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Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review

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Abstract
Baseflow is the portion of streamflow that is sustained between precipitation events, fed to stream channels by delayed (usually subsurface) pathways. Understanding baseflow processes is critical to issues of water quality, supply, and habitat. This review synthesizes the body of global literature investigating relationships between baseflow and watershed characteristics of geomorphology, soil, and land use, as well as the potential effects of climate change, with an emphasis on humid, tropical and temperate (non-snowpack-dominated) regions. Such factors are key controls on baseflow through their influence on infiltration, rates of water removal from the catchment, and subsurface storage properties. The literature shows that there is much that remains to be resolved in gaining a solid understanding of the influence of watershed characteristics on baseflow. While it is clear that watershed geomorphology influences baseflow, there is no consensus on which geomorphic parameters are most closely linked to subsurface storage and baseflow. Many studies associate higher watershed forest cover with lower baseflows, attributed to high evapotranspiration rates of forests, while other studies indicate increased baseflow with higher watershed forest cover due to higher infiltration and recharge of subsurface storage. The demonstrated effects of agriculture and urbanization are also inconsistent, due to varied additions of imported water and extremely variable background conditions. This review underscores the need for more research that addresses multiple aspects of the watershed system in explaining baseflows, and for methodological consistency to allow for more fruitful comparisons across case studies. These needs are of immediate demand, given scientific and management emphasis on environmental flows required for maintenance of key ecosystem services.

Keywords
baseflow, catchment, climate change, ecosystem services, environmental flows, watershed

I Introduction

Baseflow is influenced by natural factors such as climate, geology, relief, soils, and vegetation. Human impacts on the landscape may modify some or all of these factors, in turn affecting baseflow timing and quantity. The need for a greater understanding of streamflow response

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to external change has been recognized for decades, but previous research has tended to emphasize flood response to increased human pressures on the landscape (e.g. Choi, 2008; Knox, 2001). In this respect, the literature is lacking with regard to studies investigating baseflow response to human impact. A scientific understanding of watershed processes and baseflow is critical to effective water policy and management. Population growth is associated with increasing demands on freshwater resources for industry, agriculture, and human consumption, and water shortages are not uncommon, even in humid regions (Hornbeck et al., 1993). A firmer grasp on the controls of baseflow is pivotal in issues of contaminant dilution (Barnes and Kalita, 2001; Jordan et al., 1997; Novotny and Olem, 1994), stream ecology (Boulton, 2003; Klein, 1979; Konrad and Booth, 2005), and adequate water supply to population centers (Hornbeck et al., 1993; Illinois EPA, 2002). Ensuring safe concentrations of contaminants associated with wastewater effluent requires accurate estimation of baseflow discharge (Smakhtin, 2001), and contaminants that enter stream systems via soil or groundwater storage are most highly concentrated during baseflow. These factors carry negative implications for stream biota and human consumption if baseflows are reduced (Barnes and Kalita, 2001; Dewson et al., 2007; Novotny and Olem, 1994). Reduced baseflow is also associated with reduced stream width, warmer temperatures, lower dissolved oxygen, and higher nutrient concentrations that may promote excessive growth of habitat-choking algae (Leigh, 2010; Price and Leigh, 2006a). These conditions are often fatally stressful for sensitive, endemic species, and low water levels in streams have been associated with decreases in richness of aquatic macroinvertebrate and fish species (Boulton, 2003; Mote et al., 2003).

The objective of this review was to synthesize research from various water resources disciplines, in order to provide a cohesive summary of the current state of research knowledge regarding the influences of watershed characteristics on stream baseflows and to address the potential impacts of climate change in this context. Water resource management requires a firmer understanding of baseflow processes, and a secondary objective of this review is to identify key research questions that remain unanswered. This review emphasizes literature covering geomorphic and anthropogenic effects on baseflow in humid, temperate and tropical regions of the world. Baseflow-controlling processes in polar and arid settings are sufficiently unique to merit specific treatment elsewhere. The introductory section covers a basic definition of baseflow, as well as discussion of primary controls on baseflow and various approaches to quantification. Next, a section on geomorphic controls on baseflow discharge covers the influences of basin geology, surface topography, subsurface topography, and soils. This section is followed by an overview of anthropogenic effects on baseflow, with emphases on forest removal, agriculture, and urbanization, because of the large body of research on those topics. Next, a summary of current research evaluating and predicting baseflow response to climate change is presented. The review concludes with a discussion of key research topics, the results of which would fill large gaps in our understanding of watershed hydrology and baseflow.

I Baseflow overview

Within the literature, there is inconsistent terminology usage, with 'baseflow' and 'low flow' commonly used interchangeably to denote streamflow occurring between precipitation and/or snowmelt events, resulting from sustained subsurface inputs to the stream channel. These and other terms are also inconsistently differentiated within the literature to specify the lowest annual streamflow within a watershed or region. In this review, the term 'baseflow' will be used

