Combined Effects of Temperature and Soils on Infiltration

More people are living and working in towns near rivers and coasts, with the result that losses due to flooding are becoming increasingly more common and severe. These consequences are not solely due to development within floodplains, but also to the cumulative effects of historical watershed alterations that have changed the hydrologic, hydraulic, and sediment-carrying capacity of the watersheds. Increased emphasis on environmental and socioeconomic aspects of floods and flood damage reduction requires the development of improved methods for the planning, design, construction, maintenance, operation, and monitoring of urban flood damage reduction projects to maximize benefits in a manner that is morphologically, environmentally, socially, and economically sustainable. The U.S. Army Corps of Engineers is now engaged in innovative planning, design, operation and maintenance, construction, and emergency response methods to provide flood damage reduction for current and projected growth in urbanized inland and coastal areas. The lead research program for this effort is called Technologies and Operational Innovations for Urban Watershed Networks (TOWNS), which has been strategically designed to develop technical products targeted at the needs expressed by those involved in urban flood damage reduction.

Census data show that population growth in the arid and semi-arid west is outpacing population growth in other regions of the country (Fig. 1). Six of the ten largest cities in the United States are in arid or semi-arid areas (Table 1). Three of these (San Diego, Phoenix, and San Antonio) showed double-digit percentage increases in population between 1990 and 2000. Dramatic population growth was seen in smaller cities over the same period, with seven of the ten largest percent increases in population for cities over 50,000 population occurring in Arizona, Texas, Nevada, and California (Table 2).

Figure 1. Population growth in the arid and semi-arid west is outpacing population growth in other regions of the country.

Table 1. Census information for the 10 largest U.S. cities, 1990 and 2000.					
City	1990 Population (thousands)	Rank (1990)	2000 Population (thousands)	Rank (2000)	% Increase 1990–2000
New York, New York	7,323	1	8,008	1	9.4
Los Angeles, California	3,485	2	3,694	2	6
Chicago, Illinois	2,784	3	2,896	3	4
Houston, Texas	1,631	4	1,953	4	19.8
Philadelphia, Pennsylvania	1,586	5	1,517	5	–4.3
San Diego, California	1,111	6	1,223	7	10.2
Detroit, Michigan	1,028	7	951	10	–7.5
Dallas, Texas	1,007	8	1,189	8	18
Phoenix, Arizona	983	9	1,321	6	34.3
San Antonio, Texas	936	10	1,145	9	22.3

Table 2. Census information for largest increases in population growth for U.S. cities over 50,000 (not due to county consolidation).					
Rank	Municipality	2000 Population	1990 Population	Change in Population	Percentage Change in Population
1	Gilbert, Arizona	109,697	29,188	80,509	276%
2	Flower Mound, Texas	50,702	15,527	35,175	227%
3	Vancouver, Washington	143,560	46,380	97,180	210%
4	Henderson, Nevada	175,381	64,942	110,439	170%
5	Sugar Land, Texas	63,328	24,529	38,799	158%
6	McKinney, Texas	54,369	21,283	33,086	156%
7	Bend, Oregon	52,029	20,469	31,560	154%
8	North Las Vegas, Nevada	115,488	47,707	67,781	142%
9	Chino Hills, California	66,787	27,608	39,179	142%
10	Jacksonville, North Carolina	66,715	30,013	36,702	122%

Consideration of urban flood problems that are characteristic of the arid and semi-arid west is critical. The Urban Flood Demonstration Program (UFDP), developed through collaboration between the Corps' Engineer Research and Development Center (ERDC) and the Desert Research Institute (DRI), is exploring urban flooding in arid and semi-arid regions. Research topics are similar to those pursued in TOWNS, and include hydrology, hydraulics, sediment transport, channel stability and restoration, and ecological aspects of flooding in arid and semi-arid regions. One important aspect of hydrology and hydraulics is the estimation of the rainfall–runoff relationship for flash floods, particularly those occurring during the summer months. Anecdotal evidence suggests that there are seasonal effects on the rainfall–runoff relationship; however, this has not been studied in depth. This technical note addresses a knowledge gap: the combined effects of soil and temperature on infiltration rate.

