger with low or high flows. With calibrated equipment accuracies of 2-5% feasible.

The largest problem is without doubt the groundwater flowpath. The techniques for estimating the groundwater flows in an open hydrological system are very limited, although this is one of the most important pathways; the balance of Lund is a good example. A closed hydrological system is therefore preferable for water balance analysis. Percolated groundwater should be forced to become surface water before leaving the system. To that end both the bases and the boundaries are closed for water flow. Open systems are an invitation to inexplicable errors in the balance.

Assessment of seepage can best be made from long data series. Groundwater quality information can be helpful in case the quality of the seepage and the phreatic groundwater are different by nature. A 10-20% error in the estimates is not unlikely however.

Large relative errors are still made in the estimation of the evapotranspiration. In the water balances for Lund and Lelystad estimates based on hydrological phenomena are used, instead of energy-balance based estimates. The use of hydrological information prevents absurdities, but errors of 20% or more cannot be excluded.
Only under research conditions can the accuracy of the measurements be upgraded to a level acceptable for water balance calculations. E.g. for the annual water balance of Lund the total error is in the order of 10% of the total in- or output. Good measurements are only possible in a well-defined experimental basin with closed groundwater boundaries and with enough equipment to estimate the evapotranspiration in a number of ways.

ROLE OF THE WATER BALANCE FOR THE DESIGNING ENGINEER

Although the hydrological experience with water balances of urban areas is limited, its role in designing and practicing an integral urban water management can be substantial. The insights gained from the balance can easily be used. Some examples:
- For combined sewerage systems the runoff to the treatment plant could be minimized by using more infiltration facilities for the stormwater runoff.
- The amount of effluent from a treatment plant is large and therefore the sewage treatment plant contributes substantially to the output of pollutants from the urban area.
- In certain situations reuse of treatment effluent, e.g. for irrigation, can drastically reduce the public water supply.
- In cases like Lund and Lelystad, the amount of stormwater effluent is limited for a housing area; peak flow reduction is possible with relatively small reservoirs.
- Vegetation removes a lot of water from an urban area by means of transpiration.
- Percolation through brick and tile pavement or porous asphalt can convert a negative effect of urbanization on the groundwater recharge into a positive one. Moreover, it reduces the number of combined sewer overflows and the overflow amounts.
- Groundwater is a major pathway for water transport in the urban environment. Use this path, but be careful with pollution. Positive experiences with local infiltration of stormwater were gained amongst others in Scandinavia (VAV, 1983).
- Pay attention to small flows of polluted water, like leakage from combined sewers or traffic-induced spraying of road runoff.
- The water balance is an easy to use method for explaining (or disputing) the feasibility of a proposed integral water management system.

CONCLUSIONS AND RECOMMENDATIONS

Water balance surveys are a tool in understanding the pathways of the urban hydrological system and in estimating the flows along them. Although the importance of the balance is often mentioned, field data are hardly available. For tropical conditions measurements were not retrievable at all.

As the importance of pathways is different for water quantity than for water quality, this should stimulate hydrologists to start studying pathways that have been considered less important until now.

Water balance studies indicate that more attention should be paid to assessing the groundwater component of the balance. Although hard to study, it is one of the major
pathways for urban runoff. Another weak point is the assessment of evapotranspiration. More detailed research in well-equipped experimental basins is recommended. The value of balancing the water budget should be exploited.

Features of the water balance provide starting-points for design and operation of integral water managements in the urban environment. They enable skilful town-planners to find creative solutions in the design of urban water management systems.

ACKNOWLEDGEMENT

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RECENT TRENDS IN PRECIPITATION AND THE WATER BALANCE OF TROPICAL CITIES: THE EXAMPLE OF LAGOS, NIGERIA

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INTRODUCTION

In recent years the occurrences of hydroclimatic variabilities and their consequences on man in different parts of the world have demonstrated the sensitivity of human welfare and a nation's economic development to hydroclimatic events. Over the past three decades, for instance, drought episodes, which have been relatively persistent in many parts of the world, have indicated the vulnerability of man to climate and hydroclimate. Among the factors of climate and hydro-climate, the study of which is concerned with the energy and water balances, are solar energy, temperature, precipitation, evaporation and evapotranspiration, humidity and wind. Of these factors precipitation is generally regarded as the most important climatic and hydroclimatic factor affecting man and his productivity in the tropics. In urban areas for instance the trends of water supply depend considerably upon the trends of precipitation. This is for example the case in the tropical cities, where the impact of recent variabilities in precipitation have led to considerable shortages in water supply and a lot of hardships for the urban population. Yet in these tropical cities in general, and cities in tropical Africa in particular, there are very few studies on the trends and the characteristics of the precipitation and the water balance components.

In the present paper therefore, a survey of the recent trends in the precipitation and the water balance of tropical cities is examined with particular references to Lagos, Nigeria. The results of the water balance computation are examined in relation to current and future needs of water in the metropolis. Aspects of the water problems arising from the fluctuations of precipitation and the water balance components and the utilization of water by the projected population are also discussed. The possible solutions to these problems, for example as related to water policy formulation and planning and management of water, are also discussed.

PRECIPITATION TRENDS

Figure 1(a) shows some characteristics of the precipitation trends for Lagos metropolitan area. The figure represents the average trends for the ten locations used for this study and for the period of 1941-1984.
It can be noted from the figure that the 1961-1970 decade was generally wetter than both the previous decades (1941-1950 and 1951-1960) and the more recent period (1971-1984). To give a better insight into the variabilities of the precipitation trends, the following index, which is based on the time series of the normalized departures of rainfall (Lamb, 1985; Ojo, 1983), has been used:

\[ I_j = \frac{1}{N} \sum_{i=1}^{N} \frac{(p_{ij} - p)}{\sigma} \]

- \( I_j \) is the normalized departure;
- \( N \) is the number of stations available during the year \( j \);
- \( \sigma \) is the standard deviation at station \( i \);
Recent trends in precipitation and the water balance

$P_{ij}$ is the precipitation value at station $i$ in year $j$ and $\bar{p}_i$ is the mean precipitation at station $i$.

