Journal of Environmental Planning and Management, 40(4), 413-434, 1997

Water-sensitive Urban Planning: Protecting Groundwater

NAOMI CARMON*, URI SHAMIR† & SIGALIT MEIRON-PISTINER‡

**Faculty of Architecture and Town Planning, †Faculty of Civil Engineering, & ‡Centre for Urban and Regional Studies, Technion—Israel Institute of Technology, Haifa 32000, Israel*

(Received July 1996; revised January 1997)

ABSTRACT *Sustainable development requires the promulgation of guidelines for urban planning which consider the effects of the built environment on water resources. In this context, our paper focuses on the effects of urban development on the quantity and quality of rainwater which infiltrates into the soil on its way to recharge the aquifer. The paper includes: identification of the state of knowledge regarding the effect of urban development on runoff and infiltration; a case study—estimation of the effect of certain patterns of urban development in an Israeli neighbourhood, together with an option for mitigating them by relatively simple and inexpensive means; presentation of the components of urban planning which influence runoff and infiltration; and proposals for continuing research in this area which has been relatively neglected until recently.*

Introduction

Preservation and protection of water resources is a central imperative of sustainable development. Urban development has an effect on water in several ways. This paper focuses on its impact on groundwater, and what can and should be done to mitigate its negative effects.

Urban areas around the world are often located above phreatic aquifers. An aquifer—a layer of the soil in which water is stored and can flow—is called phreatic (in contrast to 'confined') when it is open from above to direct percolation of water from the land surface into it, through the unsaturated layer. Phreatic aquifers can be found in Long Island, USA, underneath the metropolitan area of Perth in Western Australia, and in Israel's Coastal Plain where Tel Aviv, the main metropolitan area of Israel, is sprawling. We aim at studying the effects of urban development on the quantity and quality of groundwater in phreatic aquifers.

Urban development will not be halted for water considerations. Hence, there is an urgent need to guide urban planners on how to manage urban development with minimal damage to groundwater resources. The general goal of the study reported herein is to start the way towards issuing affirmative guidelines for water-sensitive urban planning, in the context of sustainable development. Sustainable development internalizes into its goals and methods the long range impacts of development on the natural environment and on its utility for human beings in the present and future generations.

0964-0568/97/040413-22 $7.00

Water-sensitive urban development means consideration of the expected impacts on the quantity and quality of water in the sources in the area being developed and/or the water used in this area. Such planning covers two domains: one deals with the effects of urban development on the hydrological cycle and the water sources; while the other deals with the engineering aspects of water supply and use. Our work falls in the first domain, and focuses on the effects of urban development of groundwater.

In this hydrological context, the goals of water-sensitive urban development are:

- to increase the quantity of water which infiltrates into the ground and eventually reaches the groundwater;
- to reduce pollution of surface runoff which ends up recharging the aquifer.

The reduction of surface runoff which is required to achieve this serves the additional goals of reduced flooding and cutting down the cost of drainage systems.

In this paper, we present the first stage of the work leading to guidelines for water-sensitive urban development. It contains a literature survey and a preliminary empirical investigation. This enables us to identify the components of planning which have a direct influence on the quantity and quality of groundwater. The paper ends with recommendation for further studies, some of which we have already begun.

Hydrological Literature 1: Urban Land Use and the Quantity of Groundwater

Common wisdom, reflected in books, reports and other publications on hydrology, is that urban construction of buildings, roads and parking areas increases surface runoff by creating more impervious surfaces, which translates into a reduction in infiltration, and therefore, less groundwater recharge.

In describing the response of an urban watershed, as computed by the commonly used HEC-1 model, Feldman states (Singh, 1995, p. 137): "The pervious runoff surfaces have higher infiltration rates, and are typically longer in transit to the collector channels. The impervious surfaces obviously have very little infiltration and are usually a short distance from the collector channels". The HEC-1 user's manual (Hydrologic Engineering Center, 1990, p. 16) also states, "A percent impervious factor can be used with any of the loss rate methods; it guarantees 100% runoff from that percent of the sub-basin".

Urbanos & Roesner (Maidment, 1993, p. 28.1-2) state: "Urbanization increases surface stormwater runoff and modifies its quality. As land urbanizes, it is covered by impervious surfaces such as paved roads, parking lots, and roofs which prevent rainfall or snowmelt from infiltrating into the ground". They proceed to cite findings (ibid., figure 28.1.1.), which show how the runoff coefficient increases with "percent impervious", from 0.05 (i.e. 5% of the annual rainfall appears as runoff) at zero imperviousness, to about 0.32 at 50%, almost 0.6 at 80%, and 0.9 at 100% imperviousness.

Harbor (1994, p. 101) computed the effect of urbanization on groundwater recharge by assuming that the increase in surface runoff translates into an equal reduction in groundwater recharge. However, several studies have indicated that the effect of urbanization on the hydrological balance is not quite so pronounced and that, in effect, the part of the water which infiltrates is greater than often thought (Van de Ven, 1985;

Western Australia Water Authority, 1987; Ferguson, 1990; Gerti *et al.*, 1993). This is particularly true if measures are taken to increase infiltration (Ishizaki *et al.*, undated; Fujita, 1992; Herath *et al.*, 1993).

Hence, the first question we posed for this research was: is it correct that urban development reduces groundwater recharge? There are several ways to approach an answer. One is direct measurement of the effect of urbanization on groundwater and computation of the groundwater balance equation. An indirect way would be to measure rainfall, runoff and evaporation, and compute infiltration as the remaining unknown in the balance equation at the surface. A third way is to compute the effect of urbanization on surface runoff volumes, and make assumptions about the relation between the increase in runoff and the reduction in infiltration. An elaboration of each approach and the difficulties it involves appear below.

Direct Measurement and the Groundwater Balance Equation

On the face of it, there is a simple direct way to measure the effects of urban development on the groundwater in the aquifer underneath it: measurement of the groundwater levels over time, during and after urban development, computation of the groundwater balance equation, and search for correlation between the changes in land uses and the changes in the groundwater levels below.

The balance equation for groundwater describes the relation between the net inflow (inflow minus outflow) into a defined portion of the aquifer, and the change in the volume of water stored in it. The balance equation is formulated for a 'cell' of the aquifer, which is a volume created by delineating the area of interest on the land surface, then extending the boundaries of this area downward to the bottom (an impervious layer) of the aquifer.

