WATER-SENSITIVE URBAN PLANNING: MODELING ON-SITE INFILTRATION

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ABSTRACT: A hydrological micromodel was developed and applied to a neighborhood typical of urban development on Israel's coastal plain, over the phreatic coastal aquifer. The model was used for analyzing the effects of urban development on infiltration and runoff, and for evaluating a number of practices designed to enhance on-site infiltration. The effect of spatial resolution in the model on computed results was investigated. It was shown that for the range of data examined, simulation at the micro- (residential lot) level can be extrapolated to the neighborhood scale, by adding the responses of the individual microunits. Simulations by the hydrological micromodel showed that connecting roof drains to a yard/garden, and allowing the runoff from the roof to infiltrate through an "infiltration strip" or infiltration trench of an appropriate size, can increase infiltration over a residential lot as much as 18% of the annual rainfall (depending on the soil conductivity and annual rainfall). The dependence of annual infiltration on physical and planning parameters was generalized in functional relations that can be used to assess the effectiveness of measures for increasing infiltration and reducing runoff. This work was part of an effort to develop, test, and recommend policies and practices for water-sensitive urban planning for protecting water resources.

INTRODUCTION

In many places around the world urban development occurs over phreatic aquifers that are used as an important water resource. Extensive pumping from the aquifer, reduced recharge due to urbanization, and the pollution caused by human activities result in a negative impact on the quantity and quality of the ground water. Such situations are found in Long Island, N.Y. (Eckhardt and Oaksford 1986), along the California coast (Reichard 1995), Perth in western Australia (WAWA 1987; The Water 1989), the coastal plain in Israel (Carmon et al. 1997), and in the Gaza Strip. The loss of ground-water resources is of particular concern in arid and semiarid regions.

Urban development adds impervious surfaces, and therefore, increases surface runoff and decreases infiltration. Further recharge losses stem from flood control projects in which, it is common to construct a drainage system that quickly removes the runoff from built areas, and tunnels it to a waterway or the sea. Consider Israel's coastal plain, which covers 1,900 km^2 and overlies the phreatic coastal aquifer, Israel's most important over-year water reservoir. In 1990, 650 km^2 (34%) were developed areas within and between cities while 1,250 km^2 were still open. In the developed areas, some 240 km^2 were impervious (roofs, paved surfaces). It has been projected that in 2020 the developed area will almost double to 1,275 km^2 (67%, with 500 km^2 impervious) while only 625 km^2 will remain open. Our early analysis (Carmon and Shamir 1997a,b) indicated that the increase in annual runoff due to conventional urban development in this region is between 71 and 240 mm (14–47% of the annual rainfall, depending on the model used). It was also estimated that by connecting roof drains to the ground about 30–35% of this loss could be saved.

This paper focuses on protection of ground-water resources through on-site infiltration—capturing water close to the place where the rain falls, on the housing lot itself, and infiltrating it into the ground. We term this the microscale. At a larger scale, such as a neighborhood or the city as a whole, it is necessary to find space to locate large infiltration facilities, and we deem this to be impractical in most urban areas along the Israel coastal plain.

MICROSCALE ON-SITE INFILTRATION FACILITIES

There are few types of facilities that can be used for enhancing the infiltration on the microscale. Infiltration trench is used as an underground reservoir in which the rainwater is stored and infiltrates through its bottom and sides into the surrounding ground. Grassed swale can be used for conveyance of the runoff from impervious surfaces. It is a trench whose bottom and sides are pervious and covered by grass and through which the rainwater infiltrates while flowing in the trench. A filter strip is a strip of land covered by grass. It is used for capturing the rainwater from impervious surfaces when the overland flow velocities are low. Combination of such velocities and grassed cover enable the infiltration of the rainwater into the ground while a part of storm water pollutants stay on the ground surface (Schueler et al. 1992). Permeable underground pipe is a perforated pipe made of ceramics or concrete and used for storm water conveyance and infiltration (Fujita 1992).

From a literature survey and reports on field measurements we concluded that the quality of the water on-site is suitable for recharge to an aquifer used for potable purposes, and the farther from the lot one goes the more polluted the water becomes [U.S. Environmental Protection Agency (USEPA) (1983); Pitt et al. (1994, 1995)]. On-site infiltration therefore has the potential of maintaining ground-water quality, or at least reducing the degree of ground-water contamination.

Objectives of capturing and infiltrating runoff include reduced runoff and cost of drainage (Fujita 1992; Herath et al. 1993; Konrad et al. 1995a,b), reduced water consumption for garden irrigation, enhancement of a green urban environment, ease of implementation within the housing lot as compared to larger central infiltration facilities, and public participation in the implementation. Arguments against the microapproach are potential for increased flooding within the yard itself, flooding or wetting of basements, and reduction in beneficial watercourse flows downstream (Ferguson 1994).

In an earlier phase of this project (Carmon et al. 1997; Carmon and Shamir 1997a,b) the analysis was performed at the macroscale, and the annual infiltration and runoff were computed by the Soil Conservation Service (SCS) method (Harbor 1994) and the Storm Water Management Model (SWMM)

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(Huber 1988). The results of the two approaches were quite different (Carmon and Shamir 1997, p. 109). We conclude that while the results can be considered indicative and warrant continued study, a more refined model is required for the mezzoscale and definitely for the microscale on which we concentrate. We have therefore developed and tested the hydrological micromodel (HMM), which is the subject of this paper. HMM is in the same ''family'' of models as SWMM (Huber 1988; Singh 1995). The HMM is described and used for

- Computing the hydrological response of a typical urban catchment
- Investigating the effect of the spatial resolution used in the model on its results
- Analyzing a few means for increasing on-site infiltration
- Establishing functional relationships between annual infiltration and rainfall and physical characteristics of the urban catchment for the cases analyzed

BASIC APPROACH

An urban neighborhood includes several land uses such as residential lots, sidewalks and roads, public areas (such as schools and parks), shopping and community centers, and industries. We concentrated on the residential lots, together with the relatively small public areas interspersed among them and the adjacent sidewalks and roads. Large public areas, commercial, and industrial complexes deserve separate attention and are the topic of ongoing research. The model has been applied at three spatial scales: (1) The individual residential lot (micro); (2) a cluster of residential lots and their immediate vicinity (mezzo); and (3) a whole neighborhood (macro).

The residential lot contains the building, the paved impervious areas, and the pervious areas that can be a garden or just open land. On-lot parking is part of the impervious or pervious area, depending on how it is made (it is usually impervious). The public areas adjacent to the residential lots include small parks and public buildings (schools, services, commerce), sidewalks, and streets.

The objective of the work was estimation of the total annual losses of the rainwater due to increased pervious surfaces in urban residential areas, and the potential increase in annual infiltration resulting from various storm water management solutions. Thus, we performed continuous rainfall-runoff simulations of only rainy periods in a year. In the Israel coastal plain, this period lasts from October to April, with an average annual rainfall of about 550 mm. Rain intensities are mostly below 20 mm/h, with occasional values as high as 75–80 mm/h. Saturated hydraulic conductivity of the soil in this area rarely exceeds 30 mm/h. In order to account for the effect of high rain intensities (which usually last only few minutes) on infiltration, a 5-min interval was selected for simulation of the rainfall-runoff process during rain events. Overland flow as well as subsurface drainage and soil moisture redistribution between successive rain events was simulated at 1-h time intervals.

Hydraulic computation of flows on the streets and in the drainage system was not included in the rainfall-runoff model. The reason is that our objective was on-site infiltration, not design of the drainage system, for which the model could be extended by including a module for drainage system simulation. The hydrologic response is thus expressed by volumes of water (per 5-min interval, integrated over time to yield annual quantities), not by discharges.