The period of computation is 1941-1984, while the data base consists of individual monthly data totals for ten stations collected from the Nigerian Meteorological Department in Lagos.

Figure 1(b) shows the annual trends of the normalized departures ($I_j$) for the metropolitan area and for the period 1951-1984. In general, the decade of 1951-1960 showed characteristics of normal conditions with most of the indices between ± $\sigma$. Only one year (1957) has an index which is more then $+\sigma$, while no year had an index below $-\sigma$. The following decade (1961-1970) was relatively wetter than the 1951-1960 decade, while the period since 1971 shows that conditions have been persistently dry with negative indices. A comparison of the average trends in rainfall and rainfall variabilities with the locational trends (Figure 2) shows that there are some differences between the average trends and the trends for individual locations within Lagos. Similarly, there are differences in the trends between the individual locations. For example in Ikeja the trends shows less positive variations with more indices being less than $+\frac{1}{2}\sigma$, compared with the three other locations which have many more indices with values more than $+\frac{1}{2}\sigma$.

A more detailed analysis also shows that in 1960 both Ikeja and Agege have positive values, whereas Ebute Metta had slightly negative value. In more recent years the values of the indices show positive variability conditions in 1975 and 1979-1980 for Victoria Island, whereas the conditions show negative values for Ebute Metta in these years.

In general however, the average trends and the trends for individual locations show similar patterns with fairly normal conditions during the decade of 1951-1960, generally wetter conditions between 1961-1970 and generally persistently dry conditions between 1971-1984.

Figure 1(b). Trends in precipitation variations in Lagos (1951-1984).
Figure 2. Locational variabilities in rainfall in Lagos.
Recent trends in precipitation and the water balance

THE WATER BALANCE EQUATION

The water balance equation basically represents the net result of the inflow and outflow of water. For urban areas the water balance may be considered to be a box with unit surface area that extends from the roof level to a depth in the ground, below which no net exchanges of water occurs over the period of interest. In quantitative terms the water balance of urban area may be expressed in the form:

\[ P + S = E + \Delta f + g \]

where:
- \( P \) is the precipitation;
- \( S \) is the piped in water supply;
- \( \Delta f \) is the net runoff;
- \( E \) is the evaporation or evapotranspiration, and
- \( g \) is the net storage change.

The urban hydrological systems differ from those of the undeveloped areas, because in addition to the other components of the water balance or hydrological cycle, there is provision for piped water supply and organized water disposal, for example gutters, sewers, floodways and (in the middle and high latitude cities) snow removal. These differences between the urban areas and the undeveloped areas give rise to two urban water systems, namely the internal and the external systems (Grimmond et al. 1986). The internal system consists of water piped into and out of the buildings for drinking, sanitary, industrial and cooling purposes. The external system consists of water exchanges in the catchment for external purposes, such as irrigation, swimming pools, etc. This system may also include piped water. The two systems sometimes exist together and are sometimes isolated from each other, so that they exist as distinct balances.

Figure 3 shows the trend of the annual water balance for 1944-1985 as approximated by rainfall less potential evapotranspiration (P-PE) for Ikeja and Lagos Islands. The period before 1950 was generally characterized by water deficits for the two locations. The next two decades were mostly characterized by periods of water surplus, while most years since approximately 1971 were characterized by water deficits.

A comparison of the patterns of the trends in the annual water balance in Figure 3, however, shows some differences between the two locations. For example the relative amounts of the water surplus or water deficits between the two locations vary from year to year. Lagos Islands had higher values of water surplus in 1947, 1951, 1952, 1954, 1955, 1965 and 1968-1970, while Ikeja had higher values in 1951 and 1961-1963. Similarly Lagos Islands had higher values of water deficits in 1971, while for most of the other years the Ikeja deficits are greater. There were even greater contrasts between the two locations in some years, one location having water surpluses, while the other had water deficits. For example in 1944, 1951, 1953, 1958 and 1975-1976 Lagos Island had water surpluses, while Ikeja had water deficits.
Figure 3. Annual water balances of Lagos Islands and Ikeja (1944-1985) (P-PE) (mm).
Probably of greater importance for urban areas are the monthly, weekly or even daily variations in precipitation and the water balance. Figure 4, for example shows the seasonal variations which may occur on the precipitation and evaporation for some wet and dry years for both Lagos Island and Ikeja. The years 1957 and 1968 were examples of relatively wet years, while 1946, 1948, 1972 and 1973 were examples of relatively dry years. As can be noted for 1957, the highest rainfall occurred in July for Lagos Island, whereas it occurred in June for Ikeja. Moreover the two double maxima normally characteristic of Lagos were more pronounced for Ikeja than for Lagos Island. In 1968 the main rainfall maximum occurred in July for both Ikeja and Lagos Island instead of June, which is the normal month when this maximum is expected to occur. In both years, however, variations in evaporation show similar patterns and much less variations with seasons than rainfall variations.

Typically dry year conditions, as represented in Figure 4, show contrasting characteristics compared with 1957 and 1968, as already discussed above. For example P-PE values were strongly positive for the typically wet years of 1957 and 1968 between May and October, whereas for 1946 and 1948 P-PE values were positive only for May and June. Also 1973 had the highest rainfall in September in Ikeja, in contrast to 1946 and 1948 which had the highest rainfall in June. Also in contrast to 1946 and 1948 P-PE values were positive in June and August-September of 1973.

