The impacts of urbanization on groundwater systems and recharge

John M. Sharp, Jr.

Abstract: Urbanization is a major geomorphic process affecting both surface and groundwater systems. The development of cities inevitably increases paved surfaces and roofs (termed impervious cover) and storm drains. Installation of a network of subsurface structures, including utility systems, is another necessary aspect of modern cities. Urbanization alters topography and natural vegetation, stream flows and flooding characteristics, temperatures both above and below the land surface, and water quality of surface streams and groundwater. Major physical changes to the groundwater system include changes in water table elevation; a dramatically altered permeability field created by construction and utility system emplacement; and altered groundwater recharge. Subsurface permeabilities may increase by orders of magnitude in certain preferred zones, which makes prediction and remediation of subsurface contaminants difficult. Groundwater recharge commonly increases because of: 1) leakage from water distributions systems, sewer lines, detention ponds, and storm drains; 2) over irrigation of lawns, gardens, and parks; 3) artificial recharge; 4) reduced evapotranspiration and 5) infiltration through "impervious" cover. This, coupled with pumping of shallow groundwater, controls water table fluctuations. The impacts of urbanization on groundwater systems are predictable and should be considered in urban planning from geotechnical, environmental, and water resources perspectives.

Keywords: urbanization, groundwater, recharge, permeability.

Riassunto: *L'urbanizzazione è il maggiore processo geomorfico che interessa sia il sistema delle acque superficiali che quello delle acque sotterranee. Lo sviluppo delle città aumenta inevitabilmente le aree impermeabili come le superfici pavimentate, i tetti (definiti una copertura impermeabile) ed i canali di deflusso. L'installazione di una rete di strutture al di sotto della superficie, incluso i sistemi di servizio pubblico (distribuzione e canalizzazione dei reflui) è un altro aspetto delle città moderne. L'urbanizzazione altera la topografia e la vegetazione naturale, il flusso delle acque superficiali e il comportamento degli eventi di piena, le temperature sia sopra e sotto la superficie del terreno, e la qualità delle acque dei fiumi e delle acque di falda.*
I principali cambiamenti fisici nel sistema delle acque sotterranee includono le variazioni di quota della superficie freatica; la drammatica alterazione della permeabilità creata dalla costruzione e dal collocamento del sistema delle infrastrutture; l'alterazione della ricarica della falda. La permeabilità sotterranea può aumentare di ordini di grandezza in certe zone preferite, ciò rende difficile la previsione e la bonifica dei contaminanti nel sottosuolo. La ricarica della falda generalmente si incrementa a causa di 1) perdite dai sistemi di distribuzione dell'acqua, delle reti fognarie, dei bacini di immagazzinamento, e dai canali di deflusso; 2) eccessiva irrigazione dei prati, giardini e parchi; 3) ricarica artificiale; 4) riduzione di evapotraspirazione e 5) infiltrazione attraverso le coperture "impermeabili". Questo, associato al pompaggio delle acque sotterranee poco profonde, controlla le fluttuazioni della superficie freatica. Gli impatti dell'urbanizzazione sul sistema delle acque sotterranee sono prevedibili e dovrebbero essere considerati nella pianificazione urbana dal punto di vista geotecnico, ambientale e delle risorse idriche.

Introduction

Mankind is the major geomorphic agent that affects the Earth's land surfaces (Sherlock, 1922; Underwood, 2001) and, perhaps second only to agriculture, urbanization is the major process now affecting the land. Over 50% of the Earth's population now lives in cities and it is estimated that by 2025 this will increase to over 67% (Ramsey, 2003). Megacities and urban sprawl cover large areas of all continents except Antarctica. The conversion of natural, agricultural, and other low-population density lands to cities or urban areas changes to the hydrology of the area. Below I consider these changes as they affect the groundwater systems and, in particular, their physical aspects and water resources implications. The effects of urbanization on flooding have been well documented for over 40 years (Leopold, 1968). This is attributed to increasing impervious cover and storm drains that channel precipitation off roads, roofs, and parking lots to streams. "Impervious" cover is a major index or urbanization areas and is considered the most pervasive, relevant characteristic leading to hydrologic impacts (e.g., Arnold and Gibbons 1996). Urban hydrologic analysis and design has commonly only consisted of quantifying and planning for the larger peak flows associated with floods in an urban setting. Higher flood peaks, stream flashiness, and, in some cases,

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runoff volumes are the results of urbanization, but other hydrologic consequences include changes in baseflow (often mistakenly assumed to decrease); increased stream loads of nutrients, salts, heavy metals, and sediments; and changes to urban stream temperature patterns (Moglen, 2009). In addition, it has been documented that urbanization can alter the local and, perhaps, the regional climate.