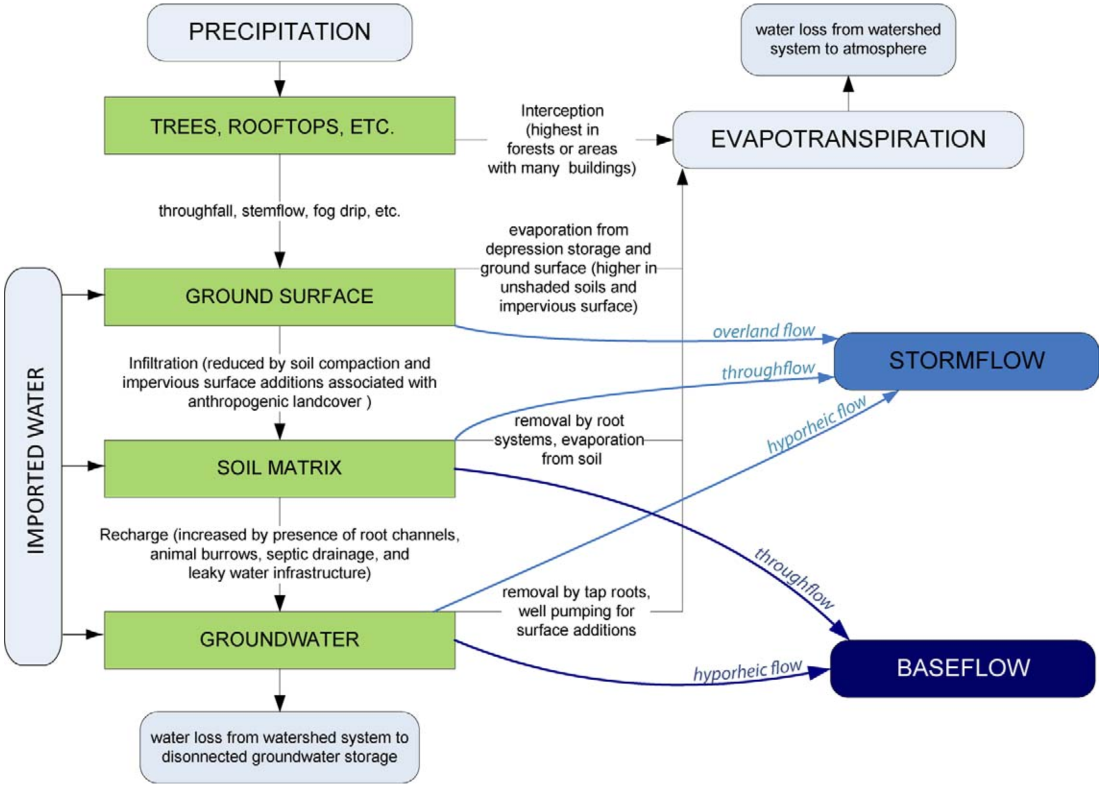

Figure 1. Conceptual model of watershed inputs, storage, and losses, and their roles in determining baseflow quantity. The primary input is precipitation, with imported water serving as an important input in some developed and agricultural watersheds. Factors of land use and climate change that increase infiltration and recharge are positively associated with baseflow, while those that increase evapotranspirative loss are negatively associated with baseflow. Prediction of baseflow response to environmental change requires consideration of both types of factors.

generally to represent streamflow fed from deep subsurface and delayed shallow subsurface storage between precipitation and/or snowmelt events (Ward and Robinson, 1990), and 'low flow' will specify dry season minimum flows (Smakhtin, 2001).

Several sources emphasize that 'baseflow' is not synonymous with groundwater flow, as it includes water transmitted from shallow unsaturated storage in addition to significant contributions as hyporheic flow from phreatic storage (Anderson and Burt, 1980; Brutsaert, 2005; Buttle, 1998; Ward and Robinson, 1990). In addition to bedrock water storage, baseflow is also derived from the drainage of near-surface valley soils and riparian zones, as water concentrates in these areas during and following precipitation events (Brutsaert, 2005; Smakhtin, 2001). Factors that promote infiltration and recharge of subsurface storage will increase baseflows, while factors associated with higher evapotranspiration (ET) will reduce baseflows (Figure 1). Baseflow is naturally influenced by a wide range of factors (Brutsaert, 2005):

- Basin physiographic characteristics;
- Distribution of storage in river channels and groundwater aquifers;
- Evapotranspiration (ET) from stream banks and throughout the catchment;

- Geomorphology of the landscape and stream network;
- Configuration and nature of the riparian aquifers and near-surface soils.

Many of these factors may be altered with human impact on the landscape, and it thus becomes critical to understand not only the relationships between basin physical properties and stream baseflow, but also the ways in which direct anthropogenic watershed impacts and climate change affect these physical properties.

2 Methods of identifying baseflow sources and residence/transit times

Many types of tracers are used for both source-apportionment ('fingerprinting') of baseflow sources and for estimation of transit times of water from the time it enters the watershed as precipitation to its exit at the stream outlet. Stable and radioactive environmental isotopes provide information on the hydrogeological characteristics of aquifers including the origin, time, and rate of recharge, and aquifer interconnections (Gonfiantini et al., 1998). Tracers as naturally occurring solutes, 'injected' solutes, and the isotopic composition of the water molecule itself have all been successfully used in baseflow studies. Solutes that originate in distinct areas of watersheds (based on geochemical or landcover differences) can be used for source-apportionment of baseflow (e.g. Gburek and Folmar, 1999; Lindgren et al., 2004). Geochemical solutes related to weathering reactions can be used to identify whether water is sourced from bedrock, where weathered ions are readily dissolved into the water, versus the regolith and soil mantle, from which these ions were long ago removed during the weathering process (Tetzlaff et al., 2007; Velbel, 1985). End-member mixing analysis (EMMA) is a method commonly used for source-apportionment of water, based on distinct ratios of multiple solutes originating in different parts of the catchment, generally based on mineralogical and geological differences (Christophersen et al., 1990; Genereaux et al., 1993). The ability to use natural geochemical signatures for source-apportionment varies with geologic setting, particularly the mineralogy and age of the landscape. In the absence of naturally occurring geochemical signatures, or to supplement such analyses, tracers may be injected into different portions of the watershed, in order to identify flowpaths and transit times. Dissolved gases, such as chloride and bromide, and plugs of highly saline water are commonly used as injected tracers (Solomon et al., 1998; Wang et al., 2009). Radioactive isotopes, such as radon, have also been used to identify baseflow sources and timing (e.g. Genereaux et al., 1993). A very active area of hydrologic research involves the use of stable isotopes in water molecules, which is thoroughly covered by Kendall and McDonnell (1998), and in more recent reviews by McGuire and McDonnell (2006) and Michel (2009). The varied concentrations of oxygen and hydrogen isotopes in precipitation versus stored water are used to fingerprint stream water for source-apportionment, and to distinguish stored water (or 'old water') from recent precipitation and surface runoff ('new water'). The potential exists for tracers to be used for the estimation of catchment water storage volumes, although to date this application is underexplored (Soulsby et al., 2009). A thorough review of the quantitative methods and issues surrounding estimation of water transit times is presented by McGuire and McDonnell (2006).

3 Quantifying baseflow and low flow

There is no standard method for quantification of baseflow, due to the large variety of research and management objectives and lengths of available streamflow records. There are four major categories of metrics used to summarize baseflow from an existing streamflow record: (1) event-based low flow statistics; (2) flow-duration curve statistics; (3) metrics that express the proportion of baseflow to total flow; and (4) baseflow recession statistics. Additionally, many researchers have attempted to build predictive equations, based on watershed characteristics and meteorological conditions, to estimate baseflow in ungauged basins.

Event-based low flow statistics associated with varied return frequencies are used in many water quality and aquatic habitat management applications. These include calculations of 'environmental flows', or the flow regime required to sustain suitable habitat conditions for a given organism (O'Keeffe, 2009; Poff et al., 2010), as well as waste-load allocations, point source discharge permits, and withdrawal allowances related to water supply planning (Stedinger et al., 1993). One of the most commonly used metrics designed to express a minimum flow over a period is the 7Q10 statistic, which is the lowest streamflow for seven consecutive days that would be expected to occur once every 10 years (US EPA, 1997). This metric targets extreme low flow and is widely used for regulatory and modeling applications, especially with respect to point-source pollution and determination of Total Maximum Daily Load (TMDL) values for contaminants and nutrients (Ames, 2006). The 7Q10 statistic can only be calculated if there is sufficient length of flow record to calculate a reasonable 10-year recurrence probability. In addition, many researchers and managers seeking to establish environmental flows for aquatic biota may be concerned with flows of a more frequent return interval than decadal. Thus, other event-based statistics are used according to research needs and data availability, such as the 7Q2 (lowest seven-day flow with a two-year recurrence interval), average annual minimum daily flow, the minimum seven-day flow over a study period, etc. (Ouarda et al., 2008; Price et al., 2011; Stedinger et al., 1993).