THE WATER BALANCE COMPONENTS AND URBAN HYDROLOGICAL PROBLEMS

The water balance and hydroclimatic characteristics, without doubt have important consequences on planning and development of the urban environment. Particularly in recent years a lot of water problems have arisen in the urban areas because of rapidly increasing water demands, which in turn arise out of a rapidly increasing population. This is for example the case in Lagos where, as noted in this paper, precipitation trends have shown a lot of variations and where, as in many other tropical cities, the last two decades have been characterized by persistently dry conditions. In many of these cities severe hydrometeorological phenomena related to precipitation and the water balance frequently occur and cause great damage leading to loss of lives and property and causing set backs in development.

A lot of the adverse effects of the hydrometeorological hazards and problems can however be considerably reduced or even completely avoided if appropriate measures are taken. In taking the necessary measures three important questions must be answered. First, what is the nature of the problem? Secondly, what is the present knowledge about this problem? Finally, what are the prospects of solving this problem?

Probably the most important aspects of the nature of the problem concerns the characteristics of the different hydrometeorological parameters and their consequences on planning and development of the urban centres. For example, as far as precipitation is concerned it is important to have good knowledge of the consequences of these characteristics such as the trends, frequencies and intensities. It is also important to have
Figure 4. Monthly distribution rainfall and evaporation for selected years in Lagos and Ikeja.
good knowledge of characteristics, for example floods, droughts and water shortages. At present, data and information on the characteristics of the various hydrometeorological phenomena are very scarce, particularly for the urban areas, and very little or no attention is paid to the problems related to the network and coverage of the data. Moreover, there are problems associated with storage, accessibility and protection of the data, the length and time of coverage for individual locations and the quality and reliability of the data available for each location.

The situation is even worse with the other components of the water balance, on which much less information then for rainfall is available. This is for example the case with evaporation and runoff parameters (Ojo, 1983). Of course the problems of data are connected with other problems, such as inadequate financing and the lack of concern for solution to the data problem of precipitation and the water balance in urban areas. The issue of what we currently know about the nature of the problem of precipitation and water in urban areas is an important base on which possible future actions can be taken. For example, although the scarcity of data is generally accepted to be a major problem in hydrometeorological research in general, and precipitation and the water balance in particular, there is the basic problem of lack of knowledge of what is available and where this can be found.

The prospects of the solution to the problems of the water balance components and the urban hydrological problems in the tropical cities therefore lies in the ability to have adequate data and use of the data for research and development. It also depends on the realization of the fact that such research must be interdisciplinary, requiring both hydrometeorological and non-hydrometeorological factors, and involving various institutions involved in water policy formulation and planning and management of water.

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CONCERNING EXPERIMENTAL MEASUREMENTS OF INFILTRATION FOR RUNOFF MODELLING OF URBAN WATERSHEDS IN WESTERN AFRICA

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ABSTRACT

The author first shows that urban runoff in cities of Western Africa is greatly influenced by contributions from natural ground. He presents the results of an experimental campaign to measure infiltration in Ouagadougou. Finally, he proposes a runoff model suitable for the African urban environment and indicates how the experimental values of the infiltration may be used to extend the use of the model to any ungauged watershed.

INTRODUCTION

Nowadays, a lot of flood damage occurs in African cities, due in a large part to bad conception of the stormwater drainage. Indeed, most of the technical methods used in Africa are European methods, and do not fit the specific conditions of African watersheds. This is especially true of the problem of sewerage sizing, which is generally solved in Africa using the well-known Rational Method. For this reason we were asked by the Comité Inter-africain d'Etudes Hydrauliques (CIEH), to design and develop a runoff model able to take into account the local conditions specific to urban watersheds in Western Africa. We have been working for two years with rainfall and runoff data collected in six cities of Western Africa: Niamey, Ouagadougou, Bamako, Lomé, Cotonou and Abidjan, in all 24 watersheds, with nearly three years of data for each.

SPECIFIC CONDITIONS OF THE URBAN RUNOFF IN WESTERN AFRICA

Precipitation

African rainstorms are very intense, as it is shown in table 1, which compares intensities, (mm h$^{-1}$) between two European cities, Paris and Montpellier (in the south of France), and three African cities, Niamey, Ouagadougou and Abidjan: these mean intensities of two year return period, are given for durations of 5, 15 and 30 minutes. It can be seen that for 30 minutes the rainfall intensity at Abidjan is more than twice that of Montpellier, and nearly four times that of Paris. Such rainfall intensities would be expected to exceed the infiltration-rate of natural ground, and thus runoff contribution from unpaved areas may not be negligible.
Table 1. Rainfall intensities ($h^{-1}$) of two-year return period rainfall

<table>
<thead>
<tr>
<th>$\Delta t$</th>
<th>5 mn</th>
<th>15 mn</th>
<th>30 mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niamey</td>
<td>160</td>
<td>110</td>
<td>79</td>
</tr>
<tr>
<td>Ouagadougou</td>
<td>184</td>
<td>128</td>
<td>92</td>
</tr>
<tr>
<td>Abidjan</td>
<td>171</td>
<td>142</td>
<td>104</td>
</tr>
<tr>
<td>Montpellier</td>
<td>126</td>
<td>69</td>
<td>48</td>
</tr>
<tr>
<td>Paris</td>
<td>82</td>
<td>41</td>
<td>27</td>
</tr>
</tbody>
</table>

The urbanization

Most of the watersheds that we have been studying are representative of traditional African urbanization. Of course, other urbanization styles can be found, but we specifically chose traditional urbanization for two reasons:

- traditional urbanization is the most common style found in African cities
- nowadays, a similar style of urbanization is growing in the suburbs, due to very high demographic rates of increase

Figure 1 represents a typical elementary unit of traditional urbanization. The unpaved areas comprise house yards (1) and a service road (2): notice that they receive all the flow coming from the impervious house roofs (3). The other impervious area is the lower road (4), which is directly connected to the drainage system (5).

This style of urbanization means that the same runoff comes from both natural grounds and impervious areas that are not connected to the sewer system. Only the impervious areas that are directly connected to the sewer system would be able to produce an earlier peak. Such areas are very few and do not exceed 10% in most of the traditionally urbanised watersheds that we have been studying.