The rainfall-runoff simulations were carried out with data for rain seasons of two hydrologic years (period from October to April) recorded in Israel's coastal plain (data taken from Bet Dagan meteorological station). The first year (1991–1992) is of an extremely high annual precipitation (968 mm) while the second year (1963–1964) is somewhat above the annual average (605 mm).

The model was based on the following assumptions:

1. The residential lot is considered a ''microcatchment,'' separated from the neighboring lots, from the sidewalk and the street by its topography (water divide) or by a structure (wall). The topography of the lot is such that surface runoff flows only in the direction of the sidewalk or street; it does not flow from one lot to another.
2. Urban neighborhoods can be divided into ''clusters'' which are groups of residential lots of the same type—the same shape of the building, pervious-impervious area layout, topography, and other relevant parameters. The clusters also include the inner pathways and sidewalks, and optionally, a small public service area.
3. The hydrologic responses of residential lots of the same type are identical.
4. The topography and street design in an urban neighborhood are such that once the runoff from a residential lot reaches the street, it flows toward the nearest inlet of the sewer system. In the case of a surcharge of the sewer system, the runoff is accumulated on the street area, and does not flow back to the residential lot, or to any other area where it can infiltrate.

The consequence of these assumptions is that the computed hydrologic response of an area that consists of n residential lots of the same type is equal to the sum of n hydrologic responses of a single residential lot. The hydrologic response of a cluster is the sum of the hydrologic responses of all its component areas (lots, streets, public areas). The hydrologic response of the whole neighborhood is the sum of the responses of all its clusters, streets, and public areas (again, the term ''hydrologic response'' relates only to the quantities of the surface runoff and infiltrated and evaporated water).

HMM

HMM is a rainfall-runoff model that simulates the following processes (Fig. 1):

- Transformation from the total rain to the ''effective'' rain, which becomes surface runoff, by subtracting the ''losses''—water trapped in the depression storage on pervious and impervious areas, infiltration, and evaporation
- Flow over pervious and impervious surfaces that transforms the effective rain into the input hydrograph to gutters and pipes, or to an infiltration facility, if it is introduced
- Flow into and from facilities used to increase infiltration, such as a ditch

Even though these processes are interconnected, they can be modeled separately. The only exception would have been the case when a drainage pipe is surcharged, and some of the water is released back into the streets, creating a backwater effect. Since the results of interest in this study are not affected by such cases (see the assumptions above) it is possible to compute the processes independently. The model enables simulation of a single rain event as well as a continuous simulation over time.

Any area that appears in the model as a separate hydrological unit is represented by a rectangle with a sloping length and a width. The units can be connected in any desired order; for example, an impervious unit may discharge onto a pervious one or be connected directly to the drainage system.

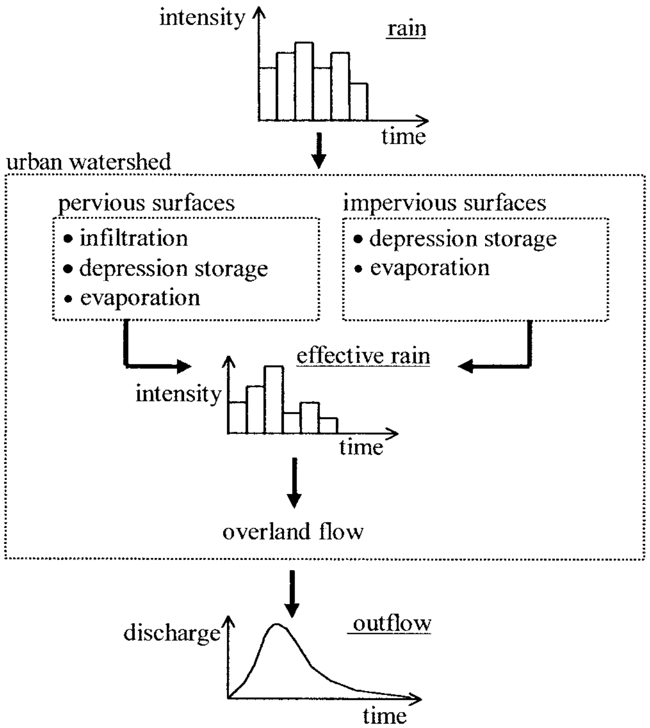

FIG. 1. Basic Components of Hydrologic Processes in Urban Catchment

HMM has been programmed in the MATLAB software package and consists of three submodels:

1. The land model accounts for evaporation losses, and calculates the evaporation and infiltration, the overland flow over pervious areas (gardens, public parks, etc.), and over impervious areas (streets, pavements, and other paved surfaces).
2. The roof model accounts for evaporation losses, and calculates the evaporation and the outflow from a roof through a drain.
3. The trench model simulates the infiltration process and outflow from an underground infiltration facility.

In the land and roof models, the evaporation is accounted for by subtracting the evaporation rate from rain intensity in every time step of simulation. The models use daily averages of hourly evaporation rates (which is the only data available), and prorate them to appropriate time intervals.

Infiltration in pervious units is computed in two stages: (1) Prior to saturation of the ground surface; and (2) after saturation, based on the Green-Ampt equation (Mein and Larson 1973). For each time increment during which the rainfall intensity i is taken as constant, the actual infiltration rate f is given by

$$\text{if } F < F_s \quad \text{then} \quad f = i$$

$$\text{and} \quad \text{if } i > K_s \quad \text{then} \quad F_s = \frac{S \cdot IMD}{i/(K_s - 1)}$$

$$\text{and} \quad \text{if } i \le K_s \quad \text{then} \quad \text{No calculation for } F_s \qquad (1)$$

$$\text{if } F \ge F_s \quad \text{then} \quad f = f_p \quad \text{and} \quad f_p = K_s \cdot \left(1 + \frac{S \cdot IMD}{F}\right) \qquad (2)$$

where F = cumulative infiltration volume since the beginning of the rain event (mm); F_s = cumulative infiltration volume required for ground surface saturation (mm); i = rainfall intensity, constant over the time step (mm/h); f_p = infiltration capacity (mm/h); f = infiltration rate (actual) (mm/h); S = capillary suction at the wetting front (mm of water); IMD = initial moisture deficit of the soil, for the rain event (mm/mm); and K_s = saturated hydraulic conductivity of the soil (mm/h).

The infiltration model describes conditions in the uppermost soil layer. It simulates subsurface drainage and redistribution of soil moisture in this layer between successive rain events. The thickness of the layer is a function of soil type and is determined empirically (Huber 1988). The infiltration simulation was verified by comparison with the results published by Mein and Larson (1973).

Overland flow simulation is based on a combination of Manning's equation and the mass-balance equation for a nonlinear reservoir (Huber 1988)

$$Q = \frac{W \cdot \sqrt{s}}{n} \cdot (d - d_p)^{5/3}; \quad \frac{dV}{dt} = i^* \cdot A - Q \qquad (3a,b)$$

where Q = outflow rate (m^3/s); W = width of the catchment (m); s = catchment slope (m/m); n = Manning's roughness coefficient; d = water depth (m); d_p = depression storage (m); V = volume of the water in the catchment (m^3); i^* = intensity of the effective rain (m/s); and A = catchment area (m^2). The two equations are coupled, and the instantaneous outflow from the catchment is calculated as a function of the water depth at the end of each time interval.

Flow along the roof and through a downspout is simulated by a reservoir with a single outlet weir. Each roof area of 100 m^2 has a rectangular outlet weir 0.314 m in width. The outlet dimension equals the circumference of a 10 cm diameter downspout, assuming a control section at the downspout entrance. The outflow is given by

$$Q_{out} = 1.84 \cdot W \cdot (H - H_0)^{3/2} \qquad (4)$$

where Q_{out} = outflow from the reservoir (m^3/s); W = length of the weir (m); H = water depth (m); and H_0 = height of the weir (m).

The continuity equation is

$$\frac{dV}{dt} = Q_{in}(t) - Q_{out}(H) \qquad (5)$$

where V = volume of water in the reservoir (m^3); Q_{in} = inflow to the reservoir (rainfall, as a function of time) (m^3/s); and Q_{out} = outflow from the reservoir (as a function of water depth) (m^3/s).

The trench model simulates infiltration through a trench which is usually lined with filter fabric and backfilled with a free-draining material such as washed rock (Konrad et al. 1995a,b). Infiltration from the trench depends on several factors, including the depth of water in the trench, the saturated hydraulic conductivity of the surrounding soil, distance to the water table, and antecedent moisture condition. The trench receives flow directly from a roof drain, and infiltration occurs through the following:

- Infiltration through trench bottom: The computation used is based on the same equations as the infiltration model. The only difference is in the calculation of the total potential under saturation conditions. In the Green-Ampt model for infiltration over an open area, the depth of the water above the soil surface is neglected and the total potential at the soil surface is zero. In the case of an infiltration trench, the total potential at the ''soil surface'' (the bottom of the trench), is equal to the water depth in the trench. Thus, the expression for the infiltration capacity f_p under saturation conditions in the soil below the bottom of the trench is:

$$f_p = K_s \cdot \left(1 + \frac{(S + H) \cdot IMD}{F}\right) \qquad (6)$$

where H = depth of the water in the trench; and the other parameters are as in (1) and (2).

- Infiltration through trench sides: According to experimental and computational results of other researchers, approximately 1/4 of the water infiltrates from a trench through its sides and 3/4 through the bottom (Duchene et al. 1994). The computed infiltration through the bottom was therefore multiplied by 4/3. The water depth is updated at the end of each time period.

EFFECT OF SPATIAL RESOLUTION IN MODEL

HMM was used to investigate the effect of the spatial resolution in the model on the computed annual quantities of runoff and infiltration. The investigation was carried out using a ''synthetic'' urban neighborhood, depicted in Fig. 2, similar to residential neighborhoods currently being constructed in Israel's coastal plain (Carmon and Shamir 1997a,b). The neighborhood consists of three clusters of residential lots, two separate public areas, and streets. Each cluster includes a number of residential lots of the same type, a small public area, and inner streets. The characteristics of the clusters and residential lots are given in Tables 1 and 2. HMM does not model flow in the drainage system itself.

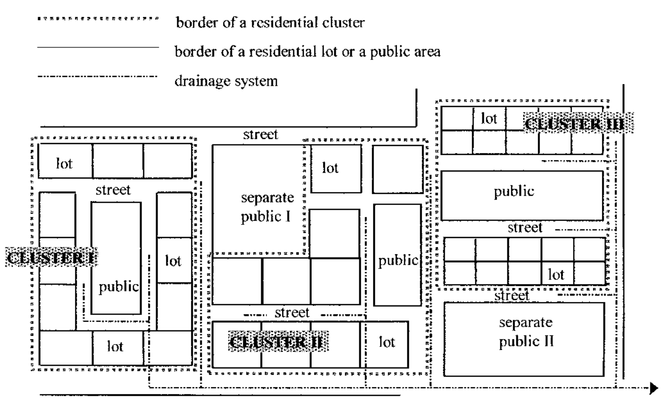

FIG. 2. Synthetic Urban Neighborhood

Rain intensities and evaporation rates are obtained from Bet Dagan meteorological station, situated nearby. All input data are adjusted as follows:

1. Rain intensities (mm/h) at 5-min time intervals are obtained from a time series of cumulative rainfall depth data during rain events, in the two selected rain seasons.
2. Available evaporation data were monthly averages of cumulative daily (24 h) evaporation. The average of these values (which ranged from 2 to 5 mm/day) was calculated for the period October–April, and then divided by 24 to obtain the average hourly rate of evaporation. Evaporation rates for day and night times were not available. There is no indication that storms in Israel occur more frequently during day or night, so the assumption was that they are evenly distributed over days and nights. The daily average of hourly evaporation rate balances higher evaporation rates during daytime with lower rates during nighttime, so that there should be no significant error in the bulk model results.

The natural soils in Israel's coastal plain range from very low permeability gromosols, through medium permeability loam, to very permeable sands. In the residential areas, the texture and infiltration characteristics of the upper layer are altered by mixing of fines and compaction during the construction of the buildings and over the years. In the absence of reliable field data, it is difficult to estimate the actual infiltration properties. Therefore the analysis is performed for a wide range of saturated hydraulic conductivity K_s = 3, 15, 30, 60,

TABLE 1. Impervious and Pervious Areas in Catchment

Land use (1)	Area (m^2) (2)	Impervious (percent) (3)	Impervious (m^2) (4)	Pervious (percent) (5)	Pervious (m^2) (6)
Cluster I					
Residential	12 × 1,100 = 13,200	50	6,600	50	6,600
Public	5,000	70	3,500	30	1,500
Inner streets	2,800	100	2,800	0	0
[Subtotal]	21,000	61.43	12,900	38.57	8,100
Cluster II					
Residential	10 × 2,500 = 25,000	60	15,000	40	10,000
Public	4,300	60	2,580	40	1,720
Inner streets	2,000	100	2,000	0	0
[Subtotal]	31,300	62.56	19,580	37.44	11,720
Cluster III					
Residential	40 × 200 = 8,000	60	4,800	40	3,200
Public	4,000	70	2,800	30	1,200
Inner streets	2,700	100	2,700	0	0
[Subtotal]	14,700	70.07	10,300	29.93	4,400
Public I	10,000	60	6,000	40	4,000
Public II	20,000	20	4,000	80	16,000
Streets	18,000	100	18,000	0	0
[Total (neighborhood)]	115,000	61.55	70,780	38.45	44,220

TABLE 2. Pervious and Impervious Areas in Residential Lots

Lot type (1)	Area (m^2) (2)	Pervious (garden) (m^2) (3)	Pervious (garden) (percent) (4)	Roof (m^2) (5)	Roof (percent) (6)	Paved (m^2) (7)	Paved (percent) (8)
I	1,100	550	50	275	25	275	25
II	2,500	1,000	40	750	30	750	30
III	200	80	40	80	40	40	20

and 100 mm/h—which certainly covers the actual values. Corresponding values of two other parameters needed for the Green-Ampt infiltration model ranged from 0.34 to 0.41 mm/mm for the maximum value of the initial soil moisture deficit, and from 102 to 780 mm for the soil suction head (Huber 1988).

Two runoff management alternatives were examined:

1. All impervious areas are connected directly to the drainage network—runoff from roofs, pavements, and other paved areas flows directly to the street, toward the nearest inlet of the drainage system.
2. Roof drains are connected to the pervious area of the lot—runoff generated over the roof areas of residential buildings flows to the pervious part of the residential lots (roof drains are connected to the surrounding garden). The impervious areas of the public zones drain directly to the streets or to the drainage network.

Simulations were performed for the following three levels of the spatial resolution (Fig. 3):

1. Macrolevel [Fig. 3(a)]: The entire neighborhood is taken as one catchment, made of two parts: (1) Pervious—Open areas within the housing lots, public parks, and other open areas; and (2) impervious—Roofs, paved surfaces, and streets. The hydrologic response of the neighborhood is calculated as the sum of the responses of these two parts.
2. Mezzolevel [Fig. 3(b)]: The neighborhood is divided into six subcatchments: (1) Three clusters; (2) two public areas; and (3) the street area. The response of each subcatchment is the sum of the responses of its pervious and impervious parts. The hydrologic response of the whole neighborhood is the sum of responses of all subcatchments.
3. Microlevel [Fig. 3(c)]: Each residential lot or a public service area within a cluster represents a ''microsubcatchment.'' Street area within a cluster is also a separate, impervious subcatchment. Two additional public areas and the street area of the neighborhood represent separate subcatchments as in the mezzolevel. The response of one residential lot of each type is calculated and multiplied by the number of such residential lots in the neighborhood. The hydrologic response of the whole neighborhood is the sum of the hydrologic responses of all of its subcatchments. Each unit is schematized in the model as a rectangle. By default, it is assumed that runoff does not cross the border between pervious and impervious areas during the overland flow (except in cases when it is especially designed otherwise). Therefore, these rectangular areas can be considered separate subcatchments.

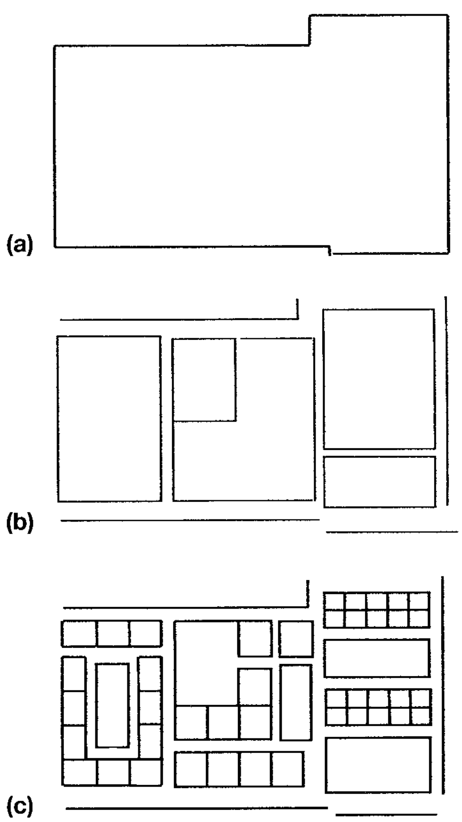

FIG. 3. Three Levels of Spatial Resolution: (a) Macro; (b) Mezzo; (c) Micro

Values of the model's parameters were selected to characterize a typical residential neighborhood in Israel's coastal plain: (1) Longitudinal slope of each rectangle s = 2%; (2) Manning's overland flow coefficient n = 0.2 for pervious surfaces and n = 0.014 for paved surfaces (sensitivity analysis performed for the range of Manning's coefficient values typical for pervious and impervious surfaces, showed that this parameter has no significant effects on the model results); and (3) depression storage d_p = 2.5 mm for pervious surfaces and = 0.5 mm for impervious surfaces.

At all levels of spatial resolution, each subcatchment consists of pervious and impervious parts. For a subcatchment of a given area, its length, slope, and roughness are the parameters that define the concentration time of flow. For fixed slope and roughness, the length can be used as a calibration parameter. To some extent this parameter affects the quantities of infiltrated and evaporated water that take place during flow over the length. At the microlevel, where subcatchments are very small, these effects can be neglected. Thus, for this level, the subcatchment's length is taken equal to the square root of its area. The length of subcatchments on mezzo- and macrolevels is equal to the maximum length of the overland flow.

Results

Alternative 1—In the case of all impervious surfaces directly connected to the drainage network, the simulations were performed with the roof and land models for the microlevel and with land model for the mezzo- and macrolevels.

Alternative 2—For the microlevel, the alternative with roof areas draining to pervious surfaces is simulated with the roof model, by connecting each 100 m^2 of the roof to a pervious ''infiltration strip'' in the lot, 1 m wide. This ''strip'' is assumed to approximate the shape of the outflow from a roof drain onto the open ground, without special facility for injecting it into the soil. The analysis was done for a 5 m long strip (Case a) and one 10 m long (Case b), to test the sensitivity of the results to the area of the infiltration strip.

For the mezzo- and macrolevels, the simulations for the impervious area were performed by the land model. First, the surface runoff was computed for the whole impervious area, including the roof. Next, the runoff from the roofs alone was obtained by multiplying this value by the ratio of roof area to the total impervious area. This runoff from the roofs was then added to the rainfall, as input to the land model for simulation of the response of the pervious surface in the subcatchment. This amounts to assuming that the water from the roofs is distributed evenly over the area outside the roof.

For a single residential lot the simulations were carried out for all three lot types. Results are shown in Fig. 4 for the lot

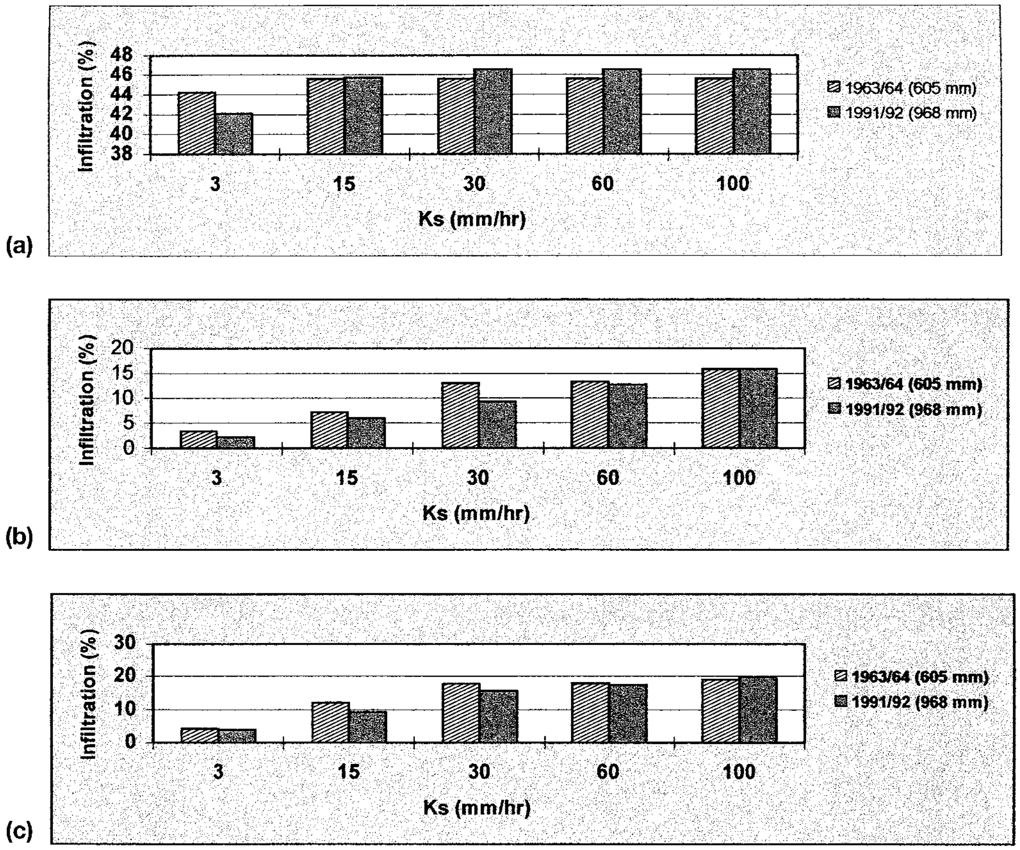

FIG. 4. Annual Infiltration over Residential Lot with 50% Pervious Area and 25% Roof Area (Type I) for Two Hydrologic Years, as Function of Soil Permeability: (a) Annual Infiltration; (b) and (c) Increase in Annual Infiltration

with 50% pervious surface and 25% roof area (Type I in Table 2).

The results for the three cases are: Case a—Infiltration (percent of rainfall) when all impervious surfaces drain directly to the drainage system; Case b—Increase in infiltration (percent of rainfall) when the roof area is connected to infiltration strips 1 m × 5 m; and Case c—Same as Case b with strips 1 m × 10 m. The maximum percentage of rain that can infiltrate into the ground when impervious areas are connected directly to the drainage system, is simply equal to the percent of the pervious part of the lot minus the percent of evaporation. This maximum infiltration has been reached with soils of K_s 15 mm/h, perhaps slightly higher for a very wet year. The conclusion is that for the meteorological conditions in Israel, a soil with K_s = 15 mm/h and above can absorb practically all of the rainfall falling on it.

In the case of a single residential lot, the increase in infiltration by connecting the roof area to pervious surface ranges from 2 to 20% of the rain, depending on soil permeability, annual rain, and the length of infiltration strips. For a 10 m strip and K_s of 100 mm/h, almost all roof-water infiltrates into the ground (allowing 2–3% of the annual rain for evaporation from the roof). The effect of K_s is relatively small, and reflects the frequency of rain intensities during the 2 years. For example, in the year with an average annual rain (605 mm), there were almost no events with rainfall intensities above 30 mm/h.

Infiltration over the whole residential neighborhood, when all impervious surfaces drain to the network, reaches its maximum value (percent of pervious area in the neighborhood minus evaporation) in cases of soil types with K_s of 30 mm/h and more. Fig. 5 shows the annual infiltration over the neighborhood's area in the alternative with roof areas connected to pervious surfaces, as a function of soil type and level of spatial resolution. Differences between results obtained on the three levels are very small. In the cases of soils with K_s more than 30 mm/h, there is almost no difference in results between the simulation with the roof water uniformly distributed over the entire pervious surface of subcatchments (levels mezzo and macro), and the simulation with infiltration strips which are 10 m long (microlevel, Case b). From these results it can be concluded that for the range of conditions examined, which are typical for many locations, the spatial resolution in the model makes little difference to the annual results.

In the alternative with roof areas connected to a pervious area, the simulation results were somewhat affected by the spatial resolution for cases of very low permeability soils (K_s = 3 and 8 mm/h). Differences are greatest for lower permeability and lower ratio between the pervious and the impervious area connected to it (which increases the apparent rainfall intensity reaching it, i.e., the actual rainfall plus the runoff from the roof).

The simulation results also show that soils with saturated hydraulic conductivity of 30 mm/h or higher do not generate runoff even in the year with very high annual precipitation. This is the result of a similar frequency and temporal distribution of high rain intensities (higher than 30 mm/h) in very rainy years and in years with an average annual precipitation. Under such conditions, the annual infiltration, as percent of rainfall, is approximately equal to the percentage of pervious area. Furthermore, pervious surfaces with K_s = 30 mm/h or higher can absorb most of the additional rainwater from an impervious area that is ten times larger (100 m^2 onto a strip of 10 m^2). Under such conditions, the percentage of annual infiltration can be approximated by the percent of pervious plus impervious-connected-to-pervious area.

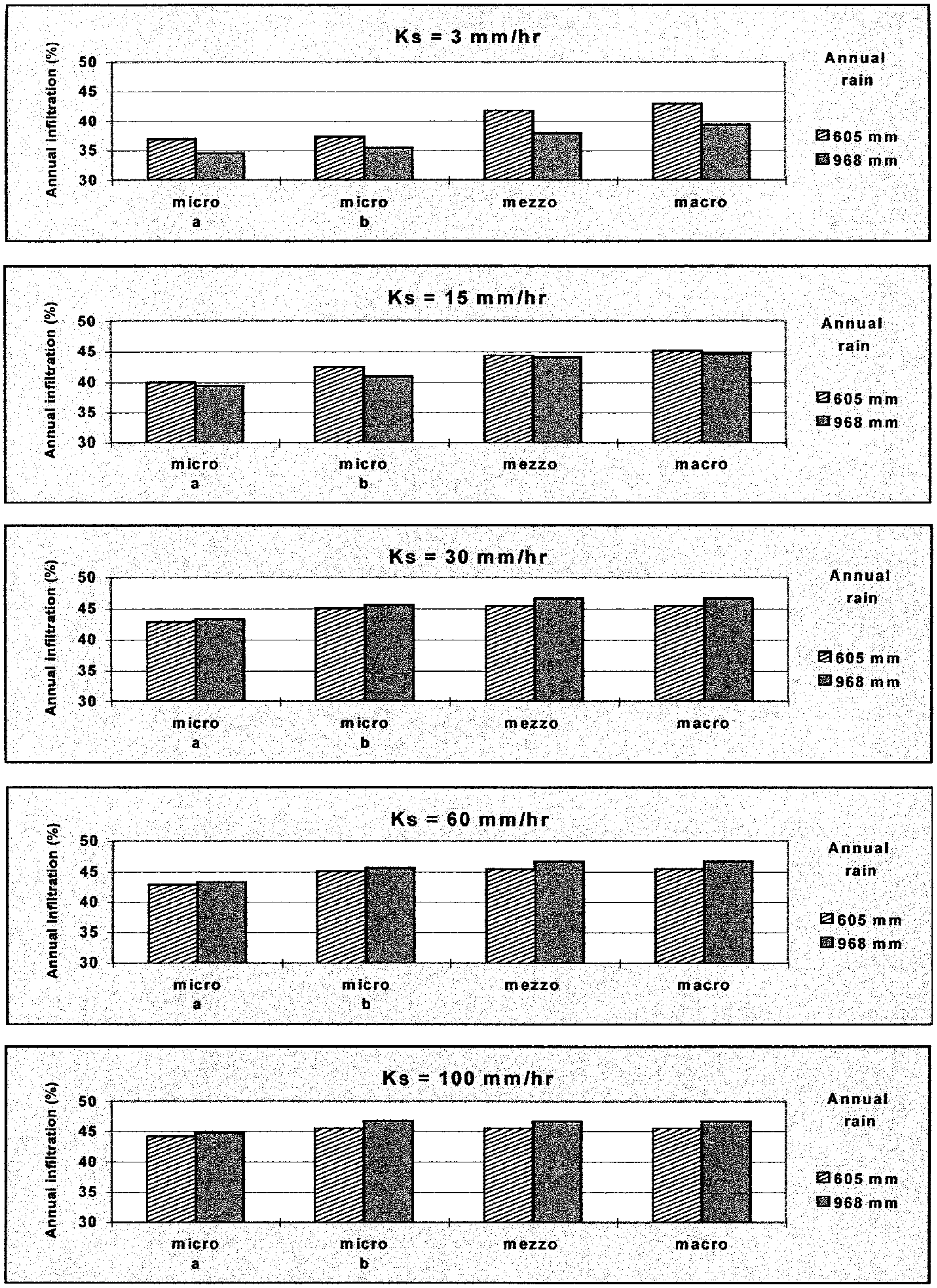

FIG. 5. Annual Infiltration over Whole Neighborhood with Roofs Drained to Pervious Area in Lot; Computed at Different Spatial Resolutions and for Different Values of Saturated Hydraulic Conductivity (K_s)

FUNCTIONAL RELATIONSHIP BETWEEN ANNUAL INFILTRATION, ANNUAL RAIN, AND PHYSICAL PARAMETERS OF URBAN WATERSHEDS

The foregoing analysis demonstrated that for the range of variables considered—layout of the urban residential neighborhood, soil types, and rainfall—the level of the spatial resolution in modeling does not significantly affect the annual mass balance. However, for conducting a detailed evaluation of proposed strategies for enhancing on-site infiltration a microlevel model is necessary. Once the response of the individual lot has been computed, the response of the entire catchment can be reasonably approximated by adding up the responses of its component subcatchments.

By running the HMM for ranges of values of annual rain, soil hydraulic conductivity, and pervious-impervious area ratio and then fitting regression equations to obtained results, we developed functional relationships of annual infiltration over a single residential lot to these parameters. The purpose of this regression analysis was to develop a ''nomogram'' that can serve for planning purposes. Using these relationships, annual infiltration in urban residential areas can be estimated without further use of the HMM itself. In the following, we demonstrate this procedure for three runoff management alternatives.

Alternative 1—Roof area and all paved surfaces drain directly to the drainage network.

Alternative 2—Roof drains connected to the pervious area of the plot. Each 100 m^2 of roof area drains through a single drain to a pervious strip 1 m wide. The length of the strip depends on the lot size; it goes from the building to the edge of the lot. Any surplus water from pervious surface drains directly to the drainage system.

Alternative 3—Roof drains connected to an underground infiltration trench. If there is overflow from the trench it goes to the drainage system.

Five-minute rainfall data for five hydrologic years in the area were selected (Bet Dagan meteorological station): Three representing maximum and minimum values of the annual precipitation, and three more spreading the range between them (Table 3). Average daily evaporation for the winter months (October–April) was used (Table 3).

Five residential lots were selected at 500, 1,000, 1,500, 2,000, and 2,500 m^2. For each, five combinations of pervious, paved, and roof areas were taken, as shown in Table 4. The values in Table 4 are considered to be typical for residential areas in Israel's coastal plain (Carmon and Shamir 1997a,b). The slope, Manning's overland flow coefficient, and depression storage for pervious and paved surfaces are the same as in the analysis of the synthetic residential neighborhood.

A range of soil properties was covered, as shown in Table 5 [(1)]. Simulations were run for each of the three alternative runoff management schemes, for the following combination of parameters: (1) Five lot sizes; (2) five combinations of pervious, paved, and roof areas (Table 4); (3) five hydrologic years (Table 3); and (4) eight soil types (Table 5). A total of 1,000 runs by the HMM were made for each alternative.

TABLE 3. Annual Rain and Average Daily Winter Evaporation (October–April) (Bet Dagan Meteorological Station)

Year (1)	Annual rain (mm) (2)	Evaporation (mm/day) (3)
1991–1992	968	3.0
1973–1974	762	2.9
1988–1989	491	3.2
1967–1968	356	3.3
1984–1985	321	3.1

TABLE 4. Pervious, Paved, and Roof Areas of Residential Lots

Percent of Different Types of Surfaces within Residential Lot			Roof/pervious area ratio	Total impervious/ pervious area ratio
Pervious (1)	Paved (2)	Roof (3)	(4)	(5)
60	20	20	0.33	0.66
50	25	25	0.50	1.00
40	20	40	1.00	1.50
40	30	30	0.75	1.50
30	30	40	1.33	2.33

TABLE 5. Soil Infiltration Parameters

Soil type (1)	K_s (mm/h) (2)	Maximum initial soil moisture deficit (mm/mm) (3)	Soil suction head, S (mm) (4)
Silty clay	3	0.41	490
Sandy clay	8	0.35	150
Silty clay loam	15	0.34	300
Sandy clay loam	20	0.34	300
Silt loam	30	0.40	780
Sands	60	0.34	102
Sands	100	0.34	102
Sands	150	0.34	102

Alternative 1: All Impervious Areas Drain Directly to Drainage Network

The results of the simulations by the HMM (Fig. 6) show that years with <491 mm of rain result in practically no runoff from open areas even with the lowest permeability soils (assuming flat areas, light turf, etc.). Annual rain of 762 and 968 mm resulted in no surface runoff in soils with K_s = 30 mm/h or more.

Figs. 7(a and b) show annual infiltration as a function of the impervious/pervious ratio for two values of soil conductivity. These results were fit by a regression equation

$$I_{(\mathrm{mm})} = b \cdot (a_1^R \cdot a_2^{K_s} \cdot a_3^r) \quad (7)$$

$$I_{(\text{percent of annual rain})} = \frac{100}{R} \cdot b \cdot (a_1^R \cdot a_2^{K_s} \cdot a_3^r) \quad (8)$$

where I = annual infiltration; R = annual rain (mm); K_s = saturated hydraulic conductivity (mm/h); r = ratio between the total impervious and pervious areas within a residential lot; and a_1, a_2, a_3, b = parameters of log-linear regression

$$\ln I = \ln b + R \cdot \ln a_1 + K_s \cdot \ln a_2 + r \cdot \ln a_3 \quad (9)$$

The correlation coefficient was always acceptably high (with the average value of 0.9908).

Alternative 2: Roof Drains Connected to Pervious Area

The annual infiltration is a function of the annual rain, soil conductivity, lot area, and ratios of roof and pervious areas to total lot area. A strip is associated with each 100 m^2 of roof area, 1 m wide, and of length given in Table 6. Runoff from the roof was directed onto the infiltration strip, expressed as mm/h over its area, and added to the rainfall on the strip. All other aspects of the calculations are as previously mentioned. Examples of the simulation results are shown in Figs. 8(a and b) for a lot of 1,000 m^2 (a building of 200 m^2 and 600 m^2 pervious area), and for a lot of 2,000 m^2 (a building of 400 m^2 and 600 m^2 pervious area). The annual infiltration is characterized by a rapid rise up to K_s values of 25–30 mm/h (depending on the lot size and the pervious-impervious area ratio), and then by a much slower rate. For the range of the rapid rise (lower K_s values), a regression equation was fit, using

$$I_{(\mathrm{mm})} = b \cdot (a_1^R \cdot a_2^{K_s} \cdot a_3^A \cdot a_4^{r_1} \cdot a_5^{r_2}) \quad (10)$$

$$I_{(\text{percent of annual rain})} = \frac{100}{R} \cdot b \cdot (a_1^R \cdot a_2^{K_s} \cdot a_3^A \cdot a_4^{r_1} \cdot a_5^{r_2}) \quad (11)$$

where I = annual infiltration; R = annual rain (mm); K_s = saturated hydraulic conductivity (mm/h); A = area of the residential lot; r_1 = ratio between the roof and total area of the lot; r_2 = the ratio between the pervious area and the total area of the lot; and a_1, a_2, a_3, a_4, a_5, b = parameters of a linear regression between the logarithms of the annual infiltration (in mm) and all the independent variables

$$\ln I = \ln b + R \cdot \ln a_1 + K_s \cdot \ln a_2 + A \cdot \ln a_3 + r_1 \cdot \ln a_4 + r_2 \cdot \ln a_3 \quad (12)$$

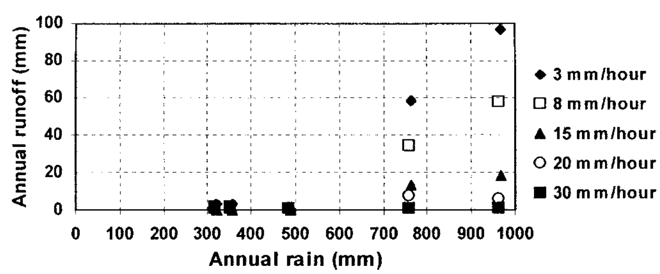

FIG. 6. Surface Runoff versus Annual Rain, for Different Values of K_s (Completely Open Area)

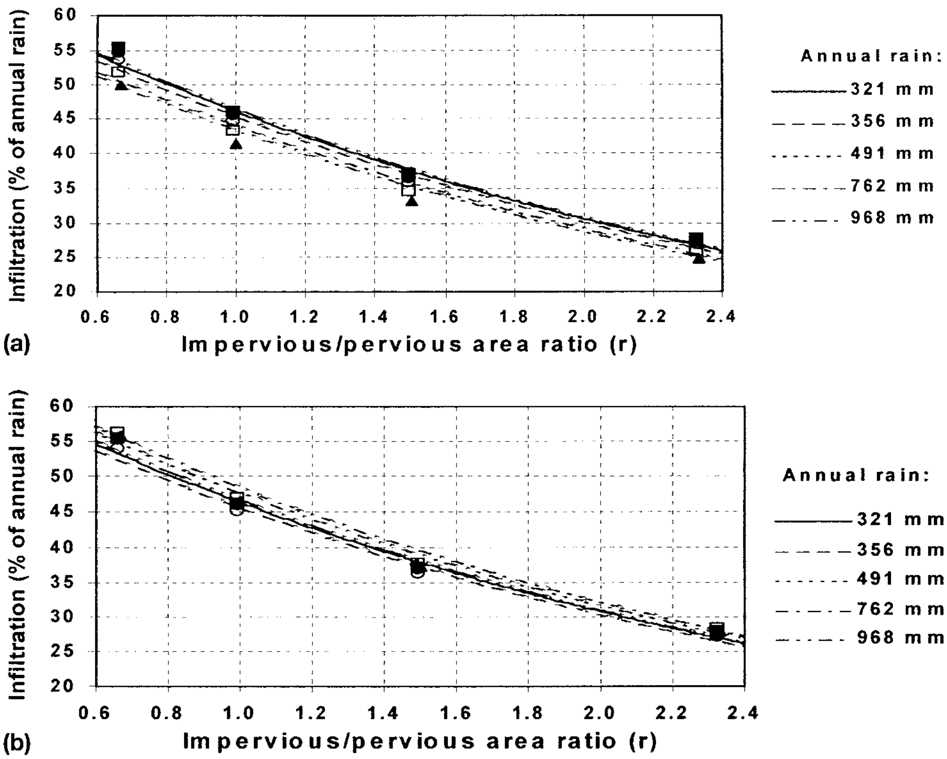

FIG. 7. Infiltration versus Ratio of Impervious/Pervious Areas [Alternative with All Impervious Areas Directly Connected to Drainage Network (Symbols: HMM Results, Line: Fitted Curves)]: (a) Saturated Hydraulic Conductivity: 3 mm/h; (b) Saturated Hydraulic Conductivity: 30 mm/h

TABLE 6. Length of Infiltration Strip

Size of residential lot (m^2) (1)	Length of strip (m) (2)
≤500	5
500–1,500	10
1,500–2,500	15

In the range of higher K_s values, the annual infiltration is a linear function of the five parameters

$$I_{(\mathrm{mm})} = b + a_1 \cdot R + a_2 \cdot K_s + a_3 \cdot A + a_4 \cdot r_1 + a_5 \cdot r_2 \quad (13)$$

$$I_{(\text{percent of annual rain})} = \frac{100}{R} \cdot (b + a_1 \cdot R + a_2 \cdot K_s + a_3 \cdot A + a_4 \cdot r_1 + a_5 \cdot r_2) \quad (14)$$

where I, R, K_s, A, r_1, and r_2 are as in (10) and (11); and a_1, a_2, a_3, a_4, a_5, b are the parameters of the linear regression between the infiltration values (in mm) and the values of all the independent variables (R, K_s, A, r_1, r_2). The best fit of these two types of functions to the values of annual infiltration and the values of R, K_s, A, r_1, r_2, was found by separating all the data in the following way. According to the annual rainfall, in two groups—up to 500 mm/year and above 500 mm/year; according to the roof area, into 4 groups—<250 m^2, 250–500 m^2, 500–750 m^2, and 750–1,000 m^2. Thus, altogether 16 relations were estimated; eight for saturated hydraulic conductivity of up to 30 mm/h, and eight for 30–150 mm/h. The fit between regression equations (lines) and the simulation results (points) can be observed in Figs. 8(a and b).

Alternative 3: Roof Drains Connected to Underground Infiltration Trench

The dimensions of an underground infiltration trench should be determined according to the roof area, soil characteristics,

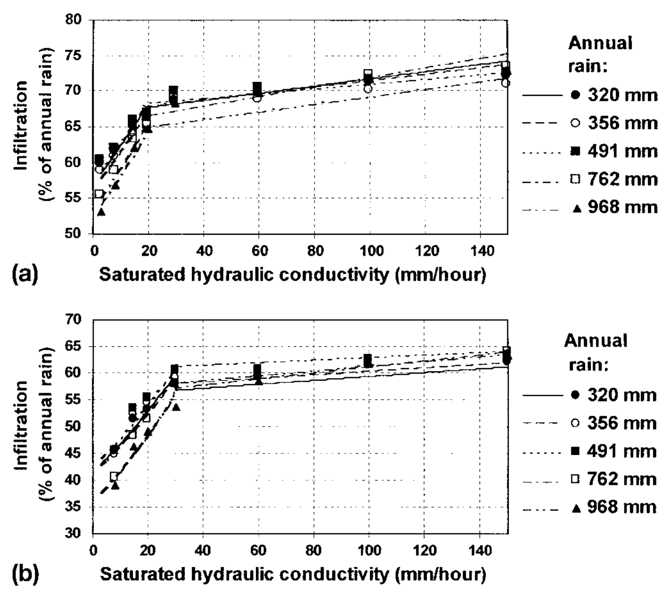

FIG. 8. Annual Infiltration over Residential Lot with Roof Area Connected to Infiltration Strips (Symbols: HMM Results, Line: Fitted Curves): (a) Total Lot Area: 1,000 m^2, Roof Area: 200 m^2, Pervious: 600 m^2; (b) Total Lot Area: 2,000 m^2, Roof Area: 800 m^2, Pervious: 600 m^2

and a selected design storm (Konrad et al. 1995a,b; Bettes 1996). We have assumed a trench 0.5 m wide and 0.6 m deep. The length is selected according to roof sizes: 5, 10, 15, 20, and 25 m, for roof sizes of <100, 100–150, 150–200, 250–300, and 350–400 m^2, respectively. Simulations were performed for all five hydrological years, eight soil types, and five different types of residential lots. The annual infiltration over a residential lot area is the sum of the infiltration over its pervious part and through the infiltration trench. The annual infiltration is a function of the annual rain (R, mm), soil type

(K_s, mm/h), total lot area (A, m^2), ratio of the roof to total lot area (r_1), and ratio of the pervious to the total lot area (r_2).

The dependence of the annual infiltration on the values of the saturated hydraulic conductivity is of a similar shape as in the alternative with the infiltration strips. Up to a saturated hydraulic conductivity of 30 mm/h the annual infiltration increases significantly with K_s, and for higher values the increase is less pronounced. As before, the highest values of the regression correlation factors for the annual infiltration and the five selected parameters (R, K_s, A, r_1, r_2), were found by dividing all the data into 16 groups as in Alternative 2 (strips). In this case, however, linear functions were the best fit in the two ranges of the saturated hydraulic conductivity.

Data represented in Figs. 8 and 9 seem to fit a linear equation. Still, a log-linear equation was used whenever it has a higher correlation coefficient than the linear equation. The values of correlation coefficients were always higher than 0.95, indicating a consistent relationship between the annual infiltration and the independent variables. F tests were also performed, and the F statistics was always substantially higher (of orders of magnitude 10^2 and 10^3) than the critical F-value for relative confidence intervals. This again indicates that the high correlation coefficient did not occur by chance.

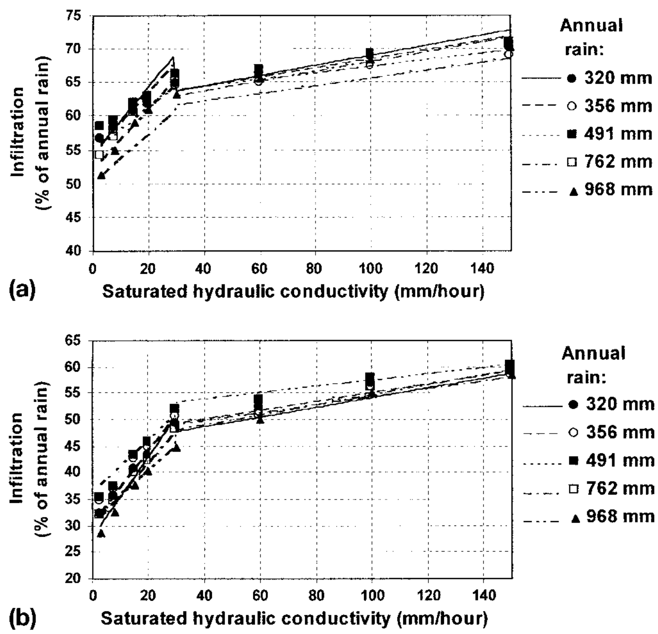

FIG. 9. Annual Infiltration over Residential Lot with Roof Area Connected to Infiltration Trench (Symbols: HMM Results, Line: Fitted Curves): (a) Total Lot Area: 1,000 m^2, Roof Area: 200 m^2, Pervious: 600 m^2; (b) Total Lot Area: 2,000 m^2, Roof Area: 800 m^2, Pervious: 600 m^2

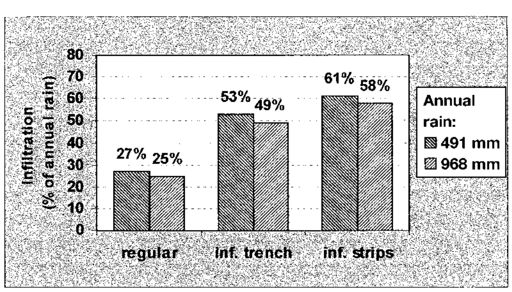

FIG. 10. Annual Infiltration for Three Stormwater Management Alternatives: Regular—All Impervious Surfaces Drain Directly to Network; Inf. Trench—Roof Area Drains to Infiltration Trench; Inf. Strips—Roof Area Drains to Infiltration Strips; Total Lot Area: 2,000 m^2; Roof Area: 800 m^2; Impervious: 600 m^2 (Saturated Hydraulic Conductivity: K_s = 300 mm/h)

Calculation of annual infiltration with the functional relationships is timesaving and avoids the preparation of time series of rain data required for computer simulations. It provides a quick evaluation of the effects of different runoff management solutions for given physical and hydrological conditions. Fig. 10 shows a comparison of annual infiltration (expressed in percent of annual rain), that can be used for selecting a storm water management alternative for a certain type of residential lot. A similar procedure can be performed and functional relationships between infiltration and physical parameters can be obtained for public and other areas in residential urban neighborhoods. Adding up calculated annual responses of all the residential lots and public areas would yield the response of the whole area.

SUMMARY AND CONCLUSIONS

Concern for the negative effects of conventional urban development on water resources, in particular, ground water in Israel's phreatic coastal aquifer—its largest over-year reservoir—has led to a series of investigations of policies and practices for water-sensitive urban planning. This paper focuses on means for increasing infiltration, in particular, on-site infiltration in the building lot. Previous phases of the study (Carmon and Shamir 1997a,b) used the SCS and SWMM models to compute infiltration, and the results obtained with the two models were quite different. It was therefore concluded that a more detailed model is needed to carry out the simulations of the hydrological processes at the lot scale.

The HMM developed in this study was used to evaluate the effects of urban development, with a number of alternative planning practices, on the hydrological responses of an urban catchment, and to study the effect of spatial resolution used in the model on its results. The following conclusions were reached:

- The hydrological response computed at the lot scale can be extrapolated to yield the response of a neighborhood—with reasonable accuracy—by adding the responses of the individual units (Fig. 5).
- For soils with saturated hydraulic conductivity (K_s) greater than 30 mm/h the differences between the infiltration computed at different spatial scales are small (under 2.5% of the annual rainfall), while for lower soil conductivity the differences are somewhat more pronounced (up to 5.5% of the annual rainfall) (Fig. 5).
- Connecting roof drains to a yard/garden, and allowing the runoff from the roof to infiltrate through an infiltration strip which is 5 m^2 for every 100 m^2 of roof area can increase infiltration over the residential lot by as much as 15% of the annual rainfall, depending on the soil conductivity and annual rainfall. For a soil with K_s = 30 mm/h the increase is 13% in an average rainfall year (78 out of 605 mm/year) and 10% in a wet year (97 out of 968 mm/year) (Fig. 4).
- With an infiltration strip of 10 m^2 for every 100 m^2 of roof area and a soil with K_s = 30 mm/h the corresponding figures are 18% for an average year (109 out of 605 mm/year) and 16% for a wet year (155 mm out of 968 mm/year).
- Draining the roof area through an infiltration trench of appropriate size can be practically as effective as connecting it to infiltration strips (Figs. 8 and 10). An infiltration trench can be especially effective where the upper soil layer is compacted by the building process, while below there is soil with higher conductivity.
- For each drainage practice (impervious areas connected to the drainage system, roof connected to infiltration strips, roofs connected to an infiltration trench) the sim-

ulation results can be generalized in functional forms, as a function of physical parameters and site characteristics [Figs. 7–9 and (7), (10), and (13)]. These relationships can be used to evaluate planning practices by comparing results. For example, the effects of different drainage alternatives for a residential lot of 1,500 m^2, with 450 m^2 (30%) pervious surface and 600 m^2 (40%) roof area, which is situated on (originally) permeable sandy soil, can be analyzed in the following way.

If the uppermost soil layer is of a low permeability with K_s = 15 mm/h and all impervious surfaces are connected to the sewer system, the annual infiltration in a year with 600 mm rainfall will be [(7)] 173 mm or 28.5%.

Draining the roof area to the pervious parts of the lot, in the same year, the annual infiltration would be [(10)] 257 mm or 43% (14.5% increase).

Draining the roof area through an infiltration trench dug into the original sandy soil with K_s = 60 mm/h [(13)], could increase the annual infiltration up to 304 mm or 50% of annual rain (an increase of 21.5 and 7% relative to the first and second alternative, respectively).

- The forms of the equations and the values of the regression parameters are based on the hydrological simulations and mathematical evaluation of the fitted curve for each combination. The regression parameters calculated here are valid only in the case of these particular solutions for each drainage practice. Furthermore, the regression equations are valid only in relatively flat areas, with slope of up to 2–3%. For any other technical solution or different characteristics of urban watersheds, hydrological simulation with HMM (or a similar model) have to be run, and curve fitting performed.

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