EXECUTIVE SUMMARY

EFFECTS OF URBANIZATION ON CATCHMENT WATER BALANCE

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WATER RESEARCH COMMISSION

EFFECTS OF UNBANIZATION ON CATCHMENT WATER BALANCE

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The steering committee comprised :

Mr H.C. Chapman	Water Research Commission
Mr. H. Maaren	Water Research Commission
Mr. S. van Biljon	Department of Water Affairs
Mr. P.C.L. Steyn	Weather Bureau, Dept. Environmental Affairs
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Prof. D. Stephenson	University of the Witwatersrand
Prof. B. Verhagen	University of the Witwatersrand
Mr. P. W. Weideman	Water Research Commission (Committee Secretary)

Assistance with the construction of weirs was given by the Sandton Town Council. The Islamic Institute permitted the monitoring of the Waterval catchment.

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BACKGROUND AND MOTIVATION

The Water Systems Research Group at the University of the Witwatersrand previously conducted research into urban hydrology, particularly the estimation of floods from Urban Catchments. It was therefore recognised that urban development affects runoff and thus water balance in catchments. It was expected that flood runoff would be more intense therefore resulting in less residual moisture to maintain ecological balance within the catchment. It was however only from a theoretical side that the factors were identified and it was considered necessary to monitor catchments to prove these effects and quantify them.

The importance of being able to estimate the effects of urbanization and catchment water balance is reflected in the potential :

i) Increased stormwater runoff and therefore larger structures and higher costs in coping with this runoff.

ii) Recession of the water table and reduction in water content in urban catchments as a result of increased storm runoff. This in turn may result in greater absorption particularly in times of less intense precipitation and could result in a greater difference between storm runoff and drought flow.

iii) The effect on receiving waters in having to cope with higher rates of inflow in times of flood and also lower inflow in times of drought. These in turn affect storage requirements and the yields of catchments.

iv) The factors affecting the water balance are complicated by the import of potable water for domestic purposes and the discharge of sewage.

v) The construction of pavements and buildings will speed up the runoff process, by providing smoother surfaces, more conduits and reducing permeability and changing vegetation cover of the catchment. The effects of these are generally to intensify storm runoff but the study of each component is not easy and the use of computer models was considered necessary to separate the different effects.

OBJECTIVES

A broad objective of the project was to evaluate the effects of urbanization on catchment water resources. The changes in runoff and in catchment water balance were to be measured and modelled enabling these effects to be generalized for transposition to other catchments.

The primary effects considered were total water runoff and loss from the catchment, with assessment of both flood runoff and drought runoff. The mass balance within the catchment must be made to assess groundwater and soil moisture variations related to catchment cover and how these affect runoff.

Secondary factors to be considered were flood volumes and peaks, water levels in streams, and the variations in ground water levels due to abstractions. The ability to transport water pollutants and effects on groundwater quality were also to be assessed.

In order to make these assessments the effect of impermeable covers such as roads and buildings was to be investigated. The construction of drains resulting in different hydraulic resistances, different gradients and more rapid runoff was to be investigated. At the same time water reticulation systems and sewerage runoff and the effect on the catchment water balance has to be considered.

METHODOLOGY

The general method of assessing the effects of urbanization was to compare two catchments, one which was natural veld and the other which was urbanized (a residential suburb). The catchments were adjacent with similar geology and of the same order in size, shape and slope. Observations were made over a period of five years and it is expected that any variation due to isolated storms would be averaged out in this period so that only the effects of urbanization would result in differences in runoff and water balance. Rainfall was measured at a number of raingauges in the catchment and runoff was monitored at the downstream end of each catchment. Although the effects of different factors in the urban catchment was not measured directly the different factors were distinguished by means of modelling using a computer programme.

If the catchments were identical before urbanization of one then the results of the research exhibit the effects of urbanization. Unfortunately the experiment was not started until after one of the catchments was essentially developed i.e. the urban catchment. It is anticipated that a future contract will investigate the gradual urbanization of a third adjacent catchment so that the research will eventually be three-cornered and cover the possibility that the two catchments were dissimilar in factors other than urbanization.

CATCHMENT DESCRIPTIONS

The catchments were situated at the northern extremity of Sandton in South Africa. The urban catchment is in Sunninghill, a suburb of Sandton and the rural catchment is on the Waterval farm to the north. The catchments were each 75 hectares in size and are situated on bushveld granitic base. There are dolomite dykes crossing the catchments and the soil is generally sandy decomposed granite.

The vegetation on the undeveloped rural catchment is essentially grass with some clumps of gum trees. The undeveloped catchment has no defined water courses except at the bottom end where the water is collected by means of a furrow and passes over a measuring weir.