More generally, the impervious area ratios do not exceed 30%. So, considering rainfall intensities, it is clear that the contribution of natural grounds must be taken into account.
Concerning experimental measurements of infiltration for runoff modelling

for a proper evaluation of both runoff volumes and peaks. This is the reason why we were interested in the infiltration processes on natural grounds and why we performed measurement campaigns in Ouagadougou, Niamey, Abidjan and Lomé.

AN EXAMPLE OF THE INFILTRATION CAMPAIGN: OUAGADOUGOU

Description of the measurement device

In order to estimate the infiltration processes, we measured plot runoff from simulated rainfall. The rain simulator that we used has been improved by ORSTOM over ten years, and reproduces with good accuracy the rainfall characteristics:
- raindrop kinetic energy: first conceived by pedologists to study ground erosion, the sprinkler lies on a framework five meters high,
- raindrop size: the sprinkler produces a spray with various sizes of raindrops available by modulating the flow from the waterpump,
- rainfall intensity: varies with the scanning of the sprinkler.

Rainfall is concentrated on a one metre sided square plot, from the downstream side of which flow is collected and run to a tank, where water level is recorded by a limnigraph.

The experimental procedure

Besides characterising the relationship between soil morphology and runoff generation, the experiments were aimed at measuring the effects of parameters such as rain intensity or soil moisture on both runoff and infiltration processes.

Quite a good representation of the soils in our study watersheds was obtained using 6 selected plots. Soil moisture influence was found by carrying out repeated experiments on a two day period: extreme soil moisture conditions were generally given by the first and the last rainfall. Initial moisture condition was characterised by a Kshler index, $I_K$, computed using the recurrence relation:

$$I_K(n) = (P(n-1)+I_K(n-1)) \exp(-0.5,ta)$$

where $ta$ (days) is the lag between the $(n-1)$th rainfall $P(n-1)$ and the $n$th one $P(n)$. We considered index values over 70 to mean a saturated soil.

The experimental results

The first important result is that, for a given $I_K$, the infiltration or runoff values obtained on all the plots were very similar. Furthermore, considering the initial soil moisture only as dry ($I_K \sim 0$) or saturated ($I_K \sim 70$):
- runoff coefficients range from 75 to 85% on dry soils, or 91 to 98% on saturated soils, (considering a forty millimetre rainfall depth).
- initial rainfall losses ranged from 1.7 to 4.0 mm on dry soils, 0.3 to 1.7 on saturated soils.
- a permanent regime of infiltration is quickly reached in 20 to 40 min on dry soils, or from 10 to 25 min on saturated soils. Infiltration rate then ranges from 4 to 6 mm/h on dry soils, or 1 to 2 mm/h on saturated soils.

- rainfall intensity has no significative influence on infiltration rate.

So, two synthetic curves have been drawn, corresponding to lower (IK ~ 0) and higher (IK ~ 70) soil moisture conditions. These curves are displayed in Figure 2, and were built from the median values obtained on all the plots, considering a 40 mm/h rainfall intensity to represent imbibition rainfall. These curves supply the values of the infiltration losses for any rainfall of a given duration: for example, in the case of a rainfall of 60 min duration, the infiltration losses are found, by integrating with respect to time, to be equal to 8.8 mm on dry soils and 4.4 mm on saturated soils.

Now, let's see how these results are used in a runoff modelling problem.

MODELLING RUNOFF VOLUME

Definition of a production function

According to conditions specific to urban watersheds in Western Africa, we looked for a model able to account for runoff contributions from natural ground. Figure 3 shows the runoff scheme that we selected. Runoff losses due to both infiltration and storage are considered in a conceptual way:

INFT is a Horton type function of the part of the rainfall whose intensity is more than 5 mm/h (the depth of this rainfall part is Pc):

\[ \text{INFT}(T_p) = aT_p/60 + b(1 - \exp(-cT_p)) \]

STO is a function of the active runoff \( R = Pc - W.(P - Pc) - \text{INFT}(T_p) \)

\[ \text{STO}(R) = \begin{cases} ST.(1 - \exp(kR)) \exp(-kR) & \text{if } R > 0 \\ 0 & \text{else} \end{cases} \]
Concerning experimental measurements of infiltration for runoff modelling

with 
\[ R_i = - \frac{1}{k} \log \left( \frac{STOC_i}{ST} \right) \]
and \( STOC_i \) = storage depth at the beginning of the rainfall, burst computed step by step by

\[ STOC_i = STOC_{i-1} \exp(-ds.t_a) \]

where \( STOC_{i-1} \) is the storage depth at the end of the rainfall burst and \( t_a \) is the lag in hours, between the beginning of the rainfall burst and the end of the rainfall burst.

Such a scheme leads to the following equations:

\[ LR = C.P + (1-C)R - (1-C-C_2)(1-\exp(-kR))(ST-STOC_i) \text{ if } R > 0 \]
\[ LR = C.P + C_2 R \text{ if } R < 0 \]

where \( C \) is the ratio of directly connected impervious area.

Overall the production function is characterized by eight parameters: four of them are conceptually connected to infiltration a,b,c, W; three of them are conceptually connected to surface storage ST, k, ds; one of them is conceptually connected to urbanization \( C_3 \).

The calibration of the production function

Determination of the parameter values has been performed by Nelder and Mead's optimization procedure (Rao, 1978).

The basic sample comprised rainfall and runoff data for 26 events observed in Ouagadougou in 1979 on a 48 ha area watershed with a 10% impervious part. 13 events were used for calibration and the other 13 were used for validation.

Table 2 indicates the parameters values derived.