The balance equation (in units of volume of water), for a specified time period, is:

$$DV = FT - P + NR + AF \tag{1}$$

where:

DV = increase in groundwater volume during the time period;
FT = net lateral inflow into the cell (inflows minus outflows);
P = pumping;
NR = natural recharge from infiltrating rainfall;
AF = infiltration from recharge wells, irrigation water, leaking pipes, etc.

While this equation has a simple form, its use in assessing the effects of urban development on groundwater is beset by difficulties. The main ones are:

(1) Lateral flows in the aquifer are determined by the gradients of the groundwater surface and properties of the aquifer material; information on these, in particular aquifer properties, is lacking and difficult to obtain, hence there are substantial uncertainties in assessing these flows.

(2) Rainfall is random, and it is therefore necessary to express recharge in a way which recognizes its variations. One possibility is to express recharge as a percentage of rainfall, but this does not overcome the problem entirely, since recharge is not a linear function of rainfall. Furthermore, the water which infiltrates at the surface may take some

time to reach the saturated zone of the aquifer.

(3) To determine the effects of land use changes it is necessary to assess the variations in groundwater recharge over a period of many years; sufficiently long and reliable field measurements are seldom available.

(4) To determine the effects of different urban land uses it is necessary to define in the groundwater model cells which follow the variations in land use on the surface. This may require a large number of cells, of various shapes and sizes, which is difficult to accommodate in the groundwater model.

The only reference we could find in the literature to direct measurement of the effect of urban development on the groundwater underneath it is the study of Perth in Western Australia (Water Sensitive Urban Design Research Group, 1989). As far as we know, the Australian researchers did not measure the groundwater levels over a long period of time, nor did they use the groundwater balance equation. They found that water levels rose, by one metre on average, after urbanization. They attributed this rise to several factors, among them: reduced evapotranspiration due to removal of vegetation, leaving more water for both recharge and runoff; reduced pumping from wells in the urbanized area; and recharge of water imported to the area. In the opposite direction, other factors contributed to reduction in recharge, among them the change of pervious to impervious areas and the construction of drainage systems. The net effect, in the Perth area, was a rise in groundwater levels, which was interpreted by the researchers as a net increase in recharge due to urbanization.

Recharge Assessment by Measurement of Surface Runoff

The relation between surface runoff and the variable in which we are interested in this study—groundwater recharge—can be deduced from the following simple equation of the hydrological balance:

$$P = R + I + E \tag{2}$$

where:

P = precipitation (input from above);

R = surface runoff (leaving the area);

I = infiltration (outflow downward);

E = evaporation (outflow upward).

The infiltration crosses the land surface into the ground, and is the source for replenishing groundwater. Not all of it reaches the saturated zone, however, since some may be taken up by plant roots, some will evaporate back, after being raised by capillary forces to the land surface, and some may remain trapped in the unsaturated zone for a long period of time. Infiltration is rarely measured directly in the unsaturated zone, where it flows downward; it can therefore be estimated only through measurements of groundwater levels and analysis of the groundwater balance.

If it is assumed that the infiltration does reach the saturated zone and becomes part of the groundwater, then equation (2) provides a way to compute groundwater recharge. Equation (2) is written for a specified time period, chosen such that conditions on the watershed can be assumed to be the same at the beginning and end of the period. Under these conditions, there is no net change in storage, or the changes are small compared to other terms in the equation and can be neglected. This period is therefore typically a year, or at least a season, and not one single storm event. For shorter time periods, such as a single storm or a few days, the change in storage in the watershed, in depressions and in soil moisture, can be a very significant element in the balance equation.

Precipitation is measured with standard equipment, and is frequently available with good accuracy and spatial and temporal coverage. Potential evaporation is measured at meteorological stations, and the data are available as typical regional values; it is, however, rather difficult to deduce from these data the actual evaporation, and even more so the evapotranspiration. Surface runoff is more difficult and expensive to measure, and there is usually little or no measured data for both open and urban areas; much of it gives peak flows only, not the volume of runoff.

Fujita (1992) and Ishizaki *et al.* (undated) describe a 10-year field study in Tokyo, in which the effect on runoff of various structural measures was measured. The researchers installed a wide variety of devices in a selected urban area of 1.32 ha: permeable pavements, porous drainage pipes, infiltration wells, trenches and ponds. An adjacent area of 1.85 ha, with the same urban construction patterns, was left in its original state, and runoff from both was measured continuously. Ishizaki *et al.* (undated) provide a table comparing the runoff volume per unit watershed area for the installed area (denoted by q', in mm) and for the area in its original state (denoted by q). This is done for the 40 largest storms during the 10-year period. The ratio (q'/q) varies from 0 to 0.322, with half the values below 0.10, 90% below 0.20, and only one of the values above 0.30, indicating that most of the runoff is prevented by the installation of these structures. We believe that for smaller storms the entire runoff is probably totally prevented, since the intensities are lower and the infiltrating devices can capture all the water. The reduced runoff amount is assumed to have infiltrated into the ground. Herath *et al.* (1993) provide an overview of this project.

Gerti *et al.* (1993) observed the hydrological behaviour during rainstorms in the vicinity of Ra'anana, a town in central Israel. They measured flows, over a 15-year period, in a creek that drains a watershed in which the built area exceeds 50% of the area. They found that the volume of runoff was considerably lower than that computed by accepted methods; their estimation of the percentage of annual surface runoff from annual rainfall in the built area of Ra'anana was 10-15% (ibid., p. 17). In addition, they found that the peak discharge of events with annual exceedence probability of 20% or less (i.e. the larger and rarer events) may even be lower than in undeveloped watersheds in the same region; their explanation is that the drainage system's limited capacity causes a greater percentage reduction in the peak than in small events. Their specific findings are for Ra'anana, which began as a rural community, and has recently developed into a city. The town has apparently maintained some of the rural patterns of building, such as stone fences around each house, which trap much of the water during storms, causing it to infiltrate in the yard and slowing the release of the excess waters into the sidewalks and streets.

This empirical evidence provides additional credence to the opinion that the effect of urban development on recharge of groundwater is not as simple and obvious as implied by most texts on hydrology. It also indicates that this effect depends on certain planning and design variables which may be under our control.

Recharge Assessment by Computation of Surface Runoff

In view of the difficulties in conducting valid, long term and reliable field measurements of the effects or urban land uses on surface runoff, not to speak of groundwater recharge, several computational techniques have been developed to enable assessment of these effects. These techniques require specification of hydrological coefficients for parts of the watershed, such as runoff coefficients for each land use and, for those models which include an infiltration module also, infiltration parameters for each soil type. Division of the watershed into sub-areas, each considered to have a homogeneous hydrological behaviour, and selection of parameter values are guided by instructions and tables which can be found in books and manuals. Many of the methods and models for computing the components of the hydrological balance are discussed in the *Handbook of Hydrology* (Maidment, 1993) and described in detail in *Computer Models of Watershed Hydrology* (Singh, 1995).

An example is the SCS method (Soil Conservation Service, 1975; Maidment, 1993) to be presented in detail later. It computes the volume of runoff for each rainfall event, given the soil types and land uses in the watershed. To estimate the effect of urbanization on groundwater recharge, two assumptions have to be made: (1) evaporation remains unchanged by urbanization; and (2) any increase (decrease) in surface runoff volume results in an equal decrease (increase) in infiltration.

Harbor (1994) used the SCS method to compute the volume of surface runoff in an urban area of Akron, Ohio, USA. His findings are quite dramatic: he computed that surface runoff increases, relative to that prior to urbanization, three-fold in areas of low density housing, 11-fold in high density housing and 19-fold in industrial areas. According to his computations, average recharge was reduced from 568-1893 m^3/day/km^2 to 216-1775 m^3/day/km^2 due to development of the urban area in the form common in Akron, Ohio. Harbor (1994, p. 103) states that the amount by which surface runoff increases due to urbanization, as computed by the SCS method, gives the maximum possible reduction in groundwater recharge, and a finer analysis is required if land use is to be developed in a manner which aims to reduce the loss to groundwater.

Ferguson (1996) also used the SCS method, after modifying it to a monthly time scale (computing the monthly runoff from the monthly rainfall), and using a moisture-dependent curve number (CN) value (according to the antecedent precipitation). His observation is that, "removal of vegetation, compaction of soil, and addition of impervious surfaces can drastically increase the amount of Q [direct runoff], leading to downstream flooding, channel erosion, and loss of riparian habitat. The diversion of rain-water into Q is a loss of potential ground water recharge and stream base flow" (ibid., p. 263).

Hydrological Literature 2: Urban Land Use and the Quality of Groundwater

Land uses affect the quality of surface runoff and the water which infiltrates into the ground (Berry & Horton, 1974). Urban development is accompanied by an increase in the quantities of several pollutants, the ones of most concern include chlorides, nitrates and heavy metals.

Common sources of pollutants in urban areas include (Hirschberg, 1989; Melloul & Bibas, 1991):

- septic tanks: in the early stages of urbanization, septic tanks are commonly the first means for dealing with the sewage; until they are replaced by sewage collection and treatment systems, they are probably the major source of nitrates and chlorides entering the groundwater system;
- sewage collection systems: these systems frequently leak, sometimes substantial amounts, and close to groundwater bodies, thereby contributing to pollution of these waters;
- landfills of solid waste: during early stages of urbanization, and sometimes for periods of many years, solid waste is dumped close to the city, at sites which are not well designed nor managed; leachates from such dumps are causes of major pollution of groundwater;
- vehicles and fuel depots: contribute hydrocarbons and their residues to the surface and groundwater;
- other human activities: wastes left throughout the urban area, accidental spills of polluting and toxic wastes, etc.

Additional pollution is caused by industry, but this is outside our interest in the present study. We consider only that pollution which is, or can be, contributed by housing and the attendant services (local roads, stores, schools, community centres, etc.) in the residential area.

Eckhardt & Oaksford (1986) studied groundwater quality in Suffolk and Nassau Counties, on Long Island, NY. The region was divided into 762 cells, each about 6000 m^2. The 1981 land uses were put into six categories: low density and high density housing (together 32%); institutions (21%); agriculture (8%); industry, commerce and transportation (together 12%); and undeveloped (27%). Water samples were taken in 903 wells, from the upper layer of the saturated zone, some 10 m below ground surface, during the period 1978 to 1984. Each well was assigned the land area within a radius of 2.4 km around it, and a correlation was sought between land use and water quality. The highest concentrations of chlorides, potassium and total dissolved solids were found under areas of high density housing. It was also found that under agricultural land, the groundwater had high concentrations of nitrate, sulfate, and calcium, and under undeveloped land there were low concentrations of inorganic pollutants.

Christensen & Rea (1993) compared groundwater quality in undeveloped and urban areas in Oklahoma. They found that the concentrations of both organic and inorganic pollutants (except fluor and cadmium) were higher under the urban areas. Atwood & Barder (1989) compared groundwater quality in Perth, Australia, with findings in the US. Their conclusion was that although the situation in the US seems to be more acute, groundwater in Australia is under more severe danger of pollution and there is urgent need to monitor its quality and protect against possible pollution.

Researchers agree that urban development results in greater quantities of certain pollutants in the developed area and these changes affect surface waters. However, the effect on groundwater quality is determined also by the fate of the pollutants as the water infiltrates through the unsaturated zone. Information regarding these processes, and the time it takes for a change in quality at the surface to affect the groundwater, is scarce, and quite inconclusive.

The unsaturated zone contains considerable quantities of various pollutants, which come from the sources listed above, and are then carried down with the infiltrating recharge waters. The greater the recharge, the greater the quantities of these constituents which reach the groundwater. For example, rainfall on the Israeli coastal plain in 1991/92 was 1.5-2 times the annual average. The recharge was computed to have been 50% of the precipitation (the percentage increases with the amount of rainfall). And, indeed, that year the salinity of the groundwater in this region rose at a rate two to five times greater than the long term average (Melloul & Goldenberg, 1993). This contradicts the expectation that with larger amounts of water recharging the aquifer, the dilution should cause a decline in salinity.

Gerritse *et al.* (1988) studied groundwater quality in the sandy aquifer of Bassendean, Australia. They found that sand apparently has a higher capacity to trap pollutants than usually thought, and concluded that further studies are required before one can forecast with some certainty the effects of land use on groundwater quality, even in sandy aquifers. Another difficulty in determining the effect of land use on groundwater quality is due to the distortion of the local flow field caused by pumping from the wells where water samples are taken (Barringer *et al*, 1990).

Ronen *et al.* (1986) studied the movement of nitrates from the surface to groundwater in Israel's coastal plain throughout this century. They showed that additional nitrates applied at or near the surface reach the groundwater, a few tens of metres below, only after several *decades.* In addition, physical and chemical processes, which are not well understood, affect the concentrations of the various pollutants which flow with the water through the unsaturated zone. Further references to publications on groundwater quality, sources of pollution, mitigation measures, and policies, can be found in Kappen (1993).

The conclusion from all the above is that additional development of research methods and much more empirical work is needed in order to determine cause and effect relations between changes in land use and groundwater quality.

Estimating Losses to Groundwater Recharge Resulting from Urban Development: A Case Study in Israel's Coastal Plain

The population growth and the rapidly rising standards of living in Israel cause large amounts of urban construction. About half of the total increase takes place, and is expected to take place in the future, in the coastal plain, especially in the metropolitan area of Tel Aviv that sits above Israel's largest and most important multi-year reservoir of water. Therefore, it is highly important to evaluate the influence of this urban development on the groundwater.

We decided to concentrate on the main bulk of urban development: the residential area and the associated services—social services, commercial areas, local roads, parking spaces and small open spaces. We left out industrial areas and main transportation corridors, because of the different implications for water quality.

The literature survey revealed the many obstacles on the way to direct measurement of the effects on quantity and quality. Considering the limited resources we had, we decided to estimate quantity only, in one case. The main objective of the case study was to provide initial estimation of the losses to groundwater recharge, resulting from the pattern of urban construction which is typical of Israel of the 1990s. Another objective was to identify the components of urban planning that seem to directly influence groundwater recharge.

The Test Location: Kiryat Ganim

Our study centres on Israel's Coastal Aquifer, which covers an area of some 1900 km^2 in Israel's coastal plain. It is a phreatic aquifer, made of sandstone, with a thickness ranging from a few metres to about 200 m. The water table, below which the aquifer is saturated, lies 5 m to 20 m below the land surface.

The neighbourhood of Kiryat Ganim, a newly constructed urban area on the coastal plain of Israel, was selected for our case study. Its construction began in 1991. By 1994 its population reached about 6400 residents in 1770 households (3.6 persons per household). The neighbourhood is part of Rishon Le-Zion, a city south of Tel Aviv that has grown from about 50 000 in the early 1970s to 100 000 ten years later, and to more than 150 000 inhabitants in the early 1990s. Most of the new residents are middle-class families with children. The population of the area and the physical plan of the neighbourhood are typical of the urban sprawl at the heart of the State of Israel, the core that spreads above the coastal aquifer.

The climate in the area is Mediterranean, mild, with an average of 58 days of rainfall (over 0.1 mm) a year, from about October to April, and dry the rest of the year. The annual rainfall averages 536 mm; the highest recorded is 912 mm, and the lowest 312 mm. The highest monthly rainfall is in December, with an average of 146 mm.

The soil on which Kiryat Ganim was constructed is primarily sandy, about 160-180 m thick to the impervious layer below. The groundwater in this area shows concentrations of chlorides in the range of 110 to 230 mg/1, and nitrates (as NO_3) in the range of 40 to 75 mg/l (the acceptable concentrations are: CI, 250 mg/1 for potable and unrestricted agricultural use; NO_3, 45 mg/1 for unrestricted potable use, with an upper limit of 90 mg/1). Hence, the groundwater in this area is suitable for most uses, but the concentrations are approaching critical limits.

Kiryat Ganim has an area of 560 dunams (1 dunam = 0.1 ha = 1000m^2). In order to study its plan and especially to differentiate between pervious and impervious areas within it, we measured the distribution of areas in the neighbourhood, rather than taking it from a general plan. Of the total area, 57% (320 out of 560 dunams) is covered by the residential area (see Table 1). The remaining 43% include: 21% open space; 10% road (those not within the residential area); 9% public and commercial services; and 3% of undeveloped open spaces (see Table 2).

As mentioned above, the building patterns of Kiryat Ganim are typical of the recent (1990s) urban sprawl above the coastal aquifer of Israel. According to Table 1, out of the average area per person in the residential area (without public services, main roads, neighbourhood open spaces, etc.), about one-quarter is covered by roofs, 40% (!) are paved areas, and the remainder (about one-third) is green (mostly private gardens). As could be expected, the lower the density (of housing units per dunam), the higher the total area per person (2.5 times higher in low density than in high density). But we also expected that, in lower densities, a larger percentage of the area per person will be open and green, but this is not the case in Kiryat Ganim; the impervious area per person in low density is 2.5 times larger than in high density.

Table 1. Characteristics of the housing area[a] in Kiryat Ganim neighbourhood

	No. floors in a building	Total no. residents[b]	Dwellings per net dunam	Average area[c] per person (m^2)	Average roof area[c] per person (m^2)	Average paved area[c] per person (m^2)	Average green area[c] per person (m^2)	Total area in dunam
Low density	2	800	3–4	75.5	17.5	33.8	24.4	60.99
Medium density	4	3370	4.1–6	56.1	14.1	21.2	20.8	191.24
High density	9	2200	6.1–9	30.9	6.8	14.1	10.0	68.02
Total/average		6370		50.3	12.2	20.5	17.6	320.25

[a] The housing area includes: the buildings; the gardens and yards around them; the private parking area areas; and the access roads.

[b] Number of dwellings × 3.6—the average size of household.

[c] Calculated for the housing area only; does not include public services or neighbourhood open space (see Table 2).

Figure 1. Row housing: notice the small gardens in front of the houses, while the rest of the area is paved.

The Computation Method

Because of the many difficulties in empirical measurement, described above, we resorted to computations and adopted the assumption that a change in surface runoff caused by urban development results in an equal and opposite change in groundwater recharge.

For computing the surface runoff we started with the hydrological balance equation in its most general form:

$$Q = P - E - R \tag{3}$$

where:

Q = surface runoff;
P = precipitation;
E = evaporation;
R = infiltration into the ground.

All quantities in equation (3) are expressed in units of volume (m^3) for a selected period of time. Instead of volumes, one may use units of depth over the entire area of the drainage basin. This is done since, for example, rainfall is more familiarly expressed in units of depth (mm, inches). Obviously, the two methods are equivalent, related simply through the area of the basin.

Precipitation data were available: total quantity for each storm, over a period of several decades. In order to compute the variable of interest, R, the infiltration into the ground before and after the urban development, we had to estimate E, evaporation. There is some evidence that urban development decreases evaporation and evapotranspiration,

Figure 2. Buildings of four floors arranged around a square, with the central area primarily for parking.

due to the removal of vegetation. However, gardens and lawns increase evapotranspiration; this is probably the case in the Israeli coastal plain. But since data were not available, we adopted the assumption that E does not change as a result of urban construction.

To estimate the change in surface runoff resulting from urban land uses, we used a well accepted method for computing runoff with different land uses: the Soil Conservation Service (SCS) method (SCS, 1975; Sheaffer *et al.*, 1982; Ferguson & Debo, 1990; Maidment, 1993; Harbor, 1994). The parameters which enter the computation are: the amount (depth) of precipitation; land cover; and soil type (including consideration of its moisture condition).

According to the SCS Method, for a precipitation event (a storm), the runoff is given by:

$$Q = [P - I_a]^2 / [P - I_a + S] \tag{4}$$

where:

Q = runoff;
P = precipitation;
I_a = initial abstractions = losses;
S = maximum water retention of the basin.

All quantities are in units of depth (mm) over the area.

Empirical studies by the US Soil Conservation Service on small watersheds (SCS, 1975, 2-2) yielded the relation:

$$I_a = 0.2\,S \tag{5}$$

There is no indication that this relation should be adjusted for specific land cover and soils, probably because these dependencies are contained in the assignment of the *S* values (see below).

Introducing equation (5) into equation (4) leads to equation (6) which was used in this study:

$$Q = [P - 0.2S]^2 / [P + 0.8S] \tag{6}$$

Computation of *Q*, the runoff, therefore hinges on the value of S, which depends on the land use, soil type and soil moisture. These factors are expressed by a Curve Number (CN), given in tables (SCS, Table 2.2, pp. 2-5; Sheaffer *et al*, 1982, p. 126; Maidment, 1993, Table 5.5.1, pp. 5.26-5.29, and Table 9.4.2, p. 9.24). The value of CN ranges from about 35-40 for meadows and woods, to 90 and above for fully developed urban areas. *S* is then given by:

$$S = (1000 / CN) - 10 \tag{7}$$

with *S* given in inches. In the metric system, with *S* in mm, equation (7) is multiplied by 25.4 mm/inch, to yield:

$$S = (25400 / CN) - 254 \tag{8}$$

The CN value is selected for the land use and the soil type (one of four types, denoted A to D), according to a table prepared by the US Soil Conservation Service (SCS, Table 2-2, p. 2-5). The table lists CN values for natural and cultivated open spaces, for impervious areas covered by roofs or paved surfaces, and for residential areas with different densities, where part of the area is impervious and the rest open. We used from this table only the following values: roofs and paved surfaces (impervious areas), 98; uncultivated open areas, 49; and cultivated open areas, 39.

We refrained from using values for residential areas, which represent a mix of different land uses, since the building patterns in Israel are quite different from those in the US, where the method was developed (1-8 housing units per acre in the US, versus 8-36 units in Israel; 1 acre = 4 dunams). We therefore measured directly the pervious and impervious areas. The neighbourhood studied was subdivided into a large number of small homogeneous segments. Within each, the area of roofs, paved surfaces, uncultivated and cultivated areas was measured, and a weighted CN computed for the segment. The weighted value of CN was computed for each segment of the area under study, then used in computing the runoff.

The Antecedent Moisture Condition (AMC) of the soil is another factor which determines how much runoff will be generated, according to effects of the previous storms. Ferguson (1996) recommends that for continuous simulation, the value of CN should be updated according to the antecedent conditions. However, for purposes of urban planning this is not done, and we took the value for the intermediate value of AMC, as recommended by Sheaffer *et al.* (1982).

It may be argued that the SCS method does not reflect properly the behaviour of the watershed, because it considers only the total pervious and total impervious areas, without taking into account their areal distribution. While an impervious area does indeed generate runoff, this water may end up infiltrating into the ground—if this flow encounters a pervious area along its flow path. Thus, the way in which the various land uses are distributed throughout the watershed, and whether impervious areas are connected directly to the drainage network, are important factors in determining the response of the basin.

In the continuing phases of the research we are using distributed models of the watershed, to take better account of the areal distribution of pervious and impervious areas, and their connection to the drainage system. Still, for the preliminary analysis presented herein, the SCS method can provide adequate answers, as has been demonstrated by Harbor (1994) and Ferguson (1996).

Data and Results

The variables needed for analysing the losses of groundwater recharge, through computing the increase of surface runoff following the construction of Kiryat Ganim, are:

- the rainfall depth of each storm in each of the selected five years;
- the soil type—sandy soil, type A by the categorization of the SCS (one type throughout the area of the neighbourhood);
- the area of the neighbourhood—560 dunams; and
- the areas of the various land uses.

Table 2 contains aggregated data on eight land uses in Kiryat Ganim; for each of them, the total area and its division into pervious and impervious areas are presented. The impervious area is further separated into roofs and paved surfaces (this is needed for a later analysis).

Table 2. Land use and pervious/impervious cover in Kiryat Ganim neighbourhood

Land use	Area		Pervious cover: cultivated and uncultivated (%)	Impervious cover (%)		
	Dunam[b]	%		Total	Roofs area	Paved area
Housing[a], including:	320.25	100	35.1	64.9	24.2	40.7
low density	*60.99*	*100*	*32.2*	*67.8*	*23.1*	*44.7*
medium density	*191.24*	*100*	*36.9*	*63.1*	*25.3*	*37.8*
high density	*68.02*	*100*	*32.5*	*67.5*	*22.3*	*45.2*
Social and commercial services	51.32	100	47.8	52.2	31.3	20.9
Main neighbourhood roads	56.73	100		100.0		100.0
Neighbourhood green area	115.29	100	100.0			
Unused area	16.28	100	100.0			
Total and averages	559.88	100	47.7	52.3	17.2	35.1

[a] Definitions of the housing area and the various densities—see Table 1.

[b] 1 dunam = 0.1 ha = 1000 m^2.

Table 3. Annual runoff depth in the neighbourhood for three development conditions in the years examined, computed by SCS method

Year	Depth of annual rainfall (mm)	Before urban development		After urban development		After urban development with roof drains that lead the water to the soil	
		Runoff depth (mm)	% of annual rainfall	Runoff depth (mm)	% of annual rainfall	Runoff depth (mm)	% of annual rainfall
1984/85	321	0.0	0.0	39.30	12.24	24.30	7.57
1967/68	356	0.0	0.0	27.80	7.8	21.84	6.14
1988/89	491	0.19	0.04	69.30	14.11	42.75	8.70
1963/64	604	1.64	0.27	78.54	13.00	51.64	8.55
1973/74	762	8.28	1.08	141.33	18.55	88.30	11.59
Average	507	2.0	0.4	71.00	14.0	46.00	9.03

Table 4. Average annual runoff volumes and differences (m^3), for three development conditions

Conditions		Annual volumes (m^3) of runoff and differences: For 560 dunams (neighbourhood area)	For 1 km^2
A	Before development	1 132	2 022
B	After development	39 902	71 254
B–A	Difference	38 770	69 232
	Range of difference	15 568 to 74 508	27 800 to 133 050
C	After, with drains	25 629	45 766
B–C	Difference	13 141	23 466
	Range of difference	3 337 to 29 697	5 960 to 53 030

Rainfall records from the nearby Beit Dagan meteorological station were examined, and five years were selected, according to their total rainfall amount: one close to the long term average; two close to the upper and lower extremes; and two more in between (see Table 3). Three development conditions were considered: before development, with the entire area having CN = 49; after development, where all roofs and paved areas (impervious) have CN = 98; and after development with the roof drains connected to the garden/yard, adding their area to that of the cultivated area with CN = 39. The SCS method was applied for each condition, for each of the years, using storm depth data. The storm runoff values were then added up to yield the total annual runoff volume (expressed in m^3 and as mm over the entire area), and then converted into percentages of the annual rainfall (see Tables 3 and 4).

The average results for the five years show that prior to development only 0.4% of the rain became runoff (the range is 0% to 1.08%), and after development this increases to 14% (range: 7.8% to 18.55%), which is the same as the 10-15% value reported by Gerti *et al.* (1993, p. 17).

The water drained from the roofs is probably the cleanest, since it has not had a chance to flow over land, streets and parking lots. The flow from the roof drain may be directed into infiltration wells—underground cavities from which the water seeps into the ground, or is allowed to pile up temporarily in the yard and then infiltrate. Issues of safety, convenience and cost need to be considered when selecting the method. Table 3 shows that by connecting the roof drains to the ground, the runoff drops from 14% to 9%.

Table 4 summarizes the findings: average annual runoff volumes; difference between volumes before and after conventional urban development (average and range); and the difference that one type of water-sensitive facility can make. These results show:

- conventional development decreases surface runoff (which serves as an estimation of the reduction in recharge) by 69 000 m^3/ year /km^2 (range 27 800 to 133 050);

- connecting roof drains to the soil, and thus increasing the 'pervious' area (actually: impervious area the runoff from which is made to infiltrate) by 17%, reduces this loss by 34%, i.e. 23 500 m^3/year/km^2 (range: 5960 to 53 030).

Note that connecting the roof drains to the ground has a non-linear effect: the reduction in loss is double the increase in the 'pervious' area. This is due to the fact that when there is more pervious area it manages to capture completely, or almost completely, more of the small rainfall events, of which there are many, thus leaving less for runoff. These findings constitute a substantial incentive to increase the pervious areas, and/or to cause runoff from impervious areas to infiltrate into the ground.

Towards Water-sensitive Urban Planning

A planning team has been preparing, since 1990, a master plan for Israel into the 21st century. It includes forecasts of population and the built areas to the year 2020 (Mazor & Trop, 1994). According to these forecasts, the urban space in Israel's coastal plain of 2020 will be double its value in 1990. Taking the results computed for Kiryat Ganim and adjusting them to the entire area of the coastal aquifer according to these forecasts (70 000 m^3/year/km^2 X 1275 km^2, of urban areas in 2020) indicates that the lost infiltration will be about 90 000 mcm/year (another approach yielded much higher values). This is a very significant amount of water, in particular in the Middle East, where water shortage may have to be alleviated through expensive desalination.

Reducing this amount by water-sensitive planning will yield other benefits, especially a decrease in surface runoff which will enable reduction in the size and cost of the drainage systems. Needless to say, consideration must be given to the effect on groundwater quality of changing from the conventional to the proposed urban development scheme.

Sustainable development and preservation of water resources require a joint effort by researchers and planners to develop and implement guidelines for water-sensitive urban planning. On the basis of the literature survey and the results of the case study presented above, we contribute to this effort by: (1) identifying the relevant components of urban planning; (2) providing preliminary practical suggestions for planners; and (3) proposing a plan for further research.

Relevant Components of Urban Planning

Based on the work conducted so far, i.e. study of the literature and the investigation of Kiryat Ganim, we identify five components of urban planning which should be considered in connection with their effect on runoff and infiltration:

(1) *The proportion of built and paved areas versus open spaces (impervious versus pervious land cover) in common building patterns.* The impervious area includes roofs, parking spaces, and internal ways and roads. The building patterns determine the amount of impervious area. In the case of Kiryat Ganim we found that the amount of impervious area per household is 2.5 times larger in low density residential areas (3-4 housing units per dunam) in comparison to high density (9-10 units). This means that unless building patterns are changed, there is an advantage, from the point of view of the water

resources, to high density housing.

(2) *The distribution of open (pervious) spaces over the area.* It is not only the amount of pervious area that matters from the point of view of water, but also its spatial distribution. There are ways (which should be investigated before implementation) to 'break' the impervious area by patches and strips of pervious area, where water accumulated over the impervious part has a chance to penetrate into the ground, and thus reduce urban surface runoff and enrich infiltration.

(3) *Sub-division of the area into small 'micro' catchments.* Each building, with its small yard/garden and a low stone wall around it, can become an infiltration basin. The pervious parts can be designed to infiltrate the rain falling on it, as well as that brought from impervious parts of the lot. This reduces the losses to groundwater, and also decreases the load on the drainage system. The water thus captured is also less polluted, and the recharge is therefore more beneficial for the groundwater. This idea should be tested with consideration of climate conditions, soil characteristics and the modes of life of residents.

(4) *Incorporation into the urban fabric of facilities designed to intercept, detain and infiltrate water from precipitation.* Such facilities may be at several scales:

- the individual lot and building—stone walls around the yard, roof drains connected to the yard or to an attached infiltration well, open soil strips bordering on the impervious areas;
- the urban cluster (urban block)—swales along the paths and local roads, perforated drainage pipes, small detention ponds;
- the larger urban area and region—collection of runoff from an entire area and conveyance to a detention and infiltration facility.

(5) *Pervious paving materials.* Sidewalks, parking areas, paths, squares and in terior roads can be paved with pervious materials. In Kiryat Ganim 41% of the residential area (not including main roads) are paved; some part could be pervious, using porous asphalt or webbed structures. Such measures require further study and experimentation, to determine their efficacy. Of special interest is their effect on water quality, to make sure that their positive effects on quantity are not outweighed by the negative effects on quality.

Information about the effectiveness and cost of several facilities and means to reduce urban runoff and increase infiltration is available in the literature (Schueler *et al.*, 1992; Kennedy Engineers, 1992; Ishizaki *et al.*, undated; Fujita, 1992; Ferguson, 1994). We continue to assemble material describing such means, and to evaluate their effectiveness and feasibility as part of the urban fabric above a phreatic aquifer.

Preliminary Practical Proposals

Urban development is expected to continue, even over aquifers whose waters are important, because of the economic pressures which are usually much more powerful than the forces of preservation. Still, we hope that by identifying actions for preserving groundwater quantity and quality, which can be harmonized with urban development, the goal of sustainable development will be served.

Given the state of knowledge at this time, as revealed in our study, we cannot as yet provide well founded recommendations, even though such are urgently needed. We can, however, already make the following initial proposals:

(1) The public, the relevant authorities, urban planners and urban designers should be made aware of the opportunities for reducing the negative effects of urban development on groundwater quantity and quality.
(2) Open spaces, especially green tracts, should be interspersed in the area to be developed, in a manner which will allow as much of the surface runoff to be intercepted by pervious areas as possible (following further research we shall be able to be more specific).
(3) Wherever possible, rainwater should be captured on site, before it flows and becomes polluted; special attention should be paid to using yards as micro-catchments.
(4) In the first stage of planning of an urban area, the sensitivity of the area in terms of potential damage to groundwater should be assessed. The sensitivity assessment is intended:

- to identify small areas above phreatic aquifers which serve as important natural infiltration basins, due to specific topographical or geological structure, and to inhibit or limit construction above them;
- to identify larger vulnerable areas above phreatic aquifers, the soil of which is permeable and the quality of groundwater underneath them is high, and to direct the planners of their development to use the best knowledge available to them in order to increase infiltration and care for the quality of the infiltrated water.

Recommendations for Further Research

In order to found planning guidelines for water-sensitive urban development on a sound basis, much more research and study are required. Assembly of an adequate information and knowledge base requires years of field measurements and analytical studies. We should, however, not wait for these to be completed before issuing some recommendations which seem justified on the basis of what we can conclude in a shorter period of time. Urban development is progressing rapidly in many areas underlain by groundwater aquifers, and we must try to protect their waters while we continue to conduct further studies.

Hence, a two-phase strategy is proposed. The goal of the short term phase is to issue recommendations for water-sensitive urban planning, based on knowledge obtained from the studies already conducted and elicited from experts. The goal of the long term phase is to issue affirmative planning guidelines, based on valid and reliable empirical research that explains cause and effect relationships between urban land uses and groundwater quantity and quality, in addition to investigation of the technical, economic, social and administrative feasibility and effectiveness of the proposed guidelines.

The short term effort is based on existing knowledge—assembly of information, summary, analysis and conclusions on:

- the effect of different ratios of pervious areas in an urban zone, and especially their

spatial distribution (few and large or small and many), on the quantity and quality of surface runoff infiltrating into the ground;
- the effects of specific devices and facilities designed to increase infiltration of surface runoff, among them: stone walls around gardens that create a micro-detention and recharge basin; roof drains connected to the surface of the yard or garden, or to an underground 'recharge well'; pervious paving materials; pervious ('leaking') drainage pipes; small detention ponds (temporary or perm anent); temporary use of playgrounds as detention and recharge facilities.

For each one of these, the analysis should address two aspects:

- The effects on the water resource, on the environment, and on the urban landscape—how much additional water, and of what quality, will reach the groundwater; how will this affect the design and operation of the drainage system; what are the effects on the urban landscape. These conclusions should be relevant to other regions and countries, with similar conditions.
- Technical, economic, administrative and social feasibility of introducing a measure, installing a device or facility, and maintaining it—investigation of economic costs; the existence or absence of legal and administrative means for enforcement; and social feasibility both at the macro level (for example: allocating scarce land for the facility) and the micro level (e.g. tolerance of low level flooding around the houses, or a requirement to install and maintain a device in one's yard, etc.). Some of the conclusions may be specific to the location, while others may be more universal.

In parallel with the above plan for the short term, there is need for a concerted long term effort to improve knowledge and generate the information upon which policies can be based, with confidence. Empirical investigations must be a central element of this effort. The objective is to collect and analyse field data on the relationships between the tractable (independent) variables—land uses, building types, and facilities installed in the urban area—and the dependent variables—quantity and quality of runoff and groundwater, with appropriate attention to intervening variables such as meteorology and soil types. These tests must be conducted over periods of years.

Measurement facilities for surface runoff and its quality should be installed at the micro scale (several typical types of houses with their yard/garden), at the meso scale (urban block) and at the macro scale (large sections of the city). Location of the measuring stations and the frequency of measurement need careful planning, to maximize the benefit of the data gathered. Some information of this type has been collected in several places in the world; it should be assembled and analysed, to provide the initial basis for the data collection effort.

Groundwater quantity and especially quality should be measured directly by observation wells, in the unsaturated and saturated zones of the aquifer, to detect the influence of land uses and activities at the surface. Such monitoring systems require a dense network of wells, because of the local nature of the pollution, but do not need frequent measurements in time, since the processes are usually quite slow.

Models of urban hydrology should be modified, to incorporate the knowledge generated by the field studies. Most existing models have concentrated on surface runoff, and even those which compute infiltration directly (for example SWMM) do not deal fully with the effect of the spatial distribution of the pervious and impervious sub-areas and the effect of the temporal and spatial variability of rainfall on infiltration.

Concluding Statements

In this paper, we have concentrated on one main aspect of water-sensitive urban development, namely its effect on groundwater, especially on the quantity of infiltration. Other important aspects include: groundwater quality; effects on other water resources; water consumption in the area; effects on the drainage system; and impacts on the downstream environment.

We believe it is feasible to reduce substantially the negative effects of urban development on the quantity and quality of groundwater in aquifers underlying the area, maybe even bring about an improvement relative to conditions prior to urban construction. Agriculture has an adverse effect on groundwater, and conversion from agriculture to urban, a common occurrence in Israel's coastal plain as in many parts of the world, may provide an opportunity to improve matters for groundwater: increase recharge and reduce pollution.

Water-sensitive urban planning has the potential to be viable technically, economically and socially, and contribute to sustainable development.

Acknowledgement

The paper is an elaboration of the MSc thesis of the third author, supervised by the first two authors. We are grateful to many who have given their time and advice freely, to help us in locating information in Israel and abroad, and guide the research to fruitful avenues. Particular thanks are due to: Aryeh Ben-Zvi of the Israel Hydrologic Service; Rami Gerti, Moshe Getker and Shmuel Arbel of the Erosion Research Station, Ministry of Agriculture; Avner Kessler, consultant; and two anonymous reviewers. The research has been supported by the Israel Water Commission, and by the Fund for Promotion of Research at the Technion.

References

Atwood, D.F. & Barder, C. (1989) The effect of Perth's urbanization on groundwater quality—a comparison with case histories in the USA, in: G. Lowe (Ed) *Proceedings of the Swan Coastal Plain Groundwater Management Conference.*

Barringer, T., Dunn, D., Battaglin, W. & Vowinkel, E. (1990) Problems and methods involved in relating land use to groundwater quality, *Water Resources Bulletin,* 26(1), pp. 1-9.

Berry, B.J.L. & Horton, F.E. (1974) *Urban Environmental Management: Planning for Pollution Control* (Englewood Cliffs, NJ, Prentice Hall).

Christensen, S. & Rea, A. (1993) Ground water quality in the Oklahoma City urban area, in: W.M. Alley (Ed) *Regional Ground-water Quality* (New York, Van Norstrand Reinhold).

Eckhardt, D.A.V. & Oaksford, E.T. (1986) Nonpoint-source groundwater contamination relation of land use to groundwater quality in the upper glacial aquifer, Long Island, New York, in: *'National Water Summary* Water-Supply Paper 2325 (Washington, DC, US Geological Survey).

Ferguson, B.K. (1990) Urban stormwater infiltration: purposes, implementation, results, *Journal of Soil & Water Conservation,* 45, pp. 605-609.

Ferguson, B.K. (1994) *Stormwater Infiltration* (Boca Raton, CRC Press Lewis).

Ferguson, B.K. (1996) Estimation of direct runoff in the Thornthwaite water balance, *Professional Geographer,* 48(3), pp. 263-271.

Ferguson, B.K. & Debo, T.N. (1990) *On-site Stormwater Management Applications for Landscape and Engineering,* 2nd edition (New York, Van Nostrand Reinhold).

Fujita, S. (1992) Infiltration facilities in Tokyo: their purpose and practice, in: *Urban Stormwater Infiltration,* 5th European Junior Scientist Workshop, October (Klintholm Havn, Denmark).

Gerritse, R.G., Barber, C. & Adeney, J.A. (1988) The effects of urbanization on the quality of groundwater in Bassendean sands, in: *Report for Western Australia Water Authority* (Perth).

Gerti, R., Arbel, S. & Getker, M. (1993) Urbanization increases peak flows and runoff volumes: truth or myth? *Special Report No M-43* (Tel Aviv, Israel Ministry of Agriculture, Erosion Research Station) (Hebrew).

Harbor, J.M. (1994) A practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology, *Journal of the American Planning Association,* 60(1), pp. 95-107.

Hydrologic Engineering Center (1990) *HEC-1 Flood Hydrograph Package—User's Manual* (Davis, CA, US Army Corps of Engineers).

Herath, S., Musiake, K. & Hironaka, S. (1993) Evaluation of basin scale effects of infiltration systems, in: H. Torno & J. Marsalek (Eds) *Proceedings of the 6th Conference on Urban Storm Drainage,* September (New York, American Society of Civil Engineers).

Hirschberg, K. (1989) Groundwater contamination in the Perth Metropolitan Region, in: D. Lowe (Ed) *Proceedings of the Swan Coastal Plain Groundwater Management Conference.*

Ishizaki, K., Seiji, M, Kagawa, A., Mochizuki, T. & Imbe, M. (undated) Rainwater infiltration technology for urban areas, paper received from the authors (possibly from same conference as Fujita, 1992).

Kappen, P.M. (1993) *Planning for Water Source Protection* (Chicago, American Planning Association, Council for Planning Libraries).

Kennedy Engineers (1992) *Handbook of Best Management Practices for Stormwater Management and Erosion and Sedimentation Control* (Spokane WA).

Maidment, D.R. (Ed) (1993) *Handbook of Hydrology* (New York), McGraw-Hill).

Mazor, A. & Trop, T. (Eds) (1994) Spatial alternatives for Israel in the 2000s, *Report No. 21* of the Second Stage of Israel 2020—A Master Plan for Israel in the 2000s (Haifa, Technion—Israel Institute of Technology).

Melloul, A. & Bibas, M. (1991) Water quantities by qualities in Israel's coastal aquifer—identification of zones with low water quality for drinking and agriculture, and implications for management of the aquifer in 1992, *Hydrologic Report 4/1991* (Jerusalem, Hydrologic Service, Water Commission, Ministry of Agriculture) (Hebrew).

Melloul, A. & Goldenberg, A. (1993) Is a wet year (1991/92) also a plentiful year? The case of Israel's coastal aquifer (Jerusalem, Hydrologic Service, Water Commission, Ministry of Agriculture) (Hebrew).

Meiron-Pistiner, S. (1995) Water sensitive urban planning: towards planning guidelines, unpublished MSc thesis, (Haifa, Technion—Israel Institute of Technology, Urban and Regional Planning (Hebrew, with English abstract).

Ronen, D., Kanfy, Y. & Magaritz, M. (1986) Nitrogen presence in ground water as affected by the unsaturated zone, in: B. Yaron, G. Dagan & Y. Goldshmid (Eds) *Pollutants in Porous Media* (New York, Springer Verlag).

Schueler, T.R., Kumble, P.A. & Heraty, MA. (1992) *A Current Measurement of Urban Best Management Practices: Techniques for Reducing Non-point Source Pollution in the Coastal Zone* (Washington, DC, Metropolitan Washington Council of Governments).

Sheaffer, J.R., Wright, K.R., Taggart, W.C. & Wright, R.M. (1982) *Urban Storm Drainage Management* (New York, Marcel Dekker).

Singh, V.P. (Ed) (1995) *Computer Models of Watershed Hydrology* (New York, Water Resources Publications).

Soil Conservation Service (SCS) (1975) Urban hydrology for small watersheds, *Technical Release No. 55,* Washington, DC, US Department of Agriculture, Engineering Division, Soil Conservation Service.

Torno, H. & Marsalek, J. (Eds) (1993) *Proceedings of the Sixth Conference on Urban Storm Drainage,* September (New York, American Society of Civil Engineers).

Van de Ven, F. (1985) From rainfall to sewer flow: a process with consequences, in: *Water in Urban Areas,* Proceedings of Technical Meeting No. 42 (The Hague, TNO Committee on Hydrological Research).

Western Australia Water Authority (1987) *Perth Urban Water Balance Study: Executive Summary* (WAWA, Perth).

Water Sensitive Urban Design Research Group (1989) *Water Sensitive Residential Design: An Investigation into its Purpose and Potential in the Perth Metropolitan Region* (Leederville, Western Australia Water Resources Council).