The urbanized catchment is middle class housing with a small shopping complex and part of the ESCOM Megawatt Park Complex. The housing is primarily single storey, separate bungalows in gardens varying in size from 1 000 to 2 000 square metres. There are some townhouses and townhouse development progressed during the period of monitoring. The urbanized catchment has running down the middle, a park strip with a man-made channel lined with gabions in places. The water is collected in a culvert at the downstream end and a crump weir was constructed under the project to monitor the outflow.

Water supply to the area is monitored by a municipal meter which is read at three-monthly intervals. Sewage outflow is monitored in a manhole at the downstream end of the catchment.

A dolerite dyke across the lower extremity of the urbanized catchment forces groundwater to the surface and artesian conditions are observed.

The mean annual rainfall of the catchment is some 700mm and this falls primarily in the summer months October to March.

MONITORING PROCEDURES

Sixteen boreholes were drilled over the catchments in order to monitor groundwater fluctuations. Eight autographic raingauges with data loggers attached monitored the rainfall over the catchment. Data loggers monitored the flow rate over the weirs at the end of each catchment and another data logger monitored the sewage outflow. Raingauges were the tipping bucket type and stream gauges were the depth sensor type and a rating curve converted flow depths to flow rates was used with a computer programme to interpret the results. Numerous problems were found with the electronic data loggers with the result that a lot of earlier data was missed. It was therefore necessary to use later data to obtain a rainfall runoff relationship in order to extrapolate back the runoff flows.

The borehole water levels were monitored by manual methods initially and sometimes with electronic sensors at a later stage.

The catchments were investigated geologically using borehole logs and in the case of the Waterval catchment resistivity and magnetic surveys for identifying dykes and discontinuities.

A weather station was installed in the Waterval undeveloped catchments. Here wind speed and direction were monitored as well as temperature, solar radiation, evaporation, barometric pressure and relative humidity from August 1987.

TECHNOLOGY

In order to distinguish between the different methods of affecting runoff a digital computer model was prepared. This model was based on the hydrodynamic laws and allows for multiple units in the drainage process, that is, it is able to connect impervious and pervious catchments, groundwater layers and conduits. Rainfall input can be obtained from the records obtained and simulated storms can also be fed in. The computer model predicts the flow rate throughout a storm and afterwards, at any selected location. The model is able to account for management methods in attenuating and concentrating storms. That is dual drainage whereby water would overflow underground sewers and run down the roads is accounted for, as well as attenuation due to flood drains such such as down the central channel in Sunninghill. Surface roughness and conduit configuration is supplied in the data sheets. The model is now used by researchers and consultants throughout the country for studying stormwater attenuation and runoff from urban catchments and it can also be used for rural catchments.

A continuous modelling exercise was also undertaken for estimating long term effects of rainfall. That is a model which is able to account for soil moisture and changes in groundwater and perched water levels was prepared.

A data management computer package was also prepared. This was necessary to read data from the chips from the data loggers. The program converted the signals to rainfall records and filed the data for subsequent analysis. The program is also able to analyze chart recorder data. This rainfall data is digitized and stored in similar tables to that from the electronic data loggers.

A program for simulating river flow was also prepared. This programme accounts accurately for water surface profile variations in unsteady flow conditions. It routes flow down channels and accounts for momentum transfer and flow transfer to flood plains and predicts the effect of the additional friction in retarding floods.

The raingauges situated throughout the catchments as well as raingauges in the catchment in Montgomery Park provided data for studying storm patterns. Research into the movement of storm patterns was undertaken and a computer program for contouring storms as they travelled across the catchments and changed, was prepared.

Initial steps were taken to study runoff water quality by means of computer models. Water quality analyses from a catchment in Hillbrow was made in order to test this model. The model will also be used by the CSIR for analysing data from catchments in Pinetown and Natal.

WATER BALANCE

Figs 1 and 2 present the cumulative rainfall (input). Surface runoff (measured) and calculated evaporation losses over the research period 1986-91. Rainfall rate appears to decrease with time, indicating a wetter period at the beginning of the observation period. Surface runoff rate showed a marked decrease after 1986, showing high sensitivity to rainfall variation, whereas evaporation continued to exhibit regular seasonal cycles. The total evaporation, transpo-evaporation, comprising mainly transpiration rate calculated from a model, used weather data only observed from 1987 (hence the plots of evaporation loss only starts then).

The corresponding calculated groundwater accretion in Waterval agrees with that observed from limited tests. The groundwater accretion best estimate including subsurface outflow from August 1987 to February 1991 was 3,5 x 200 000 m^3/a = 700 000m^3 and from Fig 5 it was 630 000m^3 for a balance which agrees reasonably.