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>W</th>
<th>ST</th>
<th>k</th>
<th>ds</th>
<th>C_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>4.7</td>
<td>0.091</td>
<td>0.7</td>
<td>16.8</td>
<td>0.076</td>
<td>0.028</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Good agreement was obtained (Figure 4) between observed and computed values of the runoff volumes, as the mean deviation is only 0.4 mm in the case of the calibration sample, and 1.4 mm in the case of the validation sample.
Transposition of the production function

We've just seen that the production function reproduced runoff volume with good accuracy. Now, to extend the use of the model to an ungauged watershed, the question is to know if the parameters are really significant as we thought they were. For infiltration in particular can the parameters a, b and c be compared to experimental values that we found from the sprinkler experiments. For our example, the answer is yes, as is shown in Figure 5, on which are displayed the infiltration depth against time: (1) and (2) were derived from the sprinkler experiment while (3) was computed with a=4.4, b=4.7 and c=0.091.

Notice that the computed curve is very close to the experimental curve corresponding to IK=0: it might be because most of the IK of our basic sample are themselves close to 0.

CONCLUSION

For most urban watersheds in Africa, runoff coefficients cannot be considered as the ratio of impervious areas. This is highlighted by the example watersheds in Niamey and Cotonou that, for the same imperviousness of 30%, have runoff coefficients that are equal to 60% in Niamey and 20% in Cotonou (considering a one year return period rainfall). Good knowledge of the infiltration processes should be very useful for prediction, as indicated by the close relationship we obtained between experimental and modelled values of infiltration in Ouagadougou.

Our work is now to improve these results using all the watersheds we are studying.

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A DETAILED WATER BUDGET FOR THE CITY OF LUND AS A BASIS FOR THE SIMULATION OF DIFFERENT FUTURE SCENARIOS

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ABSTRACT

The costs of water management in many European cities are growing rapidly. New policies with respect to waste water and storm water management must be grounded in a thorough understanding of the inter-relations between different parts of the urban water budget. An extensive project aimed at explaining the details of the water budget has been performed in the city of Lund, Sweden. The detailed knowledge about the natural and urban water cycle in Lund that was gained as a result of the project has now been used in order to simulate the outcomes of different storm water management policies which could be applied in this city. Two examples of the impacts of such different policies are supplied. In the first example, the hydrological, environmental and economical effects of a complete separation of storm water and waste water systems are described. In the second example it is assumed that permeable pavements are constructed in order to attenuate storm water runoff. Both examples are calculated by means of a detailed modelling of the entire sewage system in Lund using the Storm Water Management Model.

INTRODUCTION

The costs of waste water and storm water management are growing fast in many European cities. The reason for this is that the oldest parts of the sewage systems, constructed in the beginning of the nineteenth century, are getting old and urgently need renovation. New suburban areas are connected to already overloaded sewage systems. Both reasons result in a significant reduction of water treatment efficiency, which contributes to the further environmental degradation of surface waters. The total yearly cost of urban water management in Sweden was calculated to be about two billion Swedish Crowns for the year 1974 (Falk, 1980). Up to the present day, the costs are probably doubled.

People in the urban communities are not inclined to accept further tax increases needed for an improvement of water management, nor will they accept further degradation of the environment. Hence, more efficient, powerful and cheap methods of water management in cities must be developed. The separation of waste water and storm water systems, initially held to be an ideal solution, soon proved economically unacceptable and technically insufficient. The cost of a separation of waste water and storm water systems in Sweden was estimated to be 100 billion Swedish Crowns in the year 1982 (Darte et al, 1982). Many examples showed that the separation was wrong from an environmental point of view (Malmquist, 1977, Carlson and Falk, 1979, Hogland an Niemczynowicz, 1980). The local disposal of storm water before it enters sewage systems seems to many people the
only reasonable way to avoid overloading the system. Still, the benefits and drawbacks of different approaches are being discussed. The present paper aims at contributing to this discussion.

A DETAILED WATER BUDGET FOR THE CITY OF LUND

An extensive project has been conducted in order to establish, on the basis of direct measurements, reliable water quantity and quality budgets for the city of Lund. The project had three distinct goals:
1 to obtain the necessary data for a decision on how to improve the sewer system in Lund;
2 to evaluate the results of planned changes, and
3 to explain the impact of various pollution sources on the local receiving water.

To fulfil the aims of the project, a large gauging program was carried out. The water budgets were calculated on a daily basis for water quantity and on a weekly basis for water quality. The water quality program included analyses of SS, BOD-7, Cl, P, Cu, Zn, and Pb. Detailed results of the study were presented elsewhere (Hogland and Niemczynowicz, 1979, Niemczynowicz and Falk, 1981). One interesting conclusion that could be drawn from the studies was that the proportions of different components in quantitative and qualitative water budgets change drastically when the temporal basis of the these budgets is altered. For example, a pollution load described on a yearly basis tells us very little about the real risks to the receiving waters in terms of toxic effects. The situation when storm water and combined sewer overflows (CSO) create such a risk may last for a much shorter period of time than a year. A real risk to the receiving water occurs during summer in connection with heavy rain storms and low river flow. During heavy rain storms, combined sewer overflows may exceed 25% of the average storm water flow for as long a time as a week. About 5% of overflows consist of waste water. During a year of observation, about 20,000 m$^3$ untreated waste water was released to the river through CSO. About 30% of the observed BOD-7 and 80% of phosphorus in the storm water originated from CSO. During some weeks, pollutant loads from storm water were 3 to 5 times higher than from treated waste water.

HYPOTHETIC QUANTITATIVE AND QUALITATIVE BUDGETS, ASSUMING THAT WASTE AND STORM WATER SYSTEMS HAVE BEEN SEPARATED

Let us now assume that an area with combined sewage system has been rebuilt, and that both systems are completely separated. Knowing present conditions with regard to water flows and pollution concentrations, we can recalculate both quantitative and qualitative budgets. Figure 1 presents, graphically, the yearly water budget for the present situation and for the hypothetical situation of separated sewage systems. Some important features may be distinguished: the amount of waste water has decreased due to lack of inflow from combined conduits. The amount of storm water has grown as a result of inflow from previously combined areas and increased leakage to newly constructed storm water conduits.
The total amount of water released to the receiving conduits has increased by about 6%. The right-hand part of Figure 1 presents similar water budgets for a single day with heavy rainfall. The effect of an increased amount of storm water and a decreased amount of waste water is even more obvious during a day with heavy rainfall. Leakage to the system does not occur during this day, because pipes are nearly filled with water and no leakage can take place.