However, groundwater systems in urban areas are also impacted significantly, and these impacts can have important consequences for human activities and the environment. Because usually groundwater is out of sight, it is sometimes out of mind, but the impacts of urbanization on groundwater systems must be considered in land-use planning, construction, or in regards to water resources to make future urban areas sustainable. Urban groundwater systems remain an under-appreciated and under-underutilized urban resource (Sharp, 1997).

General hydrogeological effects of urbanization include altered topography and vegetation, increasing shallow groundwater temperatures, changes to water table elevations, and a multitude of changes associated with construction and pumping, and pollution of groundwaters and surface waters. The last topic has an extensive literature, but is not the subject of this study, but the physical alterations to the hydrogeological system need to be considered in remediation and water management. This paper focuses primarily on the imposition and effects of a highly altered shallow permeability field and on altered, generally increasing groundwater recharge. However, these effects are all interrelated.

General hydrogeologic effects

Altered topography

Urbanization tends to level off the landscape for ease of construction and for roadway design. Over time, low-lying areas are filled in and elevated areas lowered. In very old cities, younger construction cover successively older city structures. This commonly leads to burial of surface streams, which may be covered, filled-in, converted into storm sewers, or just forgotten. Case histories include London, UK (Barton, 1962), Washington D.C., USA (Williams, 1977), and Minneapolis-St. Paul, Minnesota, USA (Brick, 2009). However, the high-permeability alluvial strata often remain buried beneath streets and buildings. These will often be in the form of lenses or channels that make accurate predictions of groundwater flow and solute transport difficult.

Altered vegetation

Changes in the rates and distribution of evapotranspiration can alter recharge and groundwater flow directions. Clearly, impervious cover will decrease and may even eliminate transpiration by native vegetation. Alternatively, especially in desert cities, irrigation of lawns and gardens may increase transpiration, as can the introduction of non-native vegetation that may include phreatophytes, such as tamarisk and eucalyptus. Finally, over-watering of lawns, playing fields, and gardens may lead to irrigation return flows that increase groundwater recharge as, for example, in Lethbridge, Canada (Berg et al., 1996) and Austin, Texas, USA (Garcia-Fresca, 2004; Garcia-Fresca and Sharp, 2005).

Groundwater temperatures

The urban heat island effect is well documented. Urban areas are hotter than adjoining rural areas. The annual mean air temperature of a city with 1 million people can average (1–3°C warmer than its surroundings and in the evenings this difference can be even greater. The U.S Environmental Protection Agency maintains a website on the Heat Island Effect. Groundwater is also affected; shallow groundwater temperatures increases, which can affect water quality and groundwater dependent ecosystems. Examples include Tokyo, Japan (Taniguchi et al., 1999; 2001) and Minneapolis/St.Paul, Minnesota, USA (Taylor and Stefan, 2009).

Changing water table elevations

Water tables can either fall or rise (Simpson, 1994; George, 1992; Whitesides et al., 1983) with urbanization. Groundwater extraction in the urban area can either increase or decrease with time as imported waters are introduced, as surface water systems replace local groundwater resources, as surface water systems decline as in droughts, with reservoir-induced changes in river stages, or with the implementation of new technologies, such as desalination or ASR (aquifer storage and recovery). Except in the case of areas with relatively deep water tables, ASR effects can be significant but are presumably temporary with the possible exception of where water tables may rise until the fluctuating nature of a functional ASR commences.