Background

The hydrographic response of watersheds to precipitation is determined by their morphologies and their abilities to abstract rainfall. The abstraction ability of a soil is determined by its infiltration rate, which in turn is a function of its hydraulic properties and antecedent water content. Loss rate parameters in runoff models are typically determined by the type, condition, and cover for the hydrographic unit being considered. Seasonal effects are rarely, if ever considered. Recent research by scientists at ERDC and DRI has found that temperature can have a strong influence on loss rates. Modeling studies funded by the UFDP in the Las Vegas Valley indicate that temperature also can have a strong effect on infiltration. Further, these studies indicate that the nature of the temperature effect is strongly affected by the soil. Accordingly, modeling of hydrographic response may be improved by including temperature effects, but only if the temperature–soil interaction is included explicitly.

Infiltration

The Green and Ampt model is a widely used analytic expression of cumulative infiltration:

$$I = (\theta_0 - \theta_i)\left(2K_0 t \frac{h_0 - h_i}{\theta_0 - \theta_i}\right)^{1/2} \tag{1}$$

where I is cumulative infiltration (m); t, time (s); θ_0, volumetric soil water content at saturated surface ($m^3 \bullet m^{-3}$); θ_i, antecedent volumetric soil water content ($m^3 \bullet m^{-3}$); K_0, hydraulic conductivity at the saturated surface ($m \bullet s^{-1}$); h_0, hydraulic head at the saturated surface (m); and h_i, antecedent hydraulic head in the soil profile (m) (Jury et al. 1991). Temperature has strong influence on two of the parameters in equation (1), the hydraulic conductivity (via the effect of temperature on water's viscosity) and the antecedent hydraulic head (via an as-yet-unknown mechanism).
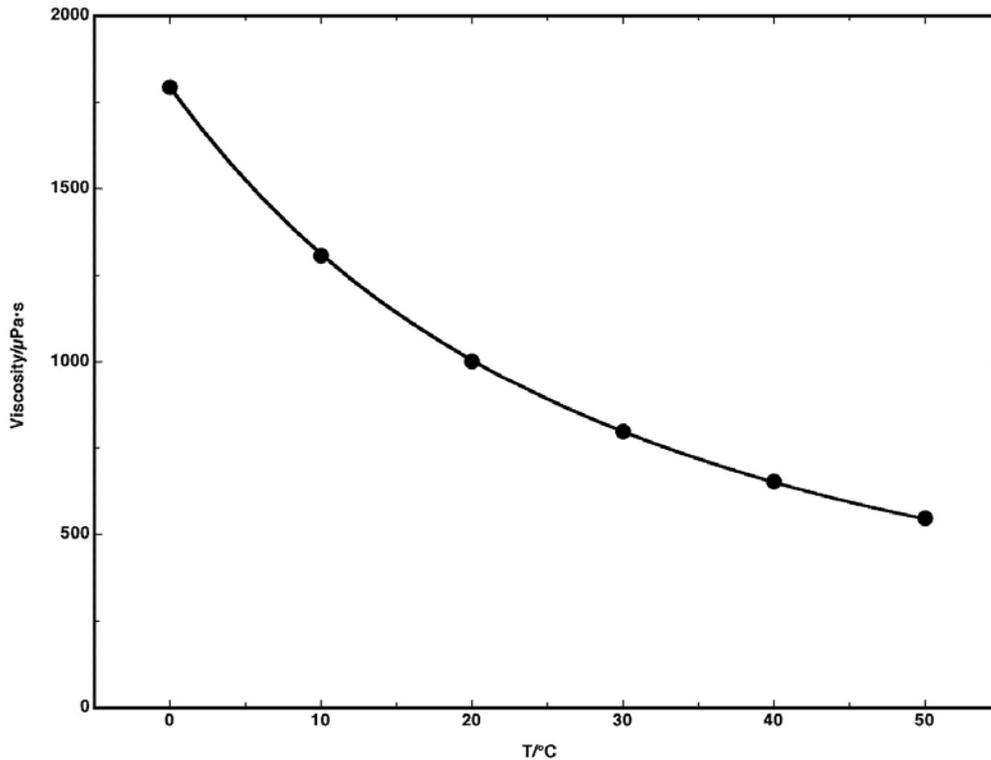
Figure 2. Viscosity of water between 0 and 50 °C.

The viscosity of water decreases with increasing temperature (Fig. 2). The following relation describes the viscosity of water (η, Pa $\bullet$ s) as a function of temperature:

$$\eta_l = \eta_0 \exp\left(\frac{B}{T + T_0}\right) \tag{2}$$

where T is temperature (°C) and η_0, B, and T_0 are fitted constants (Grant 2004). The hydraulic conductivity can be described by

$$K_0 = \frac{k\rho g}{\eta} \tag{3}$$

where ρ and η are the density and viscosity of the liquid (kg•m^{-3} and Pa•s, respectively), g is the gravitational constant (m•s^{-2}), and k is the intrinsic permeability of the porous matrix (m^2) (Muskat and Meres 1936). Equations (2) and (3) indicate that hydraulic conductivity will increase exponentially with temperature.

Hydraulic head at constant degree of saturation is a linearly decreasing function of temperature, the slope of which is specific for each soil. The behavior in many soils has been fitted to the following equation:

$$h = h(T_r)\frac{\beta_0 + T}{\beta_0 + T_r} \tag{4}$$

where h is hydraulic head (m), $h(T_r)$, hydraulic head (m) at T_r, a reference temperature (in degrees kelvin, K = °C + 273.15), and β_0, a fitted parameter (K) (Grant and Salehzadeh 1996). Figure 3 presents soil hydraulic head as a function of water content and the β_0 parameter.
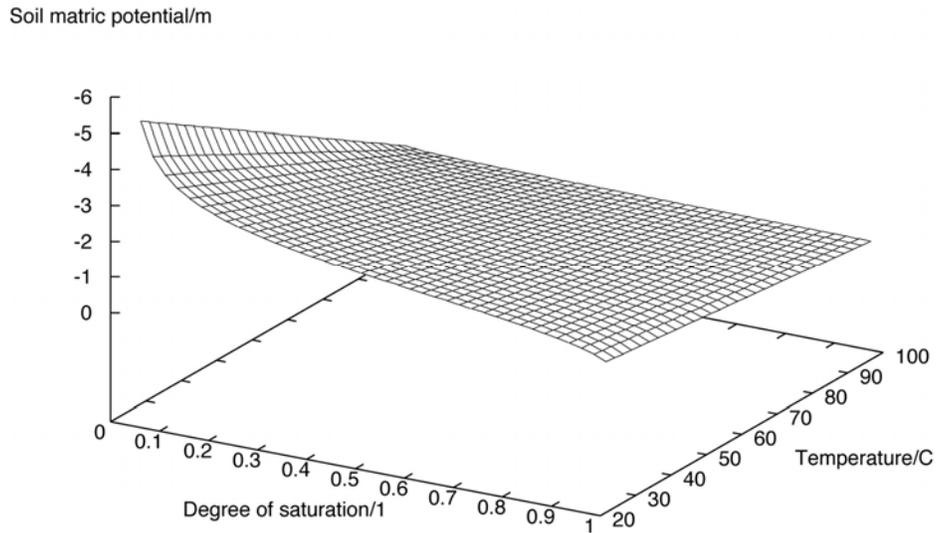
Figure 3. Soil hydraulic head as function of degree of saturation and temperature.

Depending on soil, the β_0 has values from –340 to –460 K. For infiltration or imbibition β_0 is a simple function of the geometric mean soil particle radius (Grant and Or in prep). This relationship is presented in Figure 4. In principle, therefore, the β_0 value of a soil can be estimated if its texture is available in a GIS database.

Cumulative infiltration can therefore be described by

$$I = \left[2k\rho g(\theta_0 - \theta_i)\right]^{1/2}\left[\frac{-h_i(T_r)t\left(\frac{\beta_0 + T}{\beta_0 + T_r}\right)}{\eta_0 \exp\left(\frac{B}{T + T_0}\right)}\right]^{1/2} \tag{5}$$

(Grant and Young in prep). Figure 5 presents cumulative infiltration after 180 s divided by cumulative infiltration at 25 °C by a soil with a β_0 parameter value equal to –760 K. Figure 4 shows that temperature has an effect on infiltration and that these effects are soil specific. For soils with β_0 parameter values above –400 K, cumulative infiltration was an increasing function of temperature. Coarse textured soils were likely to have β_0 parameter values equal to or more negative than –400 K. For soils with β_0 parameter values closer to –340 K, which are likely to be finer textured soils, the estimated cumulative infiltration was an increasing function of temperature to roughly 25 °C, but a decreasing function of temperature from 25 to 50 °C.
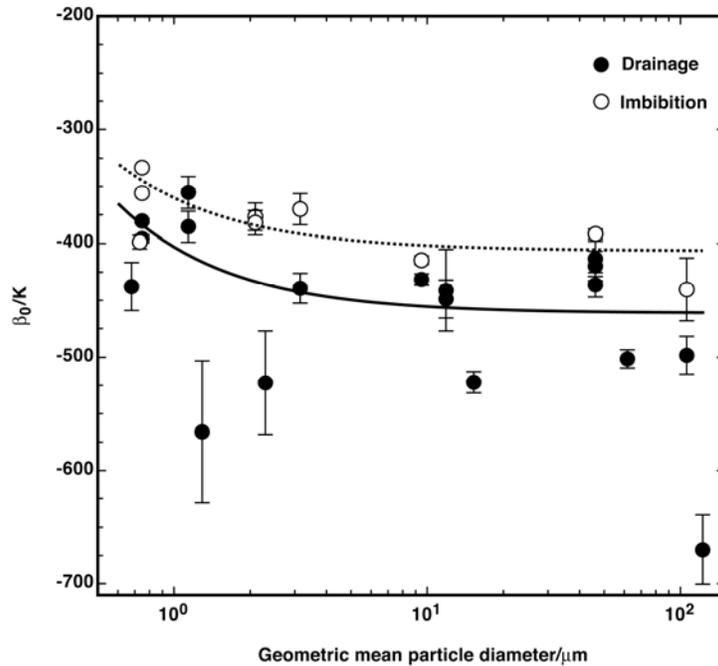
Figure 4. Relationship between ß₀ parameter and average particle diameter.

Future research

Fulfilling the Corps mission to provide flood damage reduction, predict watershed water quality, and to restore safe drinking water requires continuous improvement in watershed management tools. Although season and temperature are rarely considered a factor in hydrographic response of watersheds, field research has indicated that they are factors that deserve consideration. At the present time, no analytic method by which to simulate these effects has been suggested for field use. The results presented here provide an indication of the likely effect of temperature on infiltration, abstraction, and runoff as well as the conceptual tools for including these effects in Corps water-management products. Future research plans include the development of a method that can be included in hydrologic modeling tools such as HEC-HMS or WMS. This method will be verified using field observations collected in an urbanized watershed in the Southwest.
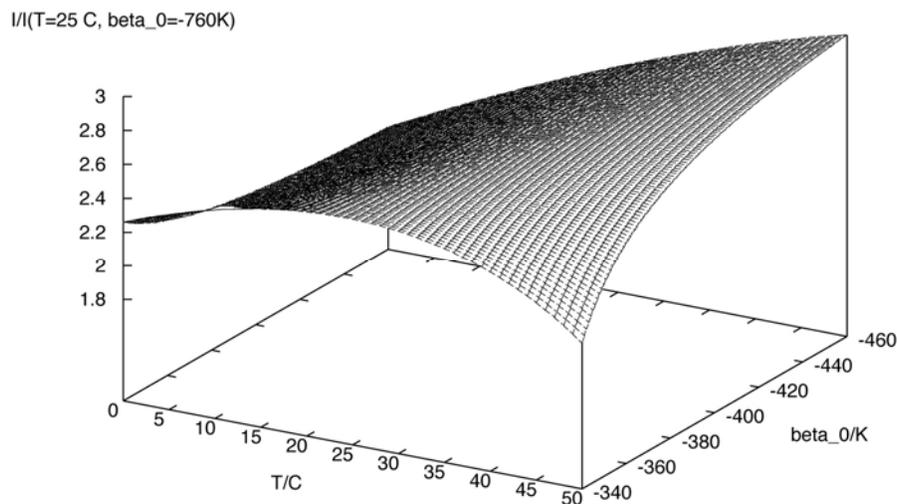
Figure 5. Normalized infiltration as a function of temperature and ß₀ parameter value.

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