Figure 1. Quantitative water budgets for the city of Lund on an yearly basis and, as an example for a day with heavy rainfall. The upper part of the figure shows the situation with a combined sewage system; the lower part shows the hypothetical situation with a separated sewage system.
Another effect of the separation of the systems would be more pronounced fluctuations in the runoff from the storm water system while the runoff from the treatment plant would fluctuate less. These effects are favourable for the water treatment process, but negative where the release of storm water to the receiving water is concerned.

Table 1 presents yearly pollution concentrations and the pollution loads for the present situation and after a separation of the systems. From Table 1 it can be noticed that the total load of SS (suspended solids) would increase by about 20% on an annual basis. This is due to an increased amount of storm water. The total load of BOD-7 and Pb would remain on the same level, while phosphorus would decrease by about 33%, mostly due to the lack of combined sewer overflows.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Present</th>
<th>Hypothetical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combined system</td>
<td>Separated System</td>
</tr>
<tr>
<td></td>
<td>waste water</td>
<td>storm water</td>
</tr>
<tr>
<td>SS concentration</td>
<td>mg/l</td>
<td>20</td>
</tr>
<tr>
<td>Pollution load</td>
<td>mg/s</td>
<td>10.2</td>
</tr>
<tr>
<td>BOD7 concentration</td>
<td>mg/l</td>
<td>5.7</td>
</tr>
<tr>
<td>Pollution load</td>
<td>mg/s</td>
<td>2.9</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>mg/l</td>
<td>0.28</td>
</tr>
<tr>
<td>Pollution load</td>
<td>mg/s</td>
<td>14.3</td>
</tr>
<tr>
<td>PB concentration</td>
<td>mg/l</td>
<td>0.11</td>
</tr>
<tr>
<td>Pollution load</td>
<td>mg/s</td>
<td>56.3</td>
</tr>
</tbody>
</table>

During periods shorter than a year, the picture is significantly changed: the loads of pollutants which originate in storm water such as SS and heavy metals Pb, Zn, Cu, would increase in comparison with the present situation. For example, during one single week, the load of Pb would increase from 24 to 41 mg/s, i.e. about 70%. Risks of toxic effects to the receiving waters during periods with high-intensive rain storms and low river flow would increase. However, pollution loads originating in CSO, like BOD-7 and phosphorus, would decrease. An additional drawback of the separation of the systems is the resulting increase in the amount of storm water and the associated drainage of the area around the city, resulting in further groundwater depletion.
The general conclusion which may be drawn is that environmental benefits of sewage system separation are doubtful and certainly do not warrant the costs and efforts involved. In the next section, we will look at the other alternative, namely storm water attenuation by means of local disposal.

EFFECTS OF THE USE OF PERMEABLE PAVEMENTS ON THE QUANTITATIVE AND QUALITATIVE WATER BUDGETS OF THE CITY OF LUND

During the last decade, storm water attenuation has become a desirable goal for storm water management in Sweden.

One of the hydrologically most attractive methods of storm water runoff attenuation is infiltration to the ground through various infiltration and percolation basins. These arrangements, frequently used in Sweden, reduce both the peak flow and the volume of the runoff, and probably also reduce pollution loads to the receiving waters. The utmost extension of the infiltration idea is to construct permeable pavements instead of the traditionally impervious surfaces of streets, parking-lots etc. This idea was put into practice in Sweden and a permeable pavement construction, the so-called Unit Superstructure has been developed. During the last six years, the number of residential areas where such pavements have been constructed has grown to about 30. So far, the experiences gained as a result of exploitation of these pavements have been good.

The effects on the runoff pattern of using Unit Superstructure pavements, as compared to the use of traditional pavements, were tested by means of runoff simulations from an 0.2 sq km catchment in Gothenburg (Niemczynowicz and Hogland, 1985). Simulation with the Storm Water Management Model (SWMM) has shown a peak-flow reduction of about 80% when the Unit Superstructure was employed.

Let us assume that all pavements in the city of Lund were constructed as permeable surfaces, and discuss the hydrological and environmental effects of such a scenario.

Simulations of the hypothetical situation with permeable pavements in the city of Lund were made using the SWMM which was calibrated on measured rainfall and runoff during another project (for a detailed description of the modelling procedure, see Niemczynowicz, 1984). With regard to the simulation of runoff from the city, it was assumed that the ground under the pavement was totally impermeable. Permeable surfaces were simulated to act as detention basins; the runoff was delayed, but the volume was not reduced. In practice of course, there would be some infiltration to the ground and the runoff volume would also be reduced. Results of the simulations for one observed rainfall event are shown in Figure 2. It can be noticed that the runoff from both combined sewers and storm water conduits is strongly attenuated. The peak-flow reduction from the combined system is about 75% and from the storm water system about 90%. Simulations made for other rainfall events show the same order of magnitude of the peak-flow reduction effect. These reductions are sufficient to stop combined sewer overflows in Lund completely.
The pollution reducing capacity of permeable pavements was studied in a full-scale field test conducted in Lund (Hogland and Niemczynowicz, 1986, Hogland et al. 1987). From analyses performed on several pollution constituents in runoff from the test areas, and from analyses of pollution in the body of the pavement, it was concluded that about 50% of the total solids, phosphorus and heavy metals contained in storm water remain in the body of the pavement. In our hypothetical example involving the use of permeable pavements in Lund, the reduction in the pollution load may be expected to be of the same proportions. The reduction in total pollution-load would also be combined with a very significant reduction of pollution concentration in the effluents, due to reduced peak flow and increased time of runoff. Risks of toxic effects on the ecological system during heavy rain storms and during low flow in the receiving water would be eliminated.