Conversion from using local aquifer systems to large surface water systems or imported water can cause rising water tables, which can, in turn, can cause engineering problems (flooding of basements, tunnels, and utility systems; mass wasting, etc.) and new boggy areas. Wet soils as in Wagga Wagga, Australia, can cause foundations problems (Cooke et al., 2001; Young, 2008), especially when the groundwater is brackish or saline. On the other hand, continued use of groundwater can cause falling water tables, which can, in turn, cause saltwater intrusion, subsidence, or the decline of groundwater dependent ecosystems, including springs.

Construction and pumping effects

Various construction activities and designs affect groundwater. If the water-table is close to the surface or if deep tunnels or subways are being built, dewatering or depressurization may be required that can lower water tables for considerable periods of time (Powers et al., 2007). In some construction the dewatering must be essentially permanent. For instance, sump pumps may be required and this may depress water tables, induce leakage from utility lines, change groundwater flow patterns, and lower natural baseflows to streams and wetland areas, although the water being pumped must be disposed and typically to some stream. If construction occurred in an historical period of low water tables (e.g., in a time when groundwater supplied the city and was eventually replaced by imported surface waters or in a time of extended drought), then the dewatering occur post-construction.

Pumping for production of groundwater or for remediation of subsurface contamination can create similar effects. In certain cases, the construction may form subsurface dams that can locally alter the groundwater flow field, such as in Hong Kong, China (Jiao et al., 2006). If subsidence is the result of pumping, this can cause alteration of surface stream gradients and flood zones, breakage of underground utility systems, and inundation near coastal areas. Examples (e.g., Johnson, 1991) where these effects have been significant include Houston, Texas, USA; Venice, Italy; and Calcutta, India.

Altered permeability field

The network (or reticulation) of water mains, sewer lines, electrical and telephone conduits, storm drains/sewers, subways, and other subsurface systems is one of the major alterations to the hydrogeology of an urban area. Although urban soils tend to be come less permeable because of compaction (Pitt et al., 2002), fill near buildings and over utility trenches (Figure 1) is more permeable. In the latter case, permeability commonly increases by several orders of magnitude.

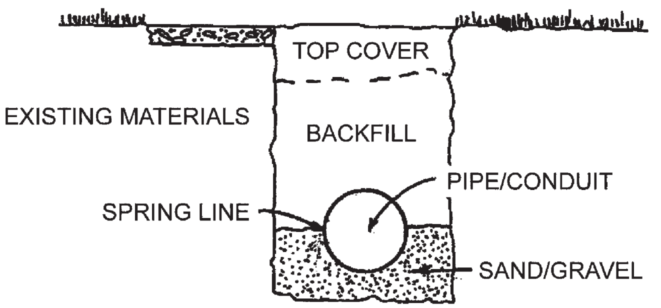

Fig. 1: *Elements of a utility trench. Typically well-sorted, high permeability sand or gravel is emplaced up to the spring line. Back fill is then placed and sometimes tamped or compacted. In some cases, there may be a top cover of soil, gravel, or other materials. Figure 2 shows one data set of how permeabilities compare in the backfill/top cover to the natural existing soils.*

Figure 2 shows data on hydraulic conductivities of utility trench fill compared to undisturbed soils developed on alluvium and terrace deposits. Similar trends are found where the trenches are excavated in carbonate rock materials in Austin, Texas, USA (Sharp et al., 2003). Further, if the conduit or pipe is breached as commonly happens in storm drains, sewers, and electrical/telephone conduits, permeabilities can be much greater in these pipes/conduits than in the fill. In older cities, abandoned utility lines and pipes, old trench fills, remnants of older structures and construction, and buried alluvial strata remain after new construction to create a very complicated secondary permeability field.

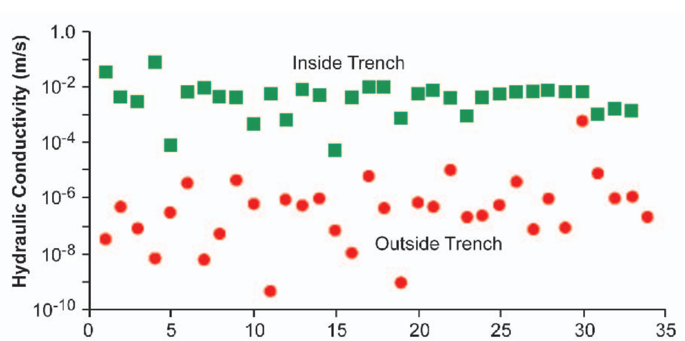

Fig. 2: *Hydraulic conductivities of soils developed in Quaternary terrace and alluvial deposits and fill materials in utility trenches in the same soils in Austin, Texas, USA. Modified from Sharp et al. (2003).*

This double- or triple-permeability system has been considered analogous to a karstic system (Sharp and Garcia-Fresca, 2003). In fact, the secondary porosity of the urban underground is roughly equivalent to that of a karstic aquifer. For instance, secondary porosity under Quebec City, Canada in a crystalline bedrock environment is essentially that estimated for the rocks of Mammoth Cave National Park, Kentucky, USA (Garcia-Fresca, 2004; Worthington, 2003; Boivin, 1990). The rate of increase of this urban secondary porosity and permeability, however, occurs in a span of only decades or perhaps a few centuries. Whereas the natural development of secondary porosity and permeability normally occurs over much longer time spans of millennia to millions of years.

This highly altered permeability field can lead to the following:

- Altered groundwater flow systems.
- Maintenance of stream baseflows and spring flows during times of limited rainfall or, alternatively.
- Reduced increased spring flows, if flow is diverted from spring orifices.
- Diversion of groundwater to different streams or catchments.
- Artificial recharge caused by leakage of water, sewage, and storm waters along the utility lines.
- Difficulty in predicting, modeling, and remediating subsurface contamination.
- Creation of multiple contaminant plumes that can migrate in different directions than might be predicted from standard analyses.
- Utility trenches and mains/sewers serving as "French drains" to limit rising water tables.

Krothe (2002) and Sharp et al. (2003) demonstrate that utility trench systems with 2-4 orders of magnitude greater permeability deflect groundwater flow patterns and that multiple contaminant plumes can arise from a single point source. Clearly, prediction of contaminant migration pathways becomes problematic under such conditions. In addition, in these high permeability zones can serve as drain pathways. For instance, storm drains in Austin, USA, are observed to flow in periods of no precipitation. If the utility trench systems are above the water table, they can serve as recharge line sources, which is discussed below.

The assessment of how urban development changes the groundwater flow system and permeability fields is site specific. It depends upon the hydrogeology of strata underlying the city, the details of urban development, the use of local aquifers for water supply, and alterations to the rates and distribution of recharge.

Groundwater recharge

Although it is commonly stated, that groundwater recharge is reduced with urbanization because of the increase in impervious cover, the reverse is the more common condition – urbanization increases ground water recharge. In some cases, groundwater dependent ecosystems are augmented by increased urban recharge (Sharp et al., 2009). Asquith and Roussel (2007), Drouin-Brisebois (2002), and Scheuler (1994) all indicate little difference in stream baseflows between urbanized and undeveloped watersheds. Figure 3 shows a compilation of data from cities around the Earth showing comparing recharge before and after urbanization. In all cases, except Birmingham, UK, increases are estimated. The increases in groundwater recharge are most notable in more arid zones and cities with that may not be able to maintain their utility system and roadway infrastructure. Of course, it should be noted that the recharge and changes to recharge in a city also vary spatially. It may be decreased in one portion of an urban area because of increases in impervious cover and soil compaction and increased in other areas because of a number of other factors. These include leakage from water mains, sewer lines, and storm drain systems; the effects of storm water detention ponds and artificial recharge; irrigation return flow from lawns, gardens, and parks; losing streams; and the fact that impervious cover is not all impervious.

Leakage from water mains estimated to range from lows approaching 5% to over 60 % of water pumped from the surface reservoirs or groundwater (Garcia-Fresca and Sharp, 2005). The lowest rates are for special low-pressure, newly constructed water delivery systems, but rates under 10% can be achieved with good, continual

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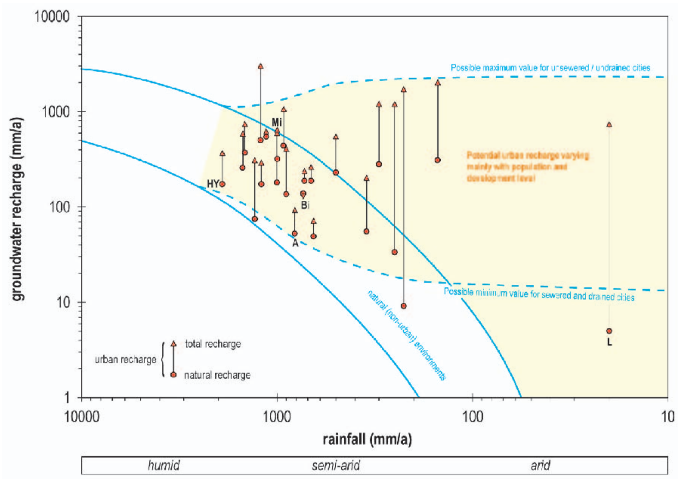

Fig. 3: *Estimates of groundwater recharge in cities prior to (circle) and after urbanization (triangle) (modified from Garcia-Fresca and Sharp, 2005, and Foster, 1996). In all estimates, only Birmingham, UK (Bi in the figure shows a decrease as documented by Knipe et al., 1993). Added to Garcia-Fresca and Sharp (2005) are Austin, USA (A) and Milan, Italy (Mi). Hat Yai, Thailand (HY) and Lima, Peru (L) are from Foster (1996).*

maintenance. However, general rates in developed countries are in the range of 16 to 25% (Lerner, 1997b; Thornton, 2002). In the absence of field data, leakage rates of water from sewer lines in the USA is estimated very conservatively at 6% and from storm drains at 5% for high flow rates and 10% at low flows rates (Rieckermann et al., 2003; Thornton, 2002; Wurbs and James, 2002). In many urban areas, storm water retention/detention ponds are installed to alleviate the effects of floods after heavy rains and for water quality protection. These ponds are shown to be significant point sources of recharge and, as stated by Milczarek et al. (2004), "If maximizing GW recharge…is desired, the design and siting of stormwater basins …merits…consideration". Artificial recharge basins have been to increase recharge significantly and lower overall evapotranspiration on Long Island New York, USA (Scorca, 1996). Stormwater retention/detention ponds can be designed to serve in this capacity.

While the effects of overwatering of lawns, gardens, and parks are relatively well understood and accepted, the competing effects of "impervious cover" are not. Figure 4 shows sources of recharge in an urban area. There are 4 styles of recharge (Wiles and Sharp, 2008; Lerner, 1997a) – direct, indirect, artificial, and localized.

Direct recharge occurs from precipitation reaching the land surface. In urban areas this is expected to decrease because of runoff from roofs and paved surfaces diverting precipitation. This also occurs if the soils are less permeable because of compaction. The diverted water generally flows onto streets and storm drains where present. The net effect of impervious cover and storm drain is increasing flood peaks and decreasing flood lag times as has been demonstrated repeatedly since Leopold (1968). However, the impervious cover also reduces evapotranspiration losses and, as is indicated below, not all precipitation reaching roadways and parking lots becomes surface runoff.

Indirect recharge includes water that flows over the land surface or in streams that recharges through a mappable recharge feature. The most notable example is that of losing streams in karstic areas. For example, over 50% of the water recharging the Edwards Aquifer in Austin, Texas, USA is indirect recharge (Hauwert, 2009). If urbanization increases stream flows to losing streams, this can increase recharge.

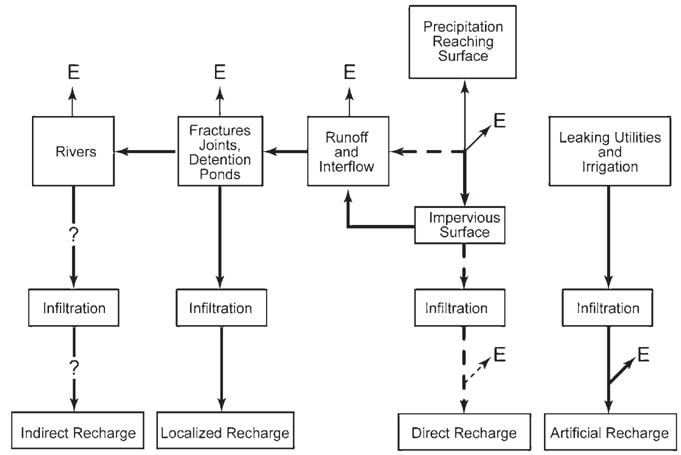

Fig. 4: *Sources of recharge in an urban area. Modified from Wiles and Sharp, (2008).*

Artificial recharge includes leakage from water mains, sewers, storm drains, and detention ponds as discussed above. It also includes irrigation return flows from overwatering and other means of artificial recharge, such as soakways, injection wells, drain fields, diversion of surface waters into sinkholes, etc. If the shallow groundwater system is not being utilized, artificial recharge is expected to raise the water table. Austin, Texas, uses water from the Colorado River, which has different chemical and isotopic signatures than groundwater that has recharged through the Cretaceous carbonates that underlie the city. As streams become more urbanized as indexed by impervious cover percentages, the chemical and Sr-isotopic signatures evolve match those of the River rather than those of the Cretaceous bedrock (Figure 5). During low flow conditions in completely urbanized reaches of the stream, it appears that nearly all stream flow originated from treated water that once flowed through the city's water distribution system (Sharp et al., 2006; Christian et al., in preparation).

Localized recharge occurs where water runs a short distance from the point of precipitation impact to where it intersects fractures or

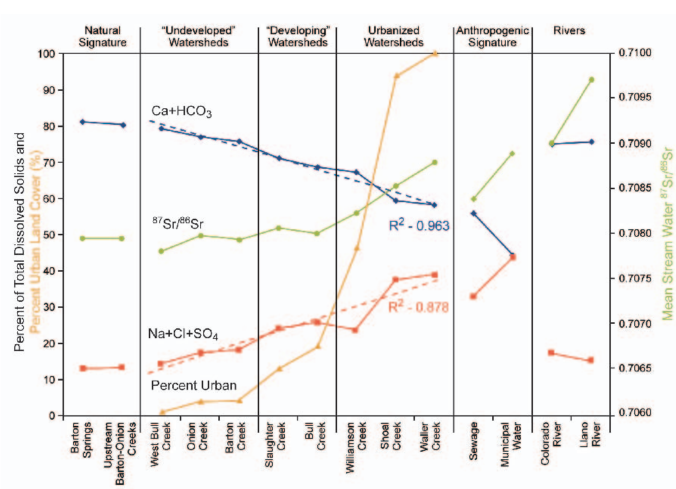

Fig. 5: *Chemical and Sr-isotopic data for streams in the Austin, Texas, USA (Christian et al., in preparation). As streams become more urbanized, their chemical and isotopic signatures approach those found in Austin tap water. Leakage (artificial recharge) from municipal water (water main leakage and over irrigation of lawns, gardens, and parks) and from sewage lines can account for this trend.*

joints in the paved surfaces, which are secondary permeability features (Wiles and Sharp, 2008). Localized recharge can also be significant and DeVries and Simmers (2002) infer that it may be the dominant recharge component in arid or semi-arid zones. Wiles and Sharp report the measurement of permeability of these secondary features in Austin, Texas, USA. They conclude by upscaling over pavement area that approximately 20% of the mean annual precipitation could become localized recharge (through "impervious" cover). This number is consistent with estimates of recharge obtained from empirical studies of sewer systems and roadway design (Wiles and Sharp, 2008, Figure 2 therein).

Although recharge rates vary spatially and temporally so that it may decrease in some areas and increase in other areas of a city because of the varying intensity of factors discussed above, recharge generally is expected to increase with urbanization for the urban area as a whole.

Conclusions

Urbanization causes changes to the land surface by altering topography and vegetation, increasing shallow groundwater temperatures, raising or lowering water tables, and extraction of groundwater during or after construction and as a water resource that can cause subsidence and its accompanying effect. These all affect the shallow groundwater systems.

Two general and important effects are:

1) The alteration of the permeability field by construction, particularly high permeability utility systems and the trenches dug to accommodate their emplacement. This alters groundwater flow paths and makes contaminant remediation difficult.

2) Changes to groundwater recharge. Recharge rates may vary spatially and temporally but recharge generally increases within urban areas.

Alterations to urban hydrogeology should be considered in planning urban design, future water resources needs, and protection of groundwater dependent ecosystems.

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