These event-based low flow statistics, by definition, highlight extreme low flows. Many aspects of environmental flow management and water supply planning, however, benefit from information about sustained conditions as well. For these purposes, flow-duration statistics are used to identify exceedence probabilities of all flow observations in a given period of record (Stedinger et al., 1993). For emphasis on baseflow, flows that are exceeded a high proportion of the time are generally isolated. For example, managers might be interested in the 1, 5, or 25 percentile flow magnitude, which are exceeded 99, 95, and 75% of the time, respectively, during the entire period of analysis (Patel, 2007). These statistics are often referred to as Q_x, with Q representing discharge, and x representing the probability of exceedence (e.g. Q_{99}, Q_{95}, and Q_{75}).

A representation of sustained conditions, as opposed to extremes and events, is the baseflow index (BFI), which is the proportion of baseflow to total streamflow over a continuous period of record (Bloomfield et al., 2009). This metric is widely used in recent literature and has been indicated as an important variable for linking watershed characteristics to baseflow, addressing water quality concerns characterizing instream habitat availability, and drawing inferences about subsurface storage capacities (Lampadariou et al., 2008; Lee et al., 2006; Tesoriero et al., 2009). Determination of BFI requires separation of baseflow from stormflow, for which many methods have been used. Eckhardt (2008) provided a thorough review and analysis of seven baseflow separation methods. If data are available, concentrations of environmental isotopes such as oxygen-18 and deuterium can be used to separate event and pre-event water in streamflow (Buttle, 1994; Didszun and Uhlenbrook, 2008; Tetzlaff et al., 2007).

For most methods of baseflow separation, some analysis or index of a stream's recession characteristics is usually necessary, and recession analysis can offer fruitful insights in its own right (Wittenberg, 2003). A review of methods of baseflow recession analysis is presented by Tallaksen (1995). Since the publication of that review, additional computational resources for recession analysis have become available, such as those described by Rutledge (1998), the spreadsheet method presented in Posavec et al. (2006), and the RECESS program created by the US Geological Survey (Rutledge, 2007). Gottschalk et al. (1997) described a method for combining recession analysis and low flow frequency analysis that has been successfully used for regionalization of low flow distribution functions. Ivanowski (2009) used the RECESS program to evaluate variability of recession characteristics of 20 watersheds in the Piedmont physiographic province of the southeastern USA, and found watershed relief to be a more important determinant of recession form than climatic factors. Wang and Cai (2010) demonstrated that recession characteristics can be used to evaluate the relative impacts of climate change and land-use change.

All four types of baseflow metrics are sometimes estimated using predictive statistical models for ungauged basins, based on regional empirical relationships between watershed characteristics and baseflow at gauged sites. There typically is a great deal of uncertainty associated with such approaches (Clausen, 1995), but they can be useful in the absence of observed data. An example of this approach is available from the US Geological Survey (Bingham, 1986), in which regionalized equations are presented for predicting low flows in Tennessee streams. These equations contain variables related to underlying geology and drainage area, and are associated with standard error ranging from 24 to 33%. Similar approaches have been used in other areas of North America and Europe (Bloomfield et al., 2009; Clausen, 1995; Gustard et al., 1989; Kent, 1999; Longobardi and Villani, 2008; Nathan et al., 1996; Neff et al., 2005; Thomas and Benson, 1970; Vogel and Kroll, 1992; Zhu and Day, 2005). These studies indicate that explanatory variables included in statistical models that best explain baseflow variability differ considerably among the various baseflow metrics. This implies that the specific watershed characteristics that influence extreme event low flows may be different than those that influence sustained baseflows and recession characteristics, and underscores the need for establishment of a consistent set of baseflow metrics to facilitate cross-study comparisons. Ouarda et al. (2008) presented a review of statistical approaches for predicting low flows based on watershed characteristics.

II Geomorphic controls on baseflow

1 Geology

Catchment geology is a primary control on baseflow-generating processes (Bloomfield et al., 2009; Farvolden, 1963; Freeze, 1972; Neff et al., 2005; Smakhtin, 2001; Tague and Grant, 2004). In regions underlain by permeable, soluble, or highly fractured bedrock, groundwater storage volumes within the bedrock itself may be highly significant, and the connectivity to the surface water network may be extremely complex. In contrast, areas underlain by crystalline or massive bedrock with minor fracturing may not store significant quantities of water and thus contribute to relatively short water residence times (McGuire et al., 2005; Smith, 1981). In addition to bedrock type, geologic structure is also of great importance to baseflow hydrology in some regions (Delinom, 2009), and boundaries between geologic units have been shown to be important zones of groundwater-surface water interaction (Arnott et al., 2009; Konrad, 2006). Smith (1981) showed that low flows in shale and sandstones in Virginia were highly dependent on the degree of bedrock folding, with massively folded regions yielding higher low flows than non-folded zones. In some settings, bedrock fractures more readily transmit water to deep subsurface storage that is not connected to the surface stream network (hereafter ‘disconnected storage’), than to more shallow storage that feeds baseflow (Seaton and Burbey, 2005). In some areas of extreme karst development, a losing effect on baseflow has been observed, due to the often very high storage capacities in limestone and dolomite solution cavities (White, 1977). Baseflow losses have also been observed in areas of highly porous sandstone (Arnott et al., 2009). Catchment geology also indirectly affects basin hydrology in its influence on drainage network structure. Easily eroded bedrock lends itself more readily to channel formation and pedogenesis, both affecting storage capacities and rates of water transmission (Farvolden, 1963; Mwakalila et al., 2002). In some regions, weathered overburden (e.g. saprolite or other regolith), may serve as a more important baseflow-sustaining reservoir than the underlying solid bedrock (Smith, 1981; Witty et al., 2003). This can lead to complications with interpreting the influence of bedrock type on baseflows, because in many areas crystalline bedrock is associated with very low porosity and storage, but lends itself to the development of thick saprolite overburden that may store and transmit substantial quantities of water (Mwakalila et al., 2002). In addition to bedrock and saprolite, substantial quantities of baseflow may also originate from the near-surface valley bottom storage, such as bank soils, alluvial fills, and wetlands, where short-term storage levels are maintained to allow continuous lateral drainage into channels (Brutsaert, 2005; Smakhtin, 2001). This variably saturated throughflow zone, which may consist of a combination of regolith, alluvium, and/or soil, is often a more important source of baseflow than deeper groundwater (Ambroise et al., 1996; Mwakalila et al., 2002).