Total above-surface loss from Waterval from August 1987 to February 1991 was 1 270 000m^3 or 67% of precipitation of 1 900 000m^3 over the period. The balance should have been in the form of groundwater outflow or accretion.

The total rainfall onto Sunninghill follows a similar pattern to Waterval. The other input, namely water supply, was only 16% of the rainfall. The surface outflow from Sunninghill was 1 480 000m3 or 67% of the inflow from August 1987 to February 1991. The balance must have been in the form of sewage and groundwater outflow i.e. 820 000m^3.

It was not possible to measure differences in surface temperature or radiation from the two catchments but this may have affected rainfall and evaporation. In particular evaporation rates from

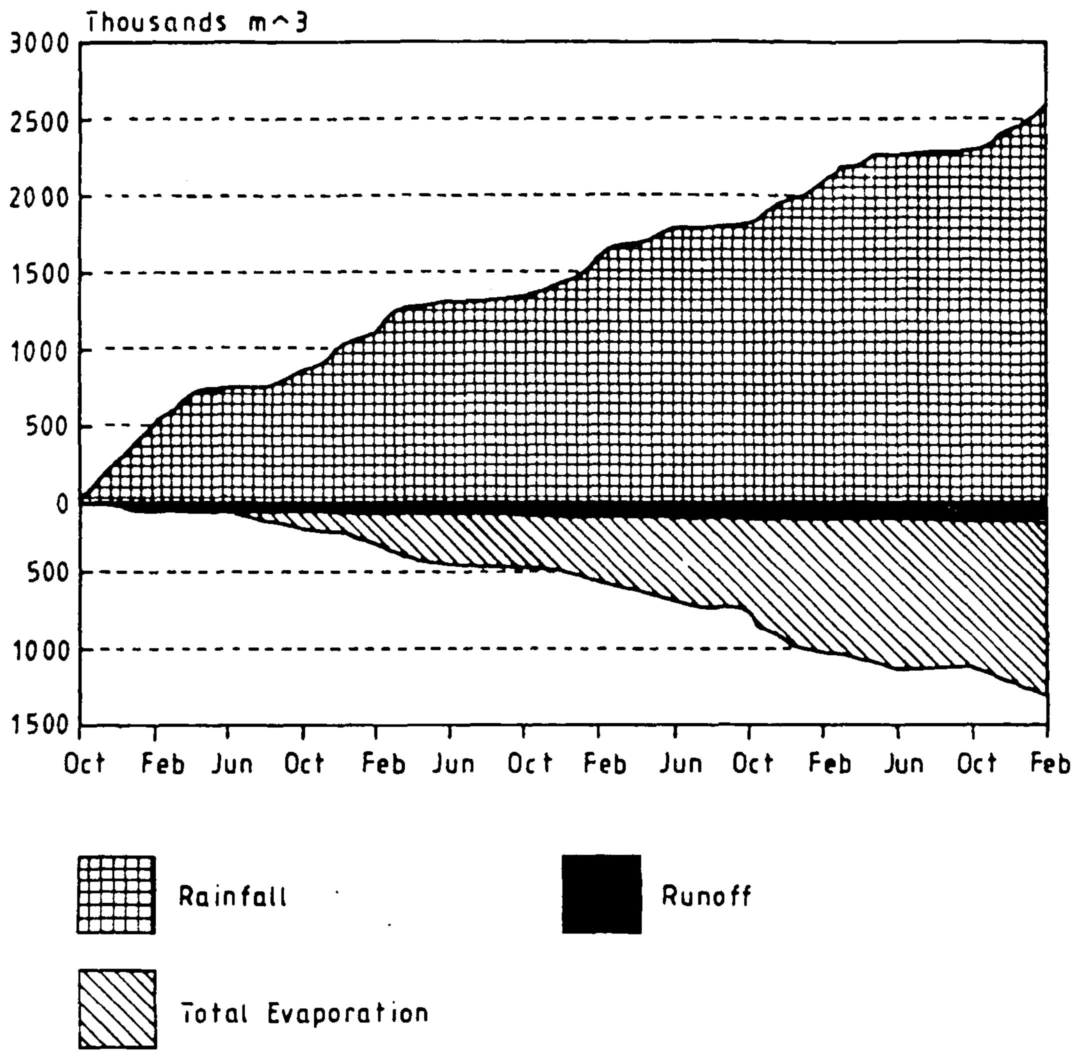


Fig. 1 Waterval Catchment Water Balance

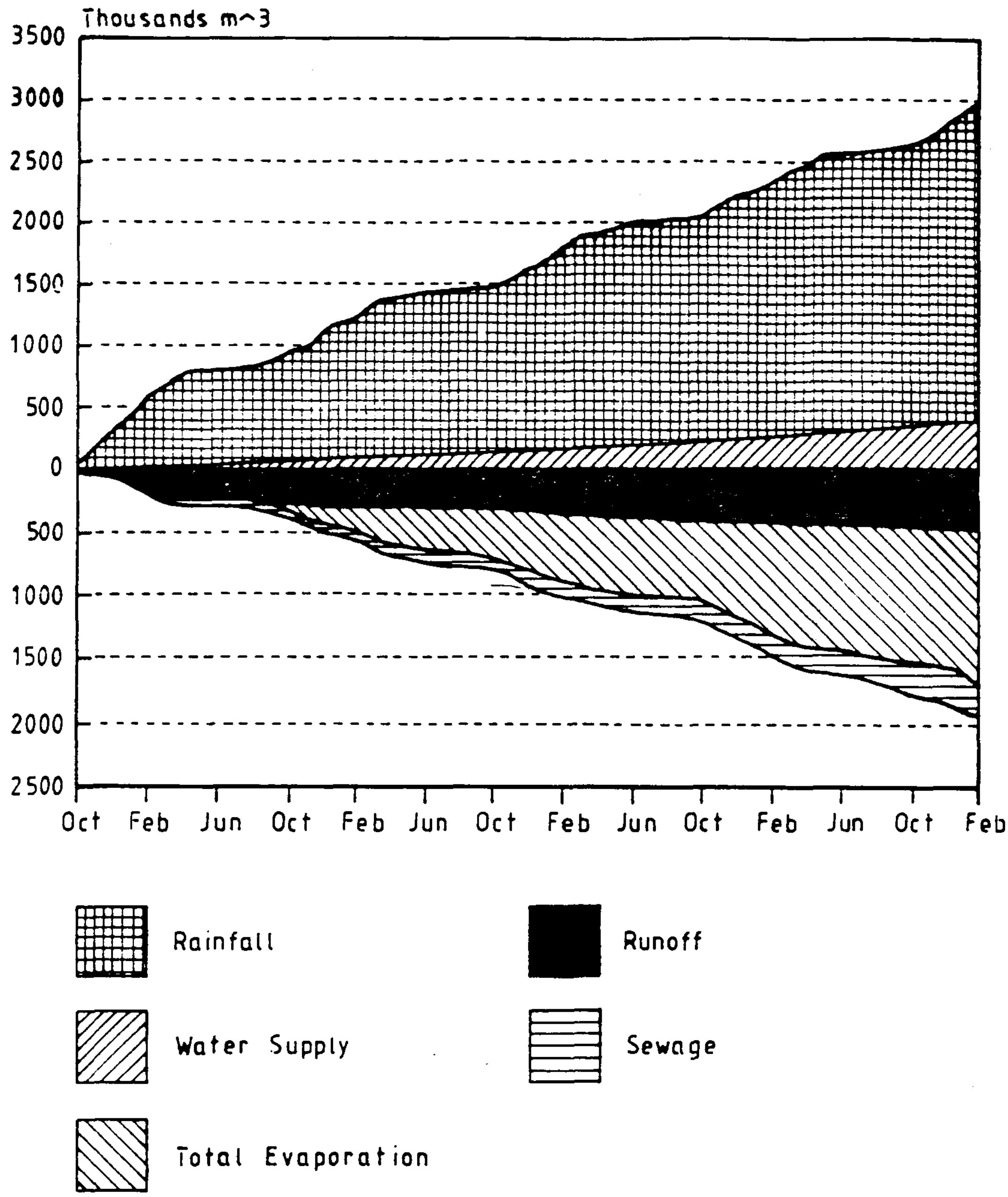


Fig. 2 Sunninghill Catchment Water Balance

roads and roofs may have been greater than from the vegetated areas.

Evaporation from Sunninghill was estimated from the model to be 1 200 000 m^3 so the total surface outflow was 530 000 m^3 more than for Waterval (primarily in the form of sewage and increased runoff). Evaporation is taken to include transpiration (the major component) here.

