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Generalising urban runoff and street network density relationship: A hydrological and remote-sensing case study in Israel

Naftaly Goldshlegera*, Lev Karnibadb, Maxim Shoshanyb and Lior Asafc

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This paper describes the relationship between urban road network density and urban runoff coefficient in the coastal plain of Israel. The study assessed 30 years of recorded changes in rainfall-runoff coefficient in an urban catchment in the coastal plain of Israel. Rain and runoff were measured and sampled at measurement stations. Insight into the factors affecting urban runoff was gained by applying GIS and remote-sensing analysis, including street network density assessment and urban impermeable area recognition. Street network density was found to be a reliable indicator for both urban impermeability ($R^2 = 0.83$) and runoff ($R^2 = 0.92$) change dynamics, showing a strong linear correlation. Thus the urban street drainage network can help explain the dynamics of change in urban runoff. To prevent urban flooding hazards, and to help conserve water resources, regional planners should take into consideration road network density in built-up areas.

Keywords: GIS; street network density; rainfall-runoff analysis; image processing; urban hydrology, runoff coefficient

1. Introduction

In the last decade, urban hydrology has been the focus of increasing attention (Jens and McPherson 1964, Massing et al. 1990) due to the environmental implications of the global expansion of built-up areas and climate change. Some of these implications are long-term, such as impaired groundwater recharging (Rogers 1994) accompanied by salination of wells (Boehmer and Boonstra 1994). Others, such as flooding, might be catastrophic, resulting in casualties and socioeconomic damage (Montz 2000). However, urban development is characterised by the construction of stormwater drainage networks that bypass natural topographic flow paths and are designed for hydraulic efficiency. The capacity for attenuation of hydraulic efficiency is likely to increase with length travelled along a topographic drainage line. In contrast, the hydraulic efficiency of stormwater drainage via constructed pipes and channels will probably convey such effects efficiently with little or no attenuation to a stream (Shuster et al. 2005). A better understanding of the urban runoff phenomenon would facilitate engineering solutions and improve management and planning (Bormil et al. 2003, Andrieu and Chocat 2004, Parkinson and Mark 2005). Such an understanding might be achieved by modelling the influence of drainage network on urban runoff flow, based on GIS analysis (Zheng and Baetz 1999) and developing extended databases of detailed spatiotemporal information. This article further extends an earlier analysis of runoff relationships with permeable areas in a case study in central Israel (Goldshleger et al. 2009) by adding a GIS analysis of changes in urban drainage density.

Street lines are known to be reliable indicators of urban infrastructure and transportation characteristics (Silva 2000, Moilanen and Nieminen 2002). Although there are a number of large databases providing urban discharge and water-quality data (e.g. USGS 2002), the relationship between street network density and runoff ratios could potentially be instrumental in urban planning by enabling a prediction of runoff intensities over wide regions (e.g., Pauleit et al. 2005). Such predictions would not only facilitate hydrological solutions, they would also enable the planning of built-up areas such that they might, first, have increased permeability and second, “absorb” the flooding events with minimal damage. Israel serves as a useful test case for this purpose as its continually
ranging population density is becoming one of the highest in the developed world (Mazor 1993). Thus, Israel represents urban processes which might be expected to occur in the developed world in the next few decades.

The aim of the reported research was to assess the mutual relationships between urban runoff and urban street network density, as expressed by drainage density, in the coastal plain of Israel.

2. The study area

The study area consists of two medium-size cities in the central coastal plain of Israel, Ra’anana (~14 km²) and Herzliya (~12 km²) (Figures 1 and 2), which were founded in the 1920s and have been expanding ever since. The area is characterised by sandy soils in the upland, and red sandy clay “Hamra” (~90% sand, 5% clay, 5% Fe-oxide) on a moderate slope.

Both soils are common in the coastal plain of Israel (Dan et al. 1968). In the early 1970s, the local population density was approximately 1000 people per km² in Ra’anana and 2000 people per km² in Herzliya. In the mid 1990s, population density increased to approximately 4000 people per km² in both cities. In early 2004, the population density reached approximately 5000 people per km² in Ra’anana and 4000 people per km² in Herzliya (Israel Central Bureau of Statistics 1975, 1990 and 2005).

3. Methods

3.1. Image processing and recognition of impervious urban areas

This study describes the use of remote-sensing methods based on aerial RGB Orthophoto, and Image processing software (Erdas Imagine 9.1 and Envi 4.7) for implementation of the remote-sensing approach. Aerial photo and orthophoto images representing six different time periods (1975, 1986, 1997, 2001, 2003, 2008) were processed for identification of urban land uses, by the methods implemented by Goldshleger et al. (2009) and Garzuzi et al. (2010). Those methods included grayscale texture analysis which makes it possible to distinguish between highly variable reflectance values in dense built-up areas and less variable or homogeneous reflectance values in sparsely built-up or agricultural areas. The outcome of this analysis was an artificial texture layer that was combined with the original grayscale orthophoto. Based on colour aerial photos, land imperviousness mapping was performed using unsupervised classification (isodata method).

The isodata method uses minimum spectral distances to assign each candidate pixel to one of the clusters. The number of clusters is preliminarily defined by the user (Swain 1978).

Six classified images were obtained demonstrating the temporal change dynamics of permeable and impermeable areas. An example of classified images is shown in Figure 3. The change in imperviousness throughout the research period was compared to corresponding values of urban runoff ratio, and these showed a strong linear correlation (Figure 4).

3.2. Urban runoff and road density

The storm runoff coefficient (C) represents the ratio between storm runoff volume and storm rainfall volume (e.g., Pandit and Gopalakrishnan 1996). An assessment of runoff coefficient variations with different surface types indicates that concrete and asphalt have the highest C values (above 0.9) (BASMAA 1999). The expansion of urban areas inevitably leads to an increase in impermeable surface cover. Roofs, paved areas and parking lots prevent soil infiltration of precipitating water (Ramier et al. 2004), resulting in an increase in the runoff coefficient (Mentens et al. 2005), higher peak flows, shorter catchment response (Leopold 1968), and concentration time, and higher flooding risks. However, predicting urban runoff potential is rather difficult because of high variability of the urban catchment characteristics such as topography, basin drainage area and especially impermeable cover area.

Olyphant and Korinek (2002) reported a change in runoff coefficient from 0.7 in dense urban areas to 0.4 in sparser urban areas; Pauleit et al. (2005) reported an increase in runoff coefficient for an urban zone in the United Kingdom from 0.49 in 1975 to 0.75 in 2000; (Supangat and Murtiono 2002) reported a range of variations in runoff coefficient, from 0.1 to 0.4 (with one sub-watershed having an average runoff coefficient of 0.65) observed between 1991 and 2000. Results from many other case studies (e.g., USGS 2002, McKee et al. 2003) provide further indications of high variability in urban runoff coefficient estimates, most of them representing individual and independent observations.

There are a variety of other factors influencing runoff coefficient potential as well, such as catchment topography, soil cover, surface micro topography (Bormil et al. 2003), and variations in rainfall intensity. All of these factors produce a very complex system. In view of this complexity, uncertainties involved in modelling this phenomenon and the limited availability of information from direct observations, it would be most sensible to try to simplify the approach as “very simple models are often sufficient to forecast the rainfall-runoff behaviour of catchments” (Chappell et al. 2004).
During storm events, the urban street network acts as a collector and conveyor of concentrated storm-water runoff draining from impervious urban surfaces. Drainage channels and pipes are usually incorporated into the road network, but their discharge capacity is limited in terms of draining storm runoff (e.g. WEF/ASCE 1992, Guo 2000a, 2000b). Ravazzani et al. (2006) refer to street networks as one of the main elements implemented in the hydrological urban network model used for urban flood mapping. Schulz et al. (1974) suggested that since each street has one channel on each side, growth of the street network contributes significantly to increased drainage density. Accordingly, a correlation should be considered between density of the urban street network and changes in storm runoff ratios. Drainage network...
Density is defined as the ratio of total channel length to catchment area and can be calculated as follows:

\[ D = \frac{L}{A} \times 100 \]  

(1)

where \( D \) is network density, \( L \) is the total length of the street network and \( A \) is the catchment area.

The drainage system in Israel is separate from the sewage system. It is mainly built along the roads which are separate from, and at a lower elevation than the sidewalk. Therefore, in addition to the underground culverts and drainage pipes built along and underneath the main roads, the roads themselves function as a drainage network. In the highly dense urban areas investigated in the present study, there were no dirt roads and thus limited water losses along the flow path.

The characteristics of hydrological and particularly network density, have been much discussed with respect to landscape ecology, agriculture and soil erosion (e.g. La Barberra et al. 1993, Pyrce 2004, Jencso et al. 2009). However, little has been done to evaluate the influence of urban hydrological network density on runoff coefficient and flood potential.

In order to cover this knowledge gap temporal urban network roads density analysis was carried out using street network based on local GIS data of the study area. To assess the influence of street network density on urban runoff, these data were incorporated with storm runoff coefficients derived for this region in a previous study (Goldshleger et al. 2009).

3.3. Runoff characteristics

The rise in urban population density has been accompanied by an increase in impermeable surface cover and urban runoff volumes, as well as in the frequency of flooding events. This is shown by an analysis of urban runoff coefficients based on hourly rainfall discharge rates, which have been monitored in the Ra’anana catchment area (10.5 km²) since the early 1980s and in several Herzliya catchment areas (1.3–4.5 km²) since 2003 (Figure 5 and Goldshleger et al. 2009).
Additional runoff stations were installed at the outlets of five stormwater drains in 2003 (four in Herzliya and one in Ra’anana). In the Herzliya municipality, hydrometric and rainfall measurements are available for the years 2003–9. Rainfall data were taken from automatic tipping-bucket rainfall recorders with a resolution of 0.1 mm installed in the basin by the Erosion Research Unit of the Ministry of Agriculture. Long term rain data for the study area are presented in Table 1. In addition, rain intensity was determined by analysis of cloud radar measurement data (Ben Gurion Airport Radar Station). Runoff flow data were collected from the conduit located in the northern part of the city (Figure 2). The continuous stage level in the Herzliya station was recorded by digital pressure transducers (divers) with a resolution of 10 mm and data logger. Flow velocities and storm discharges were calculated using the Manning formula for open channel flow (Viessman et al. 1993) The area draining into each of the stations was estimated using an ESRI GIS (ArcInfo 9) aerial orthophoto map, topographic and infrastructure data and a drainage network provided by the local municipalities. (Goldshleger et al. 2009).
Rainfall depth was calculated as the average over the drainage basin area according to Thiessen's method (Haan et al. 1994). Runoff depth was determined from the hydrographs. The relationship between rainfall and runoff is generally linear (Haan et al. 1994). The rainfall-runoff coefficient was determined from the slope of the trend lines representing the scattered data in the different periods (Figure 5). Due to the higher frequency of lower magnitude storms (Table 1), this method yielded slightly higher coefficients, which are preferable for practical reasons.

The regression coefficients of these connections (runoff coefficients) to residential areas in the coastal plain of Israel were found to be in the range of 0.06 to 0.36 (Table 2). These values are similar to other observation in urban catchments around the world (Goldshleger et al. 2009). In most of the basins, the runoff coefficient varies within narrower boundaries. These average values represent the total urban area. The sites chosen represent various urban land uses mainly residential, industrial, and roads.

Table 1. Long-term mean rainstorm events (mm) for various return periods in representative stations in the area. The annual probability for a specific event is shown.

<table>
<thead>
<tr>
<th>Station name</th>
<th>Observation (years)</th>
<th>1%</th>
<th>2%</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>80%</th>
<th>95%*</th>
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<tr>
<td>Ra’anana (y6)</td>
<td>71</td>
<td>366</td>
<td>324</td>
<td>271</td>
<td>231</td>
<td>190</td>
<td>132</td>
<td>91</td>
<td>65</td>
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<tr>
<td>Gaash</td>
<td>50</td>
<td>356</td>
<td>310</td>
<td>251</td>
<td>210</td>
<td>169</td>
<td>115</td>
<td>81</td>
<td>57</td>
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<tr>
<td>Rishpon</td>
<td>59</td>
<td>431</td>
<td>359</td>
<td>276</td>
<td>220</td>
<td>170</td>
<td>109</td>
<td>77</td>
<td>61</td>
</tr>
<tr>
<td>Kefer Shmriyuo</td>
<td>76</td>
<td>381</td>
<td>331</td>
<td>267</td>
<td>223</td>
<td>178</td>
<td>120</td>
<td>84</td>
<td>57</td>
</tr>
</tbody>
</table>

Note: *probability

Table 2. Drainage density index and rainstorm runoff, built-up area estimations in Ra’anana and Herzliya basins.

<table>
<thead>
<tr>
<th>Network roads density index</th>
<th>Built-up area (%)</th>
<th>Storm runoff ratio</th>
<th>Basin</th>
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<tr>
<td>0.06</td>
<td>18.53</td>
<td>0.06*</td>
<td>Ra’anana 1975</td>
</tr>
<tr>
<td>0.73</td>
<td>26.76</td>
<td>0.11*</td>
<td>Ra’anana 1986</td>
</tr>
<tr>
<td>0.85</td>
<td>30.88</td>
<td>0.19*</td>
<td>Ra’anana 1997</td>
</tr>
<tr>
<td>0.92</td>
<td>31.91</td>
<td>0.26*</td>
<td>Ra’anana 2001</td>
</tr>
<tr>
<td>1.04</td>
<td>46.55</td>
<td>0.29</td>
<td>*Herzliya_north (x5) 2008</td>
</tr>
<tr>
<td>1.09</td>
<td>36.55</td>
<td>0.29</td>
<td>*Herzliya_south (x2) 2008</td>
</tr>
<tr>
<td>1.10</td>
<td>40.45</td>
<td>0.31</td>
<td>*Herzliya_total 2003</td>
</tr>
<tr>
<td>1.32</td>
<td>41.61</td>
<td>0.36</td>
<td>*Herzliya_(x3) 2003</td>
</tr>
</tbody>
</table>

Note: *sub basin (Figure 2)

4. Results and discussion
Overall, 40 storm events (more than 2 mm of rainfall per event, an event being defined as lasting until a break of more than 24 h had occurred) were recorded for Ra’anana basin. Figure 5 presents the rainstorm runoff data versus rainfall data, indicating a relatively...
broad distribution of data alongside clear trends of linkage between the two data types. In general, a constant rise in runoff could be seen in both light (up to 40 mm) and heavy (up to 200 mm) rainstorms. In the latter, the distribution of runoff increased at the same rain depth. Updating the storm runoff ratio data acquired by Goldshleger et al. (2005) showed an increase in rainstorm runoff coefficient in the Ra’anana and Herzliya areas from 0.11 to 0.31 between the years 1995 and 2004 (Figure 5).

In the present research, performed in residential areas, a similar linear correlation was found between the road network density index and storm runoff coefficient ($R^2 = 0.92$) (Figure 4 and Table 2).

The relations between the runoff data and corresponding drainage density are shown in Table 2 and Figure 6 ($R^2 = 0.83$). Previously, Goldshleger et al. (2009) showed that the increase in urban storm runoff coefficient is directly correlated with an increase in impervious urban area.

Urban catchments differ significantly from natural watersheds; nevertheless, there are similarities that allow features of the drainage density concept, originally developed for natural watersheds, to be adapted to the urban setting. The unique structure and organisation of urban drainage networks along the roads and streets (both above and below the surface), as the main channels of flow, are similar to stream networks in a natural setting. Drainage density was defined as the ratio of the total length of streams in a watershed to its contributing area (Horton 1945). It describes the degree of drainage network development and has been recognised by many authors to be significantly effective factors in the formation of flood flows. Plaut Berger and Entekhabi (2001) proved that drainage density is significantly related to the basin run off coefficient in an undeveloped natural rural catchment. In Israel, most of the impervious surfaces (e.g., roofs and parking lots) are directly connected to the roads and to the drainage network. Unfortunately, water-sensitive urban design is not common practice. Only in new buildings has there been any attempt to reduce the runoff from yards. The result, based on the findings from the Israeli coastal plain, is that urban road density is one of the main factors controlling urban runoff ratios. The urban road networks serve as the main flow lines, similar to natural stream networks. The road network density is related to the efficiency of the system at channelling water from the contributing unpaved areas to the outlet of the system. Increases in road density are expected worldwide, because urban densification and compaction are regarded as essential for reaching urban sustainability (Cooper et al. 2002). This stems from a need to revitalise decaying urban zones (e.g., Porat et al. 2008), from the perspective of travel behaviour (Cooper et al. 2002) and from an ecological standpoint, as densification implies a reduction in urban sprawl (Squires 2002). Such an increase in the density of the urban infrastructure necessarily involves an increase in impermeable areas and thus, the new urban area may be expected to produce more runoff events with higher runoff.

There are similarities between the influence of the build up area and network roads density. Both parameters have similar trends to contribute to a higher runoff coefficient.

While the urban built up areas contribute directly to the increase of the run off coefficient by increasing the impermeable area, and therefore the total volume of urban runoff, the roads density is a function of the...
system. This variable defined the capacity of the road to channel the water into the drainage system. Higher road density contributes to a more efficient drainage system and therefore to a higher runoff coefficient. A sustainable design of urban infrastructure can reduce the impact of the increased sealing of the surface in the urban environment.

5. Summary and conclusions
This paper describes the relationship between urban road network density in built-up areas and storm runoff coefficient in a case study of cities in the coastal plain of Israel. The conclusion is based on a long period of data collection from the same watersheds. It shows that there is a constant increase in runoff coefficient with increasing road density and built-up area. The chosen sites well represent various urban land densities in which the residential area is dominant. In urban areas with a high-density road network and adjacent high drainage density, there is a higher runoff coefficient because of the improved conductivity between the built-up areas and the drainage network, representing the impermeable area. Therefore, to prevent flooding, city planners and hydrologists must incorporate the future increase in building area, which will yield excess storm water, in their planning.

A reduction of surface runoff in absolute terms can be achieved by a variety of measures that increase infiltration, evaporation and/or transpiration from the catchment areas that contribute to local flooding. The easiest way to do this is to preserve unsealed and green spaces in the city, and to channel the flow line to these areas. Since the potential for in-town infiltration and evapotranspiration is limited, especially in cities where convective precipitation and non-absorptive soils prevail, measures of stormwater retention are vital for the mitigation of urban floods as well as for the prevention of downstream floods.

Pursuant to the presented connection and strong correlation between runoff coefficient and drainage density, a reduction in internal roads (inside the city) by careful city planning can reduce the over road and drainage density and therefore the overall flood volumes. The empirical model may assist planners in determining storm runoff volumes and in planning the expansion and densification of small towns in an attempt to decrease potential flooding.

It is suggested that not only should the overall impervious areas be analyzed, but also the connection between these areas and the drainage network density. This connection is linked to the drainage density. The drainage density can be calculated from road density, which can be evaluated by remote-sensing aerial photo or satellite image interpretation.

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BASMAA (Bay Area Stormwater Management Agencies Association), 1999. Start at the source: design guidance manual for stormwater quality protection. Bay Area Storm Water Management Agencies Association (BASMAA) and Tom Richman & Assoc.