2 Surface topography

Meaningful assessment of basin topography is often missing from watershed analyses. Surface topography is a key control on baseflow (Vivoni et al., 2007), both directly and indirectly, and the influence of topography is most pronounced in relatively high relief settings (Tetzlaff et al., 2009). Exceptions exist in karst or highly porous settings, such as volcanic or glacial terrain, where water can move freely in the subsurface below surface drainage divides (Devito et al., 2005). Topographic gradients control the rate at which soil water moves downslope, thereby determining whether stormwater is flushed to the channel network or retained in the soil post-event (Figure 1). The effect of land-use and climate change on streamflow may be mitigated or amplified by basin surface and/or subsurface topography, and ideally these factors should be considered in assessment of stream response to human impact (Dubé et al., 1995; Iroumé et al., 2005). Little is known regarding which specific topographic variables are most useful for predicting baseflow and/or explaining baseflow variability response to land-use change, but many metrics have been demonstrated as beneficial components of hydrologic models.

Metrics of surface topography in hydrologic modeling are often reduced to single indices, with Beven and Kirkby's (1979) topographic index (TI) the most common. TI is computed as $\ln(\alpha/\tan \beta)$, where $\alpha =$ specific contributing area to a given site, and $\beta =$ the local slope angle at that site. TI increases as contributing area increases and slope angle decreases. Increasing drainage area should increase groundwater contributions, and decreasing slope angle should reduce the rate of groundwater transmission, assuming that surface topography approximates the hydraulic gradient for shallow groundwater systems (Buttle et al., 2001). Troch et al. (1993) reported that the TOPMODEL approach using TI and soil transmissivity yielded accurate depths to shallow water tables. However, many studies that test predicted versus observed water table depths, streamflows, or other related factors using this approach have reported limited success (Burt and Butcher, 1985; Buttle et al., 2001; Jordan, 1994; Moore and Thompson, 1996; Rodhe et al., 1996). Furthermore, the index is so highly generalized that mean basin TI values may not vary greatly within a study region (McGuire et al., 2005; Price et al., 2011), limiting its use in cross-site comparisons. The lack of total success of such an approach does not by any means negate the importance of surface topography in the storage and transmission of baseflow, although some of these authors arrive at that conclusion. The lack of success is at least partially due to the insufficiency of the index in characterizing elements of basin topography that directly relate to watershed storage and transmission rates. Though obviously simplistic, TI is readily computed from digital terrain data and incorporated into spatial models, and is thus widely used in popular applications, such as TOPMODEL (Beven and Kirkby, 1979).

Several studies have demonstrated that parameters expressing catchment geometry (e.g. hypsometric integral, metrics expressing degree of stream network development, and indices of flowpath length and gradient) are beneficial in prediction and analysis of baseflow and related factors (Farvolden, 1963; McGuire et al, 2005; Woods et al., 1997). Among many influences addressed, Farvolden (1963) found potential discharge (a flow component related to baseflow) to be most strongly correlated to basin geometry in a mountainous region of Nevada. Woods et al. (1997) devised a subsurface flow index based on surface topography, which the authors report to efficiently describe the time-varying spatial pattern in subsurface runoff generation, ideal for use in steep forested catchments in humid climates. Corroborating the idea that catchment-scale flow path distribution is largely a function of catchment geometry (Kirchner et al., 2001; Lindgren et al., 2004), McGuire et al. (2005) found strong correlations between catchment terrain indices representing flow path distance and gradient to the stream network in the Oregon Cascades. Santhi et al. (2008) found topographic relief to be a predictor of BFI on a regional scale. However, dimensionless topographic parameters were shown to have no relationship with BFI in southeastern Australia (Lacey and Grayson, 1998). Drainage density, or the length of stream network per unit watershed area, has been shown to have a negative relationship to baseflow in many settings (Farvolden, 1963; Gregory and Walling, 1968; Marani et al., 2001; Price et al., 2011; Tague et al., 2008; Warner et al., 2003). Higher drainage density is synonymous with greater contact area between subsurface storage and stream channels. This greater contact area may facilitate removal of water and reduce baseflows during drier times of year. Additionally, drainage density may be related to subsurface storage characteristics, with higher drainage density possibly negatively correlated with storage capacity.

In addition to its influence on subsurface flowpath distribution and transit times, surface topography also relates to the distribution of shallow storage. Surface topographic characteristics may express the amount of alluvial bottomland and floodplain storage (Brown et al., 2005), and the presence and extent of colluvium available for subsurface water storage. Alluvial aquifers are understood to be a key source of streamflow in many settings (Larkin and Sharp, 1992). In theory, the presence and extent of alluvial valleys is closely linked with baseflow quantity, though few studies have directly addressed this relationship (Brown et al., 2005; Soulsby et al., 2006). Schilling (2009) showed that groundwater recharge quantity was highly dependent on topographic position, with the greatest quantities of recharge observed in alluvial zones. Using geochemical and isotopic tracers, Tetzlaff and Soulsby (2008) demonstrated that the upper 54% of a large river catchment in Scotland supplied 71% of the river's baseflow, and that the groundwater of the lower slopes of montane headwaters (where colluvium deposits occur) provide a major source of baseflow to the river system. Colluvium has also been shown to be an important shallow reservoir in the Cascades (Galster and Leprade, 1991; Schulz et al., 2008), and was an important variable for explaining variability of baseflow magnitudes in the southern Blue Ridge Mountains of the USA (Price et al., 2011). This review has emphasized GIS-based evaluations of the influence of surface topographic characteristics on baseflows. It is important to note that ongoing research indicates that variation in digital elevation model (DEM) resolution can have a pronounced effect on rainfall-runoff analyses, and more research needs to be conducted to link DEM-based topographic characteristics with baseflow at multiple resolutions (Dixon and Earls, 2009; Lee et al., 2009).

3 Subsurface topography and soil characteristics

Subsurface topography, in addition to surface relief, exerts strong influence on water storage and throughflow pathways, and thus influences baseflow. Throughflow processes require a confining layer through which water cannot easily infiltrate, thereby initiating lateral subsurface flow (Hutchinson and Moore, 2000). It is these confining layers that prevent continued infiltration of water, thereby allowing shallow storage contributions to baseflow. In hydrologic modeling, topographic indices to estimate soil moisture properties and rates of throughflow are generally limited to metrics of surface topography, despite the known influence of confining layers on flowpaths and soil moisture characteristics (e.g. Chaplot and Walter, 2003; Chaplot et al., 2004; Gburek and Folmar, 1999; Hutchinson and Moore, 2000; McDonnell et al., 1996). During or immediately following storm or snowmelt events, when water table elevations are relatively high, the soil moisture surface is more likely to parallel the surface topography than that of the confining layer (Hutchinson and Moore, 2000). However, the influence of subsurface topography is of particular importance during relatively low moisture conditions, when the topography of the confining layer may be the predominant control on moisture retention, and, thus, an important factor for baseflow. However, no known studies have specifically addressed the influence of subsurface topographic characteristics on stream baseflows.

Subsurface strata that induce throughflow are widely varied, but are most often associated with pedogenically unaltered parent material. Bedrock with negligible fracturing and porosity (Hatcher, 1988), impermeable saprolite (Chaplot et al., 2004), heavily compacted till (Hutchinson and Moore, 2000; Reuter and Bell, 2003), and hydraulically restrictive loess layers (O'Geen et al., 2003) have all been demonstrated to influence soil and hillslope hydrology. Additionally, pedogenic features such as claypans (Wilkison and Blevins, 1999) and well-developed argillic horizons (Perillo et al., 1999) have been shown to limit vertical infiltration, although the effect is rarely widespread enough to significantly impact meso- or macroscale hydrology. Pedogenic features generally fail to function as true confining layers, primarily due to macropore and preferential flow path development across the hydraulically restrictive horizon (Bryan and Jones, 1997). Tree root growth, animal burrowing, and other bioturbation processes affect soil horizons to a much greater extent than seen with parent material confining layers such as bedrock, saprolite, or compacted till. Wilkison and Blevins (1999) used chemical tracers to demonstrate vertical preferential flow paths through a claypan to outweigh lateral throughflow above the claypan. Similarly, Perillo et al. (1999) identified vertical preferential flow pathways created by decayed roots through a well-developed argillic horizon that partially induced lateral flow. Thus, it seems that extreme circumstances are required for pedogenic features to serve as broadly influential confining layers. These circumstances seem particularly unlikely to be met in vegetated environments, where biological activity is abundant and disruptive to hydraulically resistant horizons. Thus, it is generally assumed that lithologic contacts underlying soil, such as the soil/bedrock or saprolite/bedrock interface (Hatcher, 1988; McDonnell et al., 1996), are more important in governing subsurface flow and contributions to baseflow than pedogenic features in the soil itself.

4 Combined influences of topography and soils

Soil properties influence the distribution of water storage, but correlations between soil properties and topography typically hinder isolation of the influence of soil characteristics on water storage and baseflow. Primarily, variation in soil texture plays a significant role in the rate of moisture loss due to surface or subsurface topographic gradients (Dodd and Lauenroth, 1997; Yeakley et al., 1998). Spatial variability of soil moisture is most pronounced during unsaturated conditions between storm events (Hutchinson and Moore, 2000; Kim et al., 2005; Sidle et al., 2000; van Ommen et al., 1989), and such variability is partially attributable to soil texture. However, determining the strength of this influence is complicated by the correlations between topography and soil texture. Systematic downslope variation in soil texture commonly occurs, as the result of decreasing slope and corresponding slowed rates of water movement from ridge to toeslope positions (Schaetzl and Anderson, 2005). Thus, correlations between soil texture and hillslope position are likely to exist, with finer particle size, thicker soils, and low slope gradients combining their influences to encourage soil moisture retention. Conversely, steep upper slopes are likely characterized by coarser, less developed, and thinner soils, thereby more rapidly transmitting water. Furthermore, soil hydrology is strongly affected by spatial variability of soil moisture, which may be predominantly controlled by surface and/or subsurface topography (Woods et al., 1997). From this perspective, isolating the influence of soil characteristics from topography is problematic.

III Effects of human land use on baseflow

Widespread vegetation change and soil disturbance accompany most forms of land-use change, and such impacts are often sufficient to alter the timing and quantity of baseflow (Figure 1). Additionally, human impact may involve direct water removal (abstractions) or inputs to streams or catchments. Table 1 summarizes baseflow response to several common forms of human impact. Extreme impact (e.g. urbanization) may be associated with a total rearrangement of surface and subsurface pathways, in addition to changes in soil properties, vegetation, etc. This section on anthropogenic controls on baseflow addresses patterns observed with forest removal, urbanization, and agriculture.

1 Forest removal

Globally inclusive literature investigating the role of basin forest cover on flow in small headwater catchments (i.e. < 2 km^2) indicates an increase in mean annual flow in response to removal of basin vegetation (examples of reviews: Bosch and Hewlett, 1982; Brown et al., 2005; Hibbert, 1967; Johnson, 1998; Jones and Post, 2004; Sahin and Hall, 1996; Swank et al., 1988), with many studies specifically indicating increases in baseflow (Harr et al., 1982; Hicks et al., 1991; Keppeler and Ziemer, 1990; Smith, 1991). This relationship is due to greater interception and evapotranspiration rates associated with forest cover (Bosch and Hewlett, 1982; Calder, 1990; McCulloch and Robinson, 1993). The negative relationship between watershed forest cover and baseflow volume for headwater streams results from experimentation methods where the surface infiltration characteristics are not drastically altered, thus isolating evapotranspiration changes as the key influence on recharge and baseflow (Figure 1) (Brown et al., 2005; Bruijnzeel, 2004). In some cases, these results have been interpreted as a

Table 1. Summary of studies assessing the response of baseflow and recharge to various human impacts

Impact	Baseflow response	Attributed effect	Reference(s)
Groundwater abstraction	Decrease	Lowers water tables	Owen (1991)
Wetland drainage	Decrease	accelerated removal of water from valley bottoms	Riggs (1976)
Valley bottom vegetation change	Increase or decrease	ET change, dependent on specific impact	Keppeler and Ziemer (1990); Swank et al. (1988)
Catchment afforestation	Decrease	Increased ET	Gustard and Wesselink (1993); Trimble et al. (1987)
Catchment forest harvest	Increase	Decreased ET	Harr et al. (1982); Hicks et al. (1991); Swank et al. (1988)
Catchment forest conversion	Increase or decrease	Decreased ET, decreased infiltration	Costa et al. (2003); Wilk et al. (2001)
River abstraction	Decrease	Direct removal of water from channel	Kottegoda and Natale (1994)
Effluent discharge to rivers	Increase	Direct input of water to channel	Pirt and Simpson (1983)
Irrigation return flow	Increase	Direct input of water to channel	Blodgett et al. (1992); Dow (2007)
Importation of water	Increase	Surface and subsurface water inputs	Davies et al. (1993)
Flow regulation	Increase or decrease	Channel impoundment with regulated release	Gustard et al. (1989)

potentially dangerous suggestion that watershed management approaches could include deforestation to increase water yield for public use (Brooks et al., 1991; Chang, 2003). However, because forest cover is associated with high infiltration and recharge of basin subsurface storage (Figure 1), more permanent canopy decreases associated with pasture, agriculture, or suburban land uses my decrease baseflows due to soil compaction, reduction of soil organic matter, and increase in impervious surface (Gregory et al., 2006; Ohnuki et al., 2008; Price et al., 2010; Woltemade, 2010; Zimmermann et al., 2006). Studies investigating permanent land-use change have shown decreased baseflow from conversion of forest to non-forest land use (e.g. Bruijnzeel, 2004; Line and White, 2007), or baseflow increases associated with afforestation (Ma et al., 2009). Studies relating baseflow of 30+ streams in the Piedmont and Blue Ridge provinces of the southern Appalachian Highlands indicate a significant positive relationship between basin forest cover and baseflow discharge (Price and Jackson, 2007; Price et al., 2011).

2 Urbanization

Urbanization involves a wide range of impacts, and specific stream response depends on many factors (Doyle et al., 2000). Anthropogenic impacts on watershed hydrology accompanying urbanization involve widespread and drastic reorganization of surface and subsurface pathways, and frequently are complicated by importation of water from other watersheds or previously disconnected storage (Figure 1). Following urbanization, water is more quickly flushed through catchments due to reduced hydraulic resistance of land surfaces and

Table 2. Recharge response to various aspects of urbanization (modified from Meyer, 2002)

Increased recharge	Decreased recharge
Surface distribution of imported water (irrigation and other outdoor water use)	Impervious surface coverage and soil compaction
Infrastructure leakage of imported water	Rapid transmission of event water through storm sewers and modified channels
Stormwater detention	Leakage of shallow groundwater into storm sewers
Leakage of event water into shallow groundwater via storm sewers	Shallow groundwater withdrawal
	Removal of wastewater outside of catchment

channels, as a result of impervious surface coverage, compacted soils, channelization, and subsurface storm drainage networks. Intuitively, it follows that accelerating water removal from stream systems would be linked with corresponding decreases in recharge and baseflow in urban systems. This assumption dominated hydrologic understanding of urban impacts for decades, largely due to the influence of Leopold's (1968) widely cited urban hydrology guidebook (Brandes et al., 2005). In this benchmark publication, management implications center on baseflow reduction associated with urbanization, based more on theory than observed trends. While the assumption that increased impervious surface decreases infiltration, recharge, and ultimately baseflow is theoretically solid, Leopold's conceptual model has proven to be overly simplistic and is not well supported by published data (Ferguson and Suckling, 1990). While event flows do consistently increase and result in faster recession to baseflow with increased impervious surface (Brandes et al., 2005; Burns et al., 2005; Ferguson and Suckling, 1990; Konrad, 2003), the corollary of baseflow decline does not behave quite as neatly, as a result of additional urban effects on subsurface recharge. The complete picture of hydrologic response to urbanization is extremely complex, with some factors acting to reduce recharge and others to increase recharge (Table 2).

Assumptions that urbanization decreases baseflow are generally based on reduced recharge due to increased impervious surface, which is indeed a dominant factor in urban hydrology. Impervious surface coverage in urban basins drastically exceeds that of basins with other land-use types. Road networks, parking lots, rooftops, etc., all contribute to increased impervious percentages, with individual cities demonstrating different degrees of greenspace to offset the impacts of impervious surface (Carter and Jackson, 2007). Impervious coverage undoubtedly has an enormous effect on urban hydrology, with stream corridor impervious cover having a particularly detrimental effect on baseflow quantity and quality (Landers et al., 2007). However, it is unrealistic to view urban systems in a surface-based framework as is commonly applied to systems experiencing lower-intensity impacts. In more moderately impacted settings, surface hydrology remains dominated by natural processes (e.g. evapotranspiration, soil hydrology) following landscape change. In most urban settings, however, water is completely redistributed to accommodate human activities and prevent flood damage. Water is routed across the surface and through the subsurface via ditching, storm drains, water mains, wastewater sewers, and other means, altering the rates and paths of water transmission through urban basins. Such reworking of the hydrologic system precludes explanation of baseflow response to urban land use solely in terms of the effects of vegetation removal and increased impervious surface (Lerner, 2002;

Meyer, 2005), although such simplification is still commonplace.

A major additional complication occurs in urban systems: virtually all major cities import water (Lerner, 2002). The importation of water may include pumping from deep groundwater that is otherwise disconnected from the surface water system, piping of water from other watersheds, and/or withdrawal of water from downstream reservoirs. This water is redistributed throughout cities via pipe networks that often lose substantial quantities of water (Lerner, 2002; Roy et al., 2009). Lerner (1986) reports water main leakage rates of 20–25% to be common, with rates reaching as high as 50%. Wastewater sewer systems may also leak substantial amounts of water, which often originates outside the drainage basin. Such leakage, along with surface inputs of imported water (e.g. septic drainage, lawn/garden watering, and other forms of outdoor domestic water usage) may enter subsurface storage and can significantly offset or overshadow storage losses due to other urbanization effects. Sustained baseflow with urbanization has also been attributed to ET reduction associated with vegetation removal (e.g. Appleyard et al., 1999; Rose and Peters, 2001). However, the role of ET in urban systems remains largely unresolved. For example, Oke (1979) showed that ET rates remain steady despite decreased vegetation cover in Vancouver, BC, due to heat advection from non-vegetated surfaces. While such processes may be significant in suburban areas or cities with abundant vegetation, they cannot be assumed to dominate in all urban areas.

All of the factors addressed above may be expressed to varying degrees in different cities or regions, resulting in inconsistent hydrologic response to urbanization throughout the world (Table 3). It seems that there is no predictable response of annual low flow, proportion of baseflow to total streamflow, or groundwater recharge to urbanization, as demonstrated by the case studies outlined below. Of the studies reviewed that directly address annual low flow response to urbanization, none demonstrated a pronounced decrease in discharge (e.g. Harris and Rantz, 1964; Konrad and Booth, 2002; Rose and Peters, 2001). Harris and Rantz (1964) attribute increased annual low flow to distribution and leakage of imported water, an insight issued decades before most hydrologists accepted such a source to be significant. Rose and Peters (2001) attribute the lack of annual low flow response in Atlanta, Georgia, to an offsetting of the effects of impervious surface by reduced ET associated with vegetation removal. Finally, Konrad and Booth (2002) interpret inconsistent annual low flow response in the Puget Sound basin to varying degrees of development, implying that in some cases a development threshold necessary to induce response had not yet been reached.

The response of baseflow proportion shows a weak tendency toward decline among the case studies reviewed. Streams in Pennsylvania, New York, Georgia, and Oregon all demonstrated baseflow reduction associated with urbanization (Chang, 2007; Leopold, 1968; Rose and Peters, 2001; Simmons and Reynolds, 1982). In all cases, the authors attribute observed declines to recharge loss associated with impervious surface coverage, and Simmons and Reynolds (1982) additionally cite the removal of wastewater from stream basins. In contrast, streams in Harlow, Great Britain, and southern New York demonstrated baseflow increases with urbanization, presumably due to distribution and leakage of imported water (Burns et al., 2005; Hollis, 1977). The wide variety of factors controlling baseflow discharge and system response to urbanization likely explains the disagreement among these studies. A lack of consistent results or no response was observed in the majority of the reviewed studies addressing baseflow (Beran and Gustard, 1977; Brandes et al., 2005; Ferguson and Suckling, 1990; Konrad and Booth, 2005). Explanations for the lack of clear trends include effects from pronounced seasonality in

Table 3. Summary of studies investigating baseflow and recharge response to urbanization

Location	Response to urbanization	Attributed mechanism(s)	Reference
Atlanta, Georgia	Decrease	Reduced infiltration	Rose and Peters (2001)
Coatesville, Pennsylvania	Decrease	Reduced infiltration	Leopold (1968)
Long Island, New York	Decrease	Reduced infiltration + export of sewerage water	Simmons and Reynolds (1982)
Portland, Oregon	Decrease	Reduced infiltration	Chang (2007)
Long Island, New York	Decrease	Export of sewerage water	Koszalska (1975)
Western Washington	Inconsistent	Insufficient impact in some of the study basins	Konrad and Booth (2002)
Western Washington	Inconsistent	Seasonality effects	Konrad and Booth (2005)
Delaware River Basin	Inconsistent	Varied influences among basins	Brandes et al. (2005)
Long Island, New York	Inconsistent	Seasonality effects	Ku et al. (1992)
Santa Clara County, California	Increase	Distribution and leakage of imported water	Harris and Rantz (1964)
Southern New York state	Increase	Septic effluent	Burns et al. (2005)
Harlow, Great Britain	Increase		Hollis (1977)
Caracas, Venezuela	Increase	Infrastructure leakage	Seiler and Alvarado-Rivas (1999)
Northeastern Illinois	Increase	Distribution and leakage of imported water	Meyer (2005)
Perth, Australia	Increase	Reduced ET + distribution and leakage of imported water	Appleyard et al. (1999)
Wolverhampton, U.K.	Increase	Distribution and leakage of imported water	Hooker et al. (1999)
Atlanta, Georgia	No response	Reduced infiltration offset by Reduced summer ET	Rose and Peters (2001)
Great Britain	No response		Beran and Gustard (1977)
Atlanta, Georgia	No response	Reduced inflitration offset by distribution and leakage of imported water	Ferguson and Suckling (1990)
Southern New York state	No response	Insufficient impact (suburban)	Burns et al. (2005)

the Pacific Northwest (Konrad and Booth, 2005), marked variability of background conditions and specific impacts in the Mid-Atlantic region (Brandes et al., 2005), and the offsetting of rapid transmission of stormwater by distribution and leakage of imported water (Ferguson and Suckling, 1990).

Additional case studies were reviewed that address recharge to subsurface storage, as this is inextricably linked with baseflow. Results from these studies generally indicate a more consistent response to urbanization than seen with annual low flow or baseflow proportion. Four of the studies reviewed, conducted in Caracas (Venezuela), Perth (Australia), Wolverhampton (UK), and northeastern Illinois demonstrate increased recharge with urbanization (Appleyard et al., 1999; Hooker et al., 1999; Meyer, 2005; Seiler and Alvarado-Rivas, 1999). In all of these cases, recharge increases are attributed to distribution of imported water and/or infrastructure leakage, with Appleyard et al. (1999) additionally citing reduced ET as a factor. Decreases in recharge were observed in Long Island, New York (Koszalska, 1975), Atlanta, Georgia (Rose and Peters, 2001), and the Kleine Nete basin in Belgium (Dams et al., 2008), attributed to export of wastewater in New York and reduced infiltration in the latter two studies. Two studies in southern New York failed to demonstrate a clear direction of response to urbanization (Burns et al., 2005; Ku et al., 1992). It is noteworthy that a larger percentage of recharge studies demonstrated increase than was seen in the baseflow studies. The fact that increases in recharge were slightly more common than increases in baseflow may indicate that urban manipulation detectibly complicates the pathways between subsurface recharge and channel flow. However, the only study that explicitly addressed both baseflow and recharge demonstrated the same direction of response in both components (Rose and Peters, 2001), which suggests that the discrepancies seen among recharge and baseflow studies may simply be further evidence of lack of consistent response to urbanization in different settings.

Interpretation of baseflow response to urbanization is further complicated by several considerations. Comparison of urban response across cities and regions is problematic, based on differences in natural hydrologic background variability, unique infrastructure systems, and varied management approaches. Research design and choice of parameters assessed is not universally consistent, clouding cross-study comparison. Investigators often seek clear trends in response to urbanization, and in the process may overlook complex patterns associated with geographic variability in physical setting, a point reinforced by more comprehensive analyses (e.g. Ferguson and Suckling, 1990; Konrad and Booth, 2005; Rose and Peters, 2001). Relatively intense, long-term urbanization has been the focus of most urban hydrology research, and far less is known about the impacts of lower-density or carefully mediated urban development. Land-use activities associated with moderate impact or episodic disturbance may not result in detectible stream response, given other background sources of hydrologic variability (Konrad and Booth, 2002). The conceptual model outlined by Leopold (1968) does not include consideration of these and other factors, and it unfortunately appears that baseflow response to urbanization cannot be predicted by a highly simplified set of parameters.

3 Agriculture

As seen with urbanization, baseflow response to agricultural land use may be positive or negative, depending on management practices. First, there is the obvious confounding factor of irrigation (Dow, 2007; He et al., 2009). If crops are irrigated from surface water resources linked to the stream network, increased ET may reduce baseflows (Figure 1). However, increases in baseflow may occur if irrigation water is drawn from disconnected storage resources or from outside the drainage basin. Furthermore, varied management practices are associated with a wide range of soil impacts (e.g. conventional tillage practices versus no-till and conservation tillage), differing temporal patterns to intensive cropping (e.g. perennial versus seasonal cultivation), and whether or not crop residue or other soil cover are used during the fallow season (Kent, 1999). Drainage tiling, which speeds removal of moisture from the near-surface soil layers, may also have strong impacts on baseflow in agricultural areas (Schilling and Helmers, 2008).

Accordingly, studies investigating baseflow response to agricultural land use have demonstrated mixed results. Schilling and Libra (2003) showed that many Iowa rivers have seen increases in annual baseflow magnitude and proportion, and additional work has shown that these increases were significantly related to increasing row crop intensity (Schilling, 2005). Increases in baseflow over the past 60 years within the upper Mississippi River basin have been attributed to reductions in ET associated with conversion from perennial to seasonal cultivation (Lins and Slack, 2005; Zhang and Schilling, 2006), and changes in tillage practices (Kent, 1999; Potter, 1991). Using rainfall simulation experiments, Rasiah and Kay (1995) showed that minimized tillage practices were associated with lower overland flow and increased infiltration compared with conventional tillage of corn crops in Canada. Charlier et al. (2008) showed that greater overland flow in agricultural areas of Guadeloupe reduced recharge and decreased baseflows. Decreased agricultural land use in Georgia and Wisconsin has been linked with increased baseflows attributed to higher infiltration rates (Juckem et al., 2008; Knox, 2001), while large-scale conversion of forest to agricultural land in Thailand demonstrated no significant changes in baseflow (Wilk et al., 2001). Despite the inconsistency in results from these studies, two main inferences can be drawn from the literature addressing baseflow response to agricultural influence: (1) watersheds that have been under agricultural land use for extended periods show baseflow increases in response to improved cropping and tillage practices; (2) comparison of baseflows under agricultural land use versus other land uses is precluded by the variety of management practices, variable uses and sources of irrigation, and other background sources of variability.

IV Effects of climate change on baseflow

For most of the planet, temperatures are projected to rise as a result of continually increasing atmospheric greenhouse gas concentrations (IPCC, 2007). It is unlikely that temperature increases will occur in isolation, and there is limited predictability of atmospheric feedbacks that will accompany warming due to increased greenhouse gas concentrations. At local scales, higher summer temperatures and, by extension, evaporation rates, could lead to increased convective precipitation, offsetting baseflow reductions. At regional scales, changes in global circulation patterns and higher evaporation over large water bodies will likely translate to changes in precipitation regimes in many regions of the world, but the major global circulation models (GCMs) do not agree on what these changes will be. The likely climate changes that will affect the majority of the globe will involve some combination of temperature increase and either precipitation decrease or increase, and any specific baseflow response to climate change will depend on the magnitude and direction of changes in both precipitation and temperature (Choi et al., 2009; Smakhtin, 2001; Tague et al., 2008). Another important complication to understanding the effects of climate change on baseflow is that empirical studies evaluating baseflow response to changing climate typically are confounded by concurrent land-use change during the period of record

(Choi, 2008; Juckem et al., 2008). As a result, hydrologic simulations with projections of climate change are required to evaluate baseflow response to climate change in true isolation of land-use change, and both the hydrologic and climate models are associated with substantial uncertainty. Furthermore, climate change and hydrologic response likely will exhibit considerable regional variability, such that it is impossible to make any single prediction about how, for example, continued greenhouse gas-related warming generally will affect baseflows (Lins and Slack, 2005).

Despite these obstacles, many researchers have designed studies offering insights into the issue of climate change impacts on baseflows. One recurrent prediction is that continued warming and subsequent changes in global circulation are likely to lead to more extreme hydrologic regimes in many regions, with wetter wet seasons and drier dry seasons (Nyenje and Batelaan, 2009). This, in turn, will lead to reductions in seasonal low flows, and a more pronounced impact on low flows than high flows (Choi, 2008; Smakhtin, 2001; Yang et al., 2009; Zhang et al., 2008). Multiple empirical and simulation studies suggest that this increased flow seasonality, along with warmer temperatures in summer, will lead to severe reductions in late summer baseflows (Cooper et al., 1995; Kim and Kaluarachchi, 2009; Reihan et al., 2007; Wegehenkel and Kersebaum, 2009; Xie et al., 2010; Yusoff et al., 2002). It should, however, be noted that regional analyses have shown streamflow increases across the USA from 1944 to 1999, attributed to greater warm season precipitation (Lins and Slack, 2005). It has been suggested that colder regions will experience more extreme baseflow response as a result of climate warming (Ma et al., 2009). Several empirical studies in colder regions that have recorded warming have shown that earlier snowmelt has led to reduced late-summer low flows (Barnett et al., 2008; Huntington et al., 2009; Luce and Holden, 2009; Pike et al., 2008; Poff, 1996; Schneider, 2008). In very high-latitude or high-altitude regions that are presently underlain by permafrost, baseflows may increase with warming, as a result of permafrost thaw and increased infiltration and recharge (Brabets and Walvoord, 2009).

Perhaps the greatest obstacle to predicting water quality and quantity response to climate change is the confounding factor of concurrent land-use change (Choi, 2008; Ma et al., 2009; Poff, 1996). A recent study by Wang and Cai (2010) evaluated climate versus human influences on baseflow recession in the Nebraska Sand Hills and found land-use change to be a more significant influence on recession than climate change throughout the second half of the 20th century. Juckem et al. (2008) offered the useful interpretation of their empirical analysis of baseflow changes in the Kickapoo River watershed, Wisconsin, that climate change predominantly affects baseflow timing (due to earlier snowmelt, etc.), while land-use change superimposes changes in magnitude upon these climatic effects. Additionally, climate change may be associated with changes in precipitation intensity, the hydrologic effect of which could be exacerbated by land-use change in the form of soil compaction and greater impervious surface coverage. Easterling et al. (2000) showed that most precipitation increases in global climate change are the result of increases in extreme, highly intense rainfall events. Even in the absence of concurrent land-use change, more frequent high-intensity events may lead to greater overland flow and reduced recharge, and these effects will be exacerbated if combined with anthropogenic decreases in watershed infiltration capacity.

Several studies attempting to evaluate hydrologic response to land-use change in the context of long-term climate fluctuations have shown that land-use change leads to much more drastic hydrologic response than is evident throughout prehistoric Holocene warming and cooling cycles (Knox, 2001; Leigh, 2008; Smakhtin, 2001). The results of these studies support Tomer and Schilling's (2009) observation that the impacts of anthropogenic climate change are subtle compared with persistent cycles of drought and precipitation surplus, as well as Smakhtin's (2001) recommendation that predictions of baseflow response to climate change be accompanied by as much paleoenvironmental context as possible. However, it is not clear that land-use change impacts exceed climate-change impacts in all settings, