Water-sensitive urban planning: the case of Israel's coastal aquifer

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Abstract Urban development above a phreatic aquifer can reduce substantially the amount of water that infiltrates and recharges the water resource. In Israel's coastal plain, the area of which is about 1900 km^2, 650 km^2 are already urban, and another 625 km^2 are expected to become urban by 2020. This paper presents the motivation, methodology and results of estimating the present and expected future loss of recharge to the aquifer, as a consequence of urban development above it. The paper ends with recommendations for implementing water-sensitive urban planning.

MOTIVATION: PROTECTING GROUNDWATER QUANTITY AND QUALITY

The coastal aquifer is Israel's largest reservoir, the only one that provides multi-year storage. It is a phreatic aquifer, under an area of 1900 km^2 in the coastal plain, a strip 10–30 km wide and about 130 km long, with a thickness ranging between 200 m close to the coast and tapering out at the eastern end. Average annual rainfall ranges over the area from 300 mm in the south to 700 mm in the north, with an area average of about 500 mm. Pumping has exceeded recharge for many years, causing a drop in water levels and seawater intrusion. More recently, pumping was reduced quite substantially, but has still not reached the long-term equilibrium value.

Much of Israel's urban development has taken place in the coastal plain; by 1990, some 650 km^2 had already been built, of which 250 km^2 are impervious (Carmon *et al.*, 1997). It is expected that the urban area will practically double by 2020, to an estimated 1275 km^2, with 500 km^2 impervious. Urban expansion is driven by economic and population pressures, and we do not expect that it will be dictated by considerations for protecting groundwater. The policy should therefore be to manage urban development in a manner which is least harmful to water resources. For several years we have been investigating what the benefits of such policy can be, and how the concept can be translated into practice. We gave this concept the title of "Water-Sensitive Urban Planning". In these studies we have combined our expertise in hydrology, urban planning, and water resources management with those of specialists in landscape architecture, water quality, soil properties, and the relevant laws and regulations. In this paper we present some of the results obtained so far, citing specific references in which more detail can be found.

SURVEY OF RECENT LITERATURE

Ferguson (1990) has been a leader in examining how stormwater can be managed to minimize the negative effects of urbanization on the hydrological cycle. Harbor (1994) computed the increase in runoff, using the SCS model, and equated it to the loss in infiltration, which was assumed to approximate the loss of groundwater recharge. The Western Australian "Water Sensitive Urban Design Research Group" (1989) evaluated the effect of urbanization on groundwater levels around Perth, and suggested ways to mitigate the negative effects. In the more humid regions of the world the main focus of stormwater management is on minimizing downstream flooding and preventing pollution of the receiving waters, using retention and detention on the watershed, thereby also reducing the size and cost of drainage systems. We found studies of these issues in Japan (Herath *et al.*, 1993), the northwest United States (Konrad *et al.*, 1995) and Britain (Bettes, 1996).

Runoff quality and its suitability for recharge is an issue that is still not resolved. Pitt *et al.* (1994) have examined the quality of urban runoff in an US Environmental Protection Agency study of potential groundwater contamination due to infiltration of urban runoff. Deletic & Maksimovic (1998) present analysis of water quality data collected on two 200+ m^2 street-watersheds in Yugoslavia and in Sweden. Much remains to be done in determining the quality of urban runoff at various points along its flow: roofs, drains, yards, gardens, sidewalks, roads, drainage systems. However, it is obvious that the quality is best close to where the rain falls, i.e. in the housing lot and its vicinity. Also, it should be borne in mind that often urban development replaces other land uses, frequently agriculture; in such cases, urban development may even improve the quality of runoff and infiltrated water.

In several countries, the studies have led to adoption of "good planning and development practice", intended to minimize the negative effects of urban development. In Japan (Herath *et al.*, 1993), the research was translated into regulations that require developers to provide a prescribed volume of storage per unit of developed area, for detention of stormwater. Infiltration facilities are required on individual housing lots, which receive rainwater from roof drains. In the UK (Bettes, 1996), there is a set of instructions for the construction industry, aimed at mitigating the negative effects of urban development on the hydrological cycle. In Prince George's County in Maryland, USA, a policy for low impact development (LID) was published, which seeks to minimize interference with the hydrological cycle; a design manual (1997) explains the rationale and presents planning procedures to be followed.

GOAL AND METHODOLOGY

This article presents part of a wide research study of water-sensitive urban planning, which has been conducted by the authors since 1993. The goal of this part was to estimate the present and expected loss of recharge to the Israeli coastal aquifer, as a consequence of the continuous urban development above it, in accordance with recent forecasts for the year 2020.

There is no practical way to measure directly the losses of infiltration due to changes in land use. We identified two indirect methods:

- The first is somewhat long with respect to land uses, but easy for hydrological calculations: assemble data on present and forecasted land uses over the aquifer (in terms of area), estimate the impervious areas—roofs and paved surfaces—for each land use, assume that all rainfall on these areas turns into runoff, of which an estimated 15% is trapped or evaporates, and the remainder runs into the drainage system and constitutes the loss to infiltration. The loss to infiltration will thus be 85% of the rainfall on the impervious area over the aquifer.
- The second method is more laborious for hydrological calculations: it requires estimating the loss of infiltration from a square kilometre due to urban development. This estimation is based on a combination of empirical measurement of land uses and impervious areas in selected representative urban areas, and calculation of the loss of infiltration in these areas by means of hydrological models, such as SCS or SWMM. Multiplying the calculated loss per developed km^2 by the number of existing and expected developed km^2 within and between the settlements above the aquifer, yields the desired result.

In our case it was possible to use both approaches, because we had the results of previous work, which provided the necessary data. For present and forecasted land use in the coastal plain we used data from "Israel 2020—Master Plan for Israel in Year 2000" (Mazor *et al.* 1996, in which N. Carmon participated.). For the impervious areas we supplemented this source by consultations with planners of housing projects, industries, roads, etc. Infiltration from open and built areas for selected locations in the Israeli coastal plain was taken from previous parts of our work on Water-Sensitive Urban Planning, already reported elsewhere (Carmon *et al.* (1997), with the SCS model; Kronaveter *et al.* (1999), with SWMM and a specially developed model—HMM).

Both approaches suffer from the same deficiency: the assumption that all rainfall on impervious surfaces, after evaporation and other minor abstractions, is drained away and constitutes a loss of infiltration. In reality, some of this runoff finds its way to pervious parts of the built areas or adjacent to them, and infiltrates. Therefore, the actual loss to infiltration may be lower than computed by these approaches. On the other hand, as urban development takes up more of the entire area, there are less open spaces for runoff from the impervious areas to infiltrate, so the above assumption becomes more appropriate. We weighed these factors, and decided to reduce by 30% the estimated loss of infiltration, as computed by the hydrological models.

RESULTS

Both approaches used to compute the loss of infiltration due to urban development require figures of current and forecast future land uses. The relevant findings are presented in Table 1, the situation in 1990 and the forecast for 2020, under the "business-as-usual" alternative, which means continuation of the 1990s development trends.

The conclusions from these data are: if current development trends continue, then between 1990 and 2020 the percentage of open space will be reduced from 65% to 33% of the 1900 km^2 (within the developed areas there are some open spaces, but each is small, less than 3 ha), and the impervious area will increase from 240 km^2 to 500 km^2.

Table 1 Land uses over the coastal aquifer and percent of impervious areas – 1990 and 2020.

	1990 Impervious areas %	1990 Impervious areas (km^2)	1990 Total (km^2)	2020* Impervious areas %	2020* Impervious areas (km^2)	2020* Total (km^2)	2020–1990 Added impervious areas (km^2)
Developed areas within settlements:			560.6			912.5	
Housing	43†	162.7	376.7	52†	331.0	631.5	168.3
Other	29†	53.7	183.9	30†	83.8	281.0	30.1
Developed areas between settlements:			95.2			362.7	
Engineering and industrial facilities	40	13.0	32.0	40	25.5	63.6	12.5
Roads and railways	20	12.6	62.5	20	59.8	299.1	47.2
Undeveloped areas within and between settlements			1245.8			626.8	
Protected open space	0	0	97.5	0	0	97.5	
Cultivated agricultural land	0	0	929.3	0	0	361.8	
Unused open spaces	0	0	218.8	0	0	167.4	
Total area over the coastal aquifer		242.0	1900.0		500.1	1900.0	258.1

* The figures for 2020 are for development according to trends of the 1990s (what was called the Business-as-usual" alternative in "Israel 2020" project).

† The percentages are weighted averages, based on higher values in the Tel Aviv District and lower ones in the remaining areas.

Calculation according to the first method was simple, once we had the impervious area figures. Allowing 15% of the 500 mm year^{-1} rainfall for abstractions, yields an infiltration loss of 425 mm year^{-1} over impervious areas. The computed loss of infiltration is 103×10^6 m^3 year^{-1} over 242 km^2 of impervious area in 1990, and 212×10^6 m^3 year^{-1} over 500 km^2 in 2020.

Calculation according to the second method was longer. The SCS and SWMM models were run for real land use data from a neighbourhood in the coastal plain of Israel, with average rainfall for the area and average soil permeability, using a range of rainfall years. This neighbourhood includes areas with various housing densities (units per area), open spaces, roads and community services, all typical of Israeli patterns of urban development of the 1990s. The SCS model gave an annual loss to infiltration of 70 000 m^3 km^{-2} (Carmon *et al.*, 1997) while the SWMM model gave 240 000 m^3 km^{-2} (Carmon & Shamir 1997b, Kronaveter *et al.*, 1999). We tried to reconcile the sizeable differences between the two results. Our considerations included: (a) The SCS runs were conducted with daily rainfall and not by storms, as recommended in the manual; we therefore ran the model with storm data, and the results changed only slightly. (b) The neighbourhood was divided into 19 sub-basins for the SCS model and into six for SWMM; running SCS with six sub-basins instead of 19 explained part of the difference. (c) The SCS model was run, as recommended in the manual, by first averaging the CN numbers over the land uses in each sub-basin, and then calculating the runoff. According to another approach (Carmon & Shamir, 1996), the runoff from each land use is computed with its own CN number, and the total runoff is the weighted average by the relative part of each land use. Such calculation results in a considerably higher runoff volume.

Considering all the above, we decided to use 160 000 $m^3 km^{-2}$ as a representative value of losses due to urban development. Hence, the lost infiltration is $105 \times 10^6 m^3 year^{-1}$ over 656 (= 560.5 + 95.2) km^2 of developed area in 1990, and $204 \times 10^6 m^3 year^{-1}$ over 1275 (= 912.5 + 362.7) km^2 in 2020.

Thus, the results by the two methods are quite similar: the current loss is about $100 \times 10^6 m^3 year^{-1}$ and it will reach about $200 \times 10^6 m^3 year^{-1}$ in 2020. As stated earlier, we decided to reduce the calculated results by 30%, and therefore presented the figures $70 \times 10^6 m^3 year^{-1}$ and $150 \times 10^6 m^3 year^{-1}$ for 1990 and 2020, respectively.

We then estimated the economic value of this lost water. The lowest value assigned is 20 cents m^{-3}, reflecting return on water in agriculture (a figure which is relatively low in Israel). The highest value would be that of replacing the water by the most expensive means, namely desalination, taken as 65 cents m^{-3} (a low figure for current desalination technology). These calculations are summarized in Table 2.

Table 2 Losses of water, and their financial value, due to urban development over Israel's coastal aquifer, in 1990 and 2020.

Year	1990	2020
Loss of infiltration ($10^6 m^3 year^{-1}$)	70	150
Loss of value (10^6 \$ of 1990 per year)	15-45	30-100

The annual loss of water is very large in terms of the Israeli water potential. It also results in a large economic loss. Moreover, the calculation of economic value was related to water quantity alone. One should add the deterioration in water quality by urban development and the high costs of drainage systems constructed to remove urban runoff. These losses, which are expected to grow significantly, provide the rationale for continuing our work on water-sensitive urban planning.

FURTHER RESEARCH AND GUIDELINES FOR IMPLEMENTATION

We distinguish three levels at which research and "good practice" of water-sensitive urban planning can and should be exercized: macro, mezzo and micro. "Macro" is the scale of the whole city, or a major section of it, for which large infiltration facilities may be considered. Competition from other land uses, in particular urban development itself, precludes such macro projects in Israel's coastal plain. Even if in certain areas it may still be possible to find land for such infiltration facilities, this will become impossible in the near future.

The "mezzo" scale is the urban block and neighbourhood; we shall return to it towards the end of this paper. At the "micro" scale we find the individual building lot. We have concentrated our work on this scale as part of adopting the concept of "on-site" infiltration, i.e. capturing rainwater as close as possible to where it falls, in order to infiltrate the largest quantities possible of the cleanest runoff. Our work took two directions: developing a hydrological model especially suitable for this scale, the HMM model (Kronaveter, 1998), and developing good practice guidelines for planning and design of individual yards and gardens so that they enable maximum infiltration.

The HMM model follows the approach of. It performs continuous simulation of the hydrological processes on a roof and the adjacent yard, and the runoff to the drainage system. It enables evaluation of various options for increasing infiltration on site.

While the hydrologists focused on developing the HMM model, the urban planners and landscape architects concentrated on issues of planning and design at the micro level. The main conclusion is that it is feasible and recommended to convert the yards of individual buildings into "micro-basins", by properly shaping the ground or with a low-rise solid wall around the yard, as is already common in some communities. Calculations with HMM, show that under the conditions prevailing in Israel's coastal plain micro-basins can trap and infiltrate all or most of the rainfall that falls on the entire lot, on both its pervious and impervious parts. To accomplish this, some guidelines of good practice should be followed:

- Leaving about 15% of the lot pervious—under the conditions in Israel's coastal plain (construction patterns, rainfall, soil types) it is possible to infiltrate practically all the rainfall by leaving 15% of the lot pervious.
- Roof drains should be directed to the pervious areas in the yard. By this means alone it is possible, according to our calculations for the coastal plain of Israel, to reduce by one-third the losses to infiltration.
- The soil in the yard should be kept as pervious as possible, aiming for a saturated permeability of 30 mm h^{-1} or more, by removing debris and fines, avoiding compaction, and possibly using mulching or similar means.
- Slopes should be kept gentle and direct water flow towards the pervious areas of the yard.
- Appropriate design of the vegetation in the garden.
- Installing infiltration ditches or wells—experience in some countries shows positive results. We are currently looking into the suitability of such methods in the Israeli context, in particular in older housing areas where lots cannot be re-planned according to the rules proposed above.

As stated, we continue our work on water-sensitive urban planning. We have recently begun an evaluation of the mezzo scale, at which public areas within the neighbourhoods can be used to enhance infiltration.

Our efforts parallel those in several other countries, among them: UK (Bettes, 1996), Japan (Herath *et al.*, 1993), US (Konrad *et al.*, 1995; Prince George's County, 1997), Australia (The Water Sensitive Urban Design Research Group, 1989), and Yugoslavia (Deletic & Maksimovic, 1998). Collaboration with colleagues in other locations adds to the knowledge-base, and strengthens our joint position that:

in water-scarce areas, urban runoff should be viewed as a resource, not a nuisance.

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