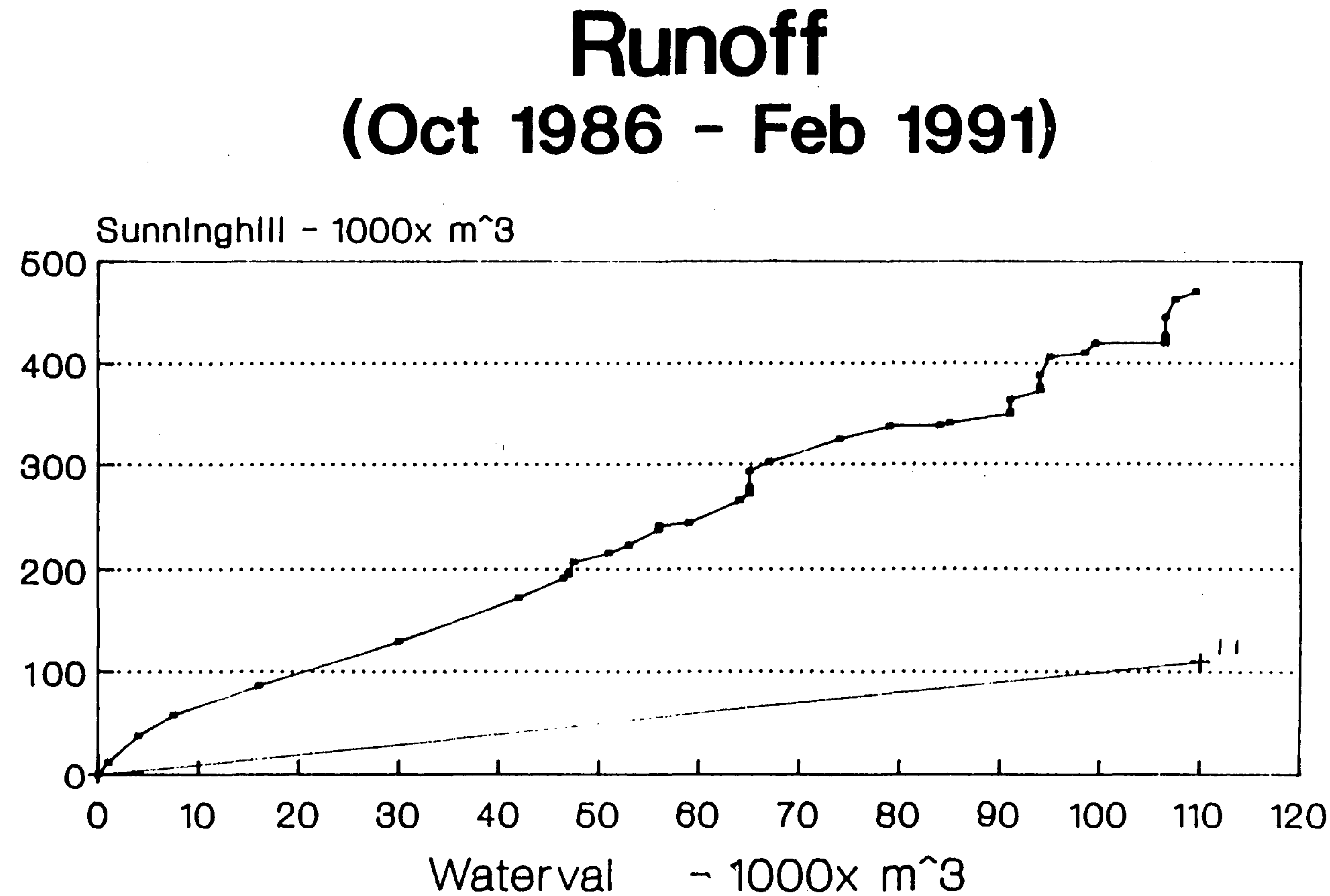
Total surface stormwater runoff from Sunninghill appears four times that from Waterval (Fig 3). No difference in evaporation resulted from the figures (Fig 4) indicating the increased garden watering balanced the reduced vegetated area. Surface runoff for Aug '87 to Feb '91 from Waterval was 4% of the rainfall (bear in mind the runoff was not entirely observed and the record had to be patched by correlation with rainfall). Surface runoff from Sunninghill was 15% of the rainfall. Sewage flow was 83% of water supply but only 11% of total outflow from Sunninghill. A large proportion of sewage was probably stormwater ingress as garden watering was known to take a large proportion of water supply (30%) which could not reach the sewers directly.

The Sunninghill runoff showed an initial spurt over Waterval (Fig 3) which may be associated with the higher rainfall rate, then exhibits a steady increase over Waterval. There is no trend away from this steady increase except in 1990/91 when the Sunninghill curve deviates noticeably upwards. This could be associated with the construction of two townhouse complexes resulting in a larger proportion of runoff.

Fig 5 shows the corrected mass balances.

SUMMARY OF RESULTS OF RESEARCH

The results indicated that stormwater runoff for developed catchments was increased by a factor of up to four over that from an undeveloped catchment. This is largely because of the



(Cumulative volumes)

Fig. 3 Runoff (Oct 1986 - Feb 1991)

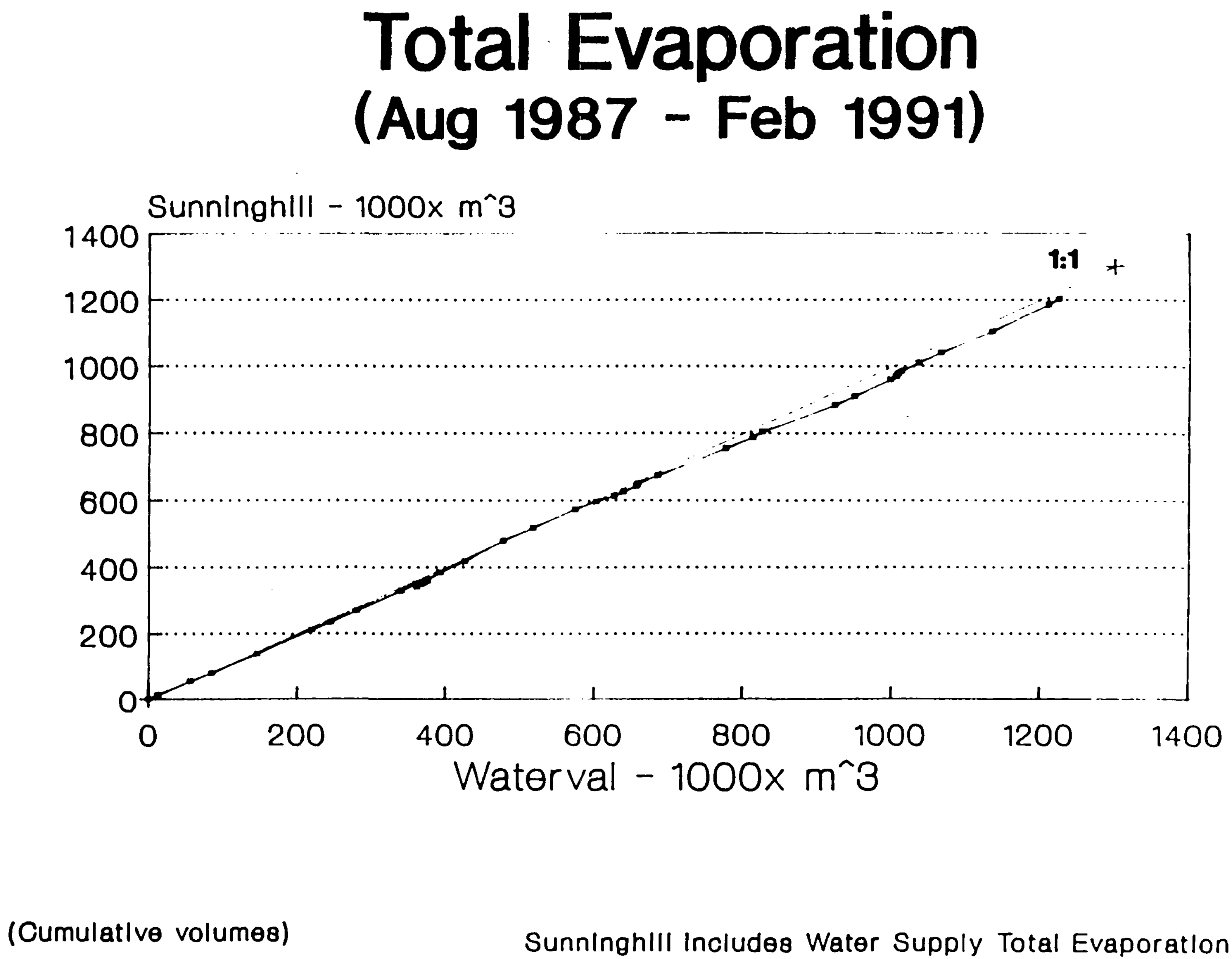


Fig. 4 Total Evaporation (Aug 1987 - Feb 1991)

construction of roads and roofs which channelizes the flow and results in a faster concentration. The reduction in infiltration due to some 20% of the area being covered by pavements, roofs etc further increased the flow rates. The layout of roads which runs directly to the bottom of the catchment concentrates the floods.

The practice of leading drains from building roofs direct to paved areas and then to storm drains increases volume and intensity of runoff. The more rapid runoff also results in higher volumes of runoff and therefore less infiltration than for the natural catchment.

Evapotranspiration from parks and gardens in the urban catchment amounts to 55% of water supply input from this catchment. This is the same as for the natural catchment despite the smaller area vegetated because of the preference for green gardens. In addition 83% of the water supply to urban areas was discharged to sewers and lost to the catchment although some of this is probably illegally connected storm drainage.

There was a net loss of water from the urban catchment by a groundwater flow but his appears to be balanced to some extent by excessive garden watering.

Computer models developed to assess the individual effects of urbanization on stormwater runoff and catchment water balance can now be used for planning future drainage systems. Town planners and civil engineers will be able to minimize runoff and therefore minimize the recirculation of water in the giant Witwatersrand and other urban complexes. The results highlight the necessity for changes to town planning regulations. That is the discharge of water from roofs should where possible be onto gardens in order to encourage infiltration. Use of dual drainage systems to enable floods to be stored on roads or preferably parks and infiltration strips is important.

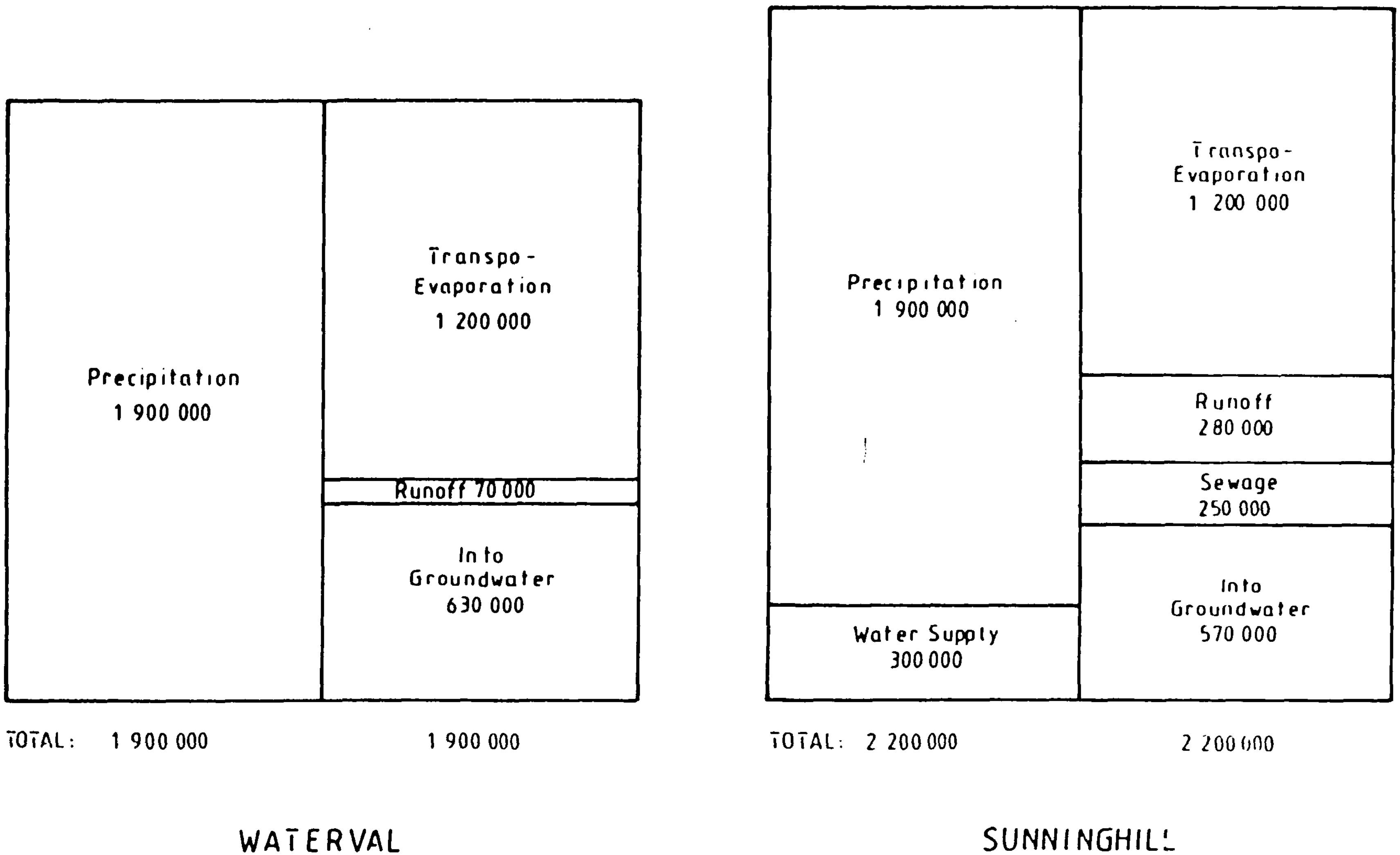


Fig. 5 Total water balance of both catchments.
Cumulative flow in m3 over 3,5 years, August 1987 to February 1991

EXTENT TO WHICH OBJECTIVES WERE MET

A number of valuable general conclusions can be made from the project. It has been realized that the subject is a bigger one than can be entirely covered in one contract. Not only were there frustrations in applying the technology and in obtaining results but also the uncertainty of certain measurements makes the results tentative but nevertheless useful.

The biggest losses from the catchments namely evapotranspiration and groundwater flow could not be measured accurately. Evapotranspiration had to be estimated from models and potential evapotranspiration had to be broken down into actual losses for both catchments.

The groundwater flow rate from the urban catchment was probably most easily assessed because a proportion appeared to emerge to the surface owing to the dyke at the bottom of the catchment. This flow was therefore monitored over the crump weir as it all appeared to reach the stormwater channel. In the case of the undeveloped catchment there were a number of complicated subdivisions of the geology and indirect assessment had to be made of the outflow. That is, a number of tests were made to assess groundwater flow velocities and age. These volumes were in excess of stormwater runoff which for this catchment were remarkably low compared with the urban catchment. Whether this catchment is in fact a representative rural catchment it cannot be proved but the lack of defined storm water channels made the infiltration rates higher than would have been the case if there were many channels.

The assessment of water supply which was on a sporadic basis was not as accurate as the sewage outflow but volume-wise it was satisfactory. Exactly what happened to each stream of water was difficult to say but is anticipated that the majority is accounted for. The variations in groundwater levels proved marginal. There were minor daily fluctuations probably due to thermal effects but also attributable to solar and lunar effects. No general depletion of the water table in the urban catchment was however observed and this could be due to contributions by garden watering balancing what would have otherwise been a depletion in the water table.

Although the rainfall over the period was probably above average especially in early years there was no notable increase in water tables in the rural catchment either.

The computer models available from this project will enable planners to assess the effects of proposed township plans on runoff in particular. It will also enable management methods to be assessed prior to construction as simulation of storm flow through alternative drain layouts and drainage systems or even detention in dual drainage systems can be made for larger type conduits. The analysis of surface flow profiles can be made and storm patterns can be assessed for highveld conditions. The fact that intense storms are in fairly small cells which move rapidly over catchments can influence flood peaks and these should therefore be allowed for in such planning.

The data management packages prepared will make monitoring in future research contracts by this group or other groups more economical and some standardisation can be expected as a result of the management package.

A number of research papers emanating from the study have been published in local and overseas journals and presented at conferences and these papers are compiled in one of the reports forming part of the contract.

Preliminary estimates of water quality from a highrise urban area namely Hillbrow were made but these cannot be generalized at this stage and will be used for future modelling. Future contracts should attack the low cost housing water pollution problems and proposed management methods.

The volumes of runoff proved to be fairly small in particular for the undeveloped catchment and as a result future projects should identify methods of evapotranspiration and groundwater outflow. Drought runoff could only be assessed by modelling as no extreme drought was encountered during the project. The interaction of surface and subsurface flows can however be modelled with the computer simulation programs compiled within the project. The effects on flood peaks can also be modelled and these were assessed with the instrumentation installed in the contract and preliminary methods for modelling pollution transport in stormwater were prepared.

RECOMMENDATIONS FOR FURTHER RESEARCH AND TECHNOLOGY TRANSFER

Steps have already been made to impart the knowledge to practising hydrologists and civil engineers. Continuing education courses and post graduate courses have been given at the University of the Witwatersrand on stormwater and catchment management. Such courses will be ongoing and in addition papers on the work have been and will be presented at international conferences.

A new project in parallel with the present project has been embarked on by the research group and monitoring of these catchments will continue at least for the duration of the new contract. The new contract allows for monitoring of a new catchment adjacent to the other two which is to be developed over the next few years.

Improved methods of assessing evapotranspiration must be developed and this will be investigated during the new contract but further research into both the assessment of evapotranspiration and ground water moisture changes and methods of affecting them would be of great use in managing our water resources more efficiently. On the other hand the assessment of groundwater discharge may be more difficult in view of the difficulty of assessing sub-surface catchment characteristics. It may be that remote sensing will assist in estimating infiltration and evapotranspiration methods as borehole monitoring and geophysical methods have proved to be of limited use.

Studies of the changes in runoff intensity frequency relationships due to urbanization will be a long term task.

Data on the interaction between weather, water consumption, sewage discharge and groundwater changes will be of great value and some of these aspects will be dealt with in a new contract between the Water Research Commission and the Water Systems Research Group of the University of the Witwatersrand.

Guidelines for town planners and drainage and water engineers should be prepared from the research project.