Figure 2. Examples of runoff hydrographs from the city of Lund for the present situation and assuming that permeable pavements were constructed instead of traditional pavements.
A detailed water budget for the city of Lund

The economic consequences of using permeable pavements on a larger scale were tested by calculating the total costs of the pavements in two versions: traditional; and Unit Superstructure pavements. The use of Unit Superstructure results in total costs which are approximately 25% lower in comparison with traditional pavements. Most of the cost-saving is due to a reduction in the number of necessary inlets and to a reduction of the diameters of storm water pipes (Niemczynowicz et al. 1985).

CONCLUSIONS

The separation of waste and storm water systems in cities in Sweden is economically unacceptable and technically insufficient to prevent a further degradation of water quality in receiving waters. The only real benefit of such a separation is the elimination of combined sewer overflows. However, the total pollution loads from the city would hardly be reduced. The risks of toxic effects on ecologic systems in rivers during heavy rainfalls could be increased.

The porous pavement constructions of the Unit Superstructure type have a great potential when it comes to reducing and attenuating storm water runoff. It is highly tempting to use this construction on a larger scale. Still, many questions concerning, first of all, the long-term environment risks of groundwater pollution must be answered before it can be recommended. Another issue concerns longterm clogging problems. It is our hope that these and other questions will be answered in full-scale tests, field experiments, and laboratory tests now going on in Lund.

REFERENCES

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GROUNDWATER RECHARGE IN URBAN AREAS

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ABSTRACT

The two interlinked networks of hydrological pathways in urban areas are described with particular reference to the links with groundwater. As well as reducing direct recharge, urbanization creates new pathways and sources of water for recharge, including leaking water mains, sewers, septic tanks and soakaways. The net effect is often to increase recharge to pre-urbanization rates, or higher in dry climates and cities with high densities and large imported water supplies.

INTRODUCTION

Much of the surface of urban areas is rendered impermeable by buildings, roads and surface coverings. Because of this covering, the classical view of the effect of urbanization on groundwater is that recharge is reduced. For example,

"... groundwater outflow ... decreases with urbanization, with direct runoff ... increasing." (Douglas, 1983)

and similarly from Lindh (1983)

"Infiltration to the groundwater is markedly reduced ... with less water reaching the aquifer, wells may have to be deepened"

In fact urbanization alters all parts of the hydrological cycle so much that no simple analysis of the effects on groundwater is possible.

However, many of the alterations will increase recharge where there is permeable ground below the city. This has been recognised in principle by some writers, for example Gray & Foster (1972) and Monition (1977), but the increases have rarely been quantified. It has not been realised that urban recharge is often as high, of higher, than pre-urbanization rates (Lerner, 1986).

URBAN HYDROLOGICAL PATHWAYS

Water does not often follow a cycle in the urban environment because it enters and leaves across the urban boundary. Rather it follows a network of pathways. There are two such networks of pathways in urban areas which are interlinked at many points. These are the (heavily modified) natural pathways and the water supply-sewage pathways. The principal pathways of the natural network are precipitation, evapotranspiration, runoff, infiltration, recharge and groundwater flow.
The principal paths of the water supply network are shown in Figure 1, which particularly emphasises the interconnections with groundwater. Boreholes bring groundwater into the network; a variety of paths including leakage from pipes, over-irrigation and septic tanks carry water down to the groundwater system.

The water supply network carries large flows. Table 1 compares, for a number of major cities, precipitation - usually the main input to the natural network - with imports of water and local groundwater abstraction, which are the inputs to the water supply network. In highly urbanised areas, e.g. Hong Kong, and in arid or semi-arid climates, e.g. Doha and Lima, flows in the water supply network exceed those in the natural system. Even in temperate, moderate density cities (Vancouver, Birmingham) flows in the two systems are comparable in size.

**RECHARGE IN URBAN AREAS**

Recharge from the natural network

Large urban areas often have a micro-climate which may alter rainfall and evapotranspiration rates. These are probably second order effects on recharge when compared to the changes caused by surface coverings which generally reduce infiltration, and increase and accelerate runoff.
This runoff is often carried in storm sewers, drains, or other artificial waterways. Thus it is probable that direct recharge is reduced in urban areas. It should be noted in passing that permeable pavements are sometimes used to reduce runoff, and these will increase recharge by allowing infiltration while reducing vegetation cover and so reducing evapotranspiration (van Dam & van der Ven, 1984).

There is potential for recharge from storm sewers and drains, even when these are designed to carry water out of the city. Aside from the well known tendency for sewers to leak, Lerner (1986) presents evidence that such recharge occurs in Hong Kong. In a water resources study of Liverpool, the University of Birmingham (1984) concluded that significant amounts of storm water leaked from sewers into the groundwater systems.

Storm water is often deliberately recharged. In the U.K. for example, soakaways are commonly used to dispose of runoff from domestic roofs, and for road runoff from some motorways and in some cities. Recharge basins for storm water are used, for example, on Long Island and are thought to bring recharge up to pre-urbanization rates (Seaburn & Aronson, 1974). In arid climates there is often no provision for storm runoff, and the (rare) increased runoff from impermeable surfaces will infiltrate into the permeable surroundings.

Table 1. Relative sizes of inputs to the urban hydrological networks

<table>
<thead>
<tr>
<th>City</th>
<th>Area</th>
<th>Date</th>
<th>Precipitation</th>
<th>Imports</th>
<th>Local Units</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Sweden</td>
<td>4024</td>
<td>c.1970</td>
<td>701</td>
<td>235</td>
<td>nd</td>
<td>mm</td>
</tr>
<tr>
<td>Mexico City</td>
<td>nd³</td>
<td>1980</td>
<td>86</td>
<td>14</td>
<td>nd³</td>
<td>%</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>1046</td>
<td>1971</td>
<td>1912</td>
<td>1310</td>
<td>64</td>
<td>mm</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>0.61-0.35</td>
<td>1980</td>
<td>2000</td>
<td>650-7500²</td>
<td>0</td>
<td>mm</td>
</tr>
<tr>
<td>Sydney</td>
<td>1035</td>
<td>1962-71</td>
<td>1150</td>
<td>333</td>
<td>16</td>
<td>mm</td>
</tr>
<tr>
<td>Vancouver</td>
<td>0.21</td>
<td>1982</td>
<td>1215</td>
<td>576</td>
<td>0</td>
<td>mm</td>
</tr>
<tr>
<td>Lima</td>
<td>400</td>
<td>1978</td>
<td>10</td>
<td>1650⁹</td>
<td>950⁹</td>
<td>mm</td>
</tr>
<tr>
<td>Doha, Qatar</td>
<td>294</td>
<td>1981/82</td>
<td>167</td>
<td>175</td>
<td>27</td>
<td>mm</td>
</tr>
<tr>
<td>Birmingham</td>
<td>500</td>
<td>1985</td>
<td>730</td>
<td>675</td>
<td>30¹²</td>
<td>mm</td>
</tr>
</tbody>
</table>

1 Many of the areas are for a supply zone and include rural and semi-rural land
2 Grimmond and Oke, 1986
3 nd - no data given in source document
4 Whole city
5 Lerner, 1986; Geotechnical Control Office, 1982
6
Recharge from the water supply network

All water supply networks leak. Few authorities claim to be able to reduce leakage below 10% of supply, and rates of 50% have been reported. This sources alone can generate a potential recharge of up to 3000 mm/yr, although rates of 100-300 mm/yr are more common (Lerner, 1986). Sewers leak, as shown by the many examples of groundwater pollution below cities sewage. Many urban areas do not have sewers, relying on septic tanks and soakaways to dispose of effluents - this water must recharge groundwater. For example in Bermuda, with an average rainfall of 1460 mm/yr, water supply is from roof catchments and sewage is disposed of to septic tanks. These, and soakaways for storm drainage, increase recharge from 365 mm/yr in rural areas to 575 mm/yr in the urban area (Thompson & Foster, 1986).

The third main source of recharge from the water supply network is over-irrigation of parks and gardens. These are irrigated for aesthetic rather than commercial reasons. Application is often by unskilled labour. The amount of water applied rarely depends on plant water needs, but on the affluence of consumers, pricing policies for water supplies and, in the case of municipal parks, on bureaucratic procedures. For these reasons over-irrigation is normal with many multiples of the potential evapotranspiration being applied. Excess water percolates deep to recharge groundwater. An example is Doha in Qatar where over-irrigation has raised groundwater levels to the surface in many low lying areas.

Net effect of urbanization

Figure 2 summarises the changes in recharge that urbanization can cause. With so many changes, and with different conditions in every city, it is difficult to generalise about the net effect. However it is clear that there will be always be man-made sources of recharge. In drier climates, or with large imported supplies, or with poor maintenance of piped systems, recharge in urban areas is likely to exceed that in rural areas. Table 2 gives some examples of water balances for urbanised aquifers.
Table 2. Example water balances of urbanised aquifers (10^3 m^3/d)

<table>
<thead>
<tr>
<th>City</th>
<th>Lima</th>
<th>Doha</th>
<th>Bermuda</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (km^2)</td>
<td>400</td>
<td>294</td>
<td>6.3</td>
</tr>
<tr>
<td>Recharge from:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>precipitation</td>
<td>0</td>
<td>11.5</td>
<td>4.83</td>
</tr>
<tr>
<td>rivers</td>
<td>280</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Agricultural irrigation</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>park irrigation</td>
<td>390</td>
<td>37.6</td>
<td>0</td>
</tr>
<tr>
<td>leaking mains</td>
<td>340</td>
<td>25.3</td>
<td>0</td>
</tr>
<tr>
<td>sewers and septic tanks</td>
<td>0?</td>
<td>17.6</td>
<td>3.13</td>
</tr>
<tr>
<td>soakaways</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Urban effects on groundwater recharge.
ESTIMATING RECHARGE IN URBAN AREAS

The multiplicity of recharge sources and complexity of landuse and surface cover, make it extremely difficult to estimate recharge in urban areas. For example, consider the possible sources of recharge from the water supply network:

\[
\text{recharge} = \text{leakage from water mains} \\
\quad + \text{external losses from consumers' properties} \\
\quad + \text{leakage from sewers} \\
\quad + \text{flow to septic tanks} \\
\quad + \text{deep percolation from domestic irrigation} \\
\quad + \text{deep percolation from municipal irrigation}
\]

(1)

Considering all these components individually, with their associated errors, can lead to a large accumulated error in the recharge estimate. To reduce errors, it is preferable to consider the overall balance and estimate recharge as follows:

\[
\text{net recharge} = \text{imports of water} \\
\quad + \text{local abstractions of groundwater} \\
\quad - \text{consumptive use} \\
\quad - \text{effluent leaving area} \\
\quad + \text{increase in water table}
\]

(2)

Methods of using both equations are discussed by Lerner (1988). Estimating recharge from the natural network presents even greater problems, the most difficult of which is losses from storm sewers. All studies of leaking sewers have been those which collect water, not lose it, because this is an important factor in design. Except in research studies, water balance over individual storms is unlikely to be accurate enough because of the uncertainties in both measurement of precipitation and runoff, and in estimates of detention and evaporation. Field tests in combined sewers at times of low flow, or injecting and tracking known flows or tracers, or analysis of groundwater responses may provide more accurate estimates for small parts of a city, but are impractical for the whole system. The best approach will be to set upper and lower bounds on recharge by water balance methods. These estimates can then be refined by calibration of a groundwater flow model against groundwater responses and outflows.

REFERENCES

Groundwater recharge in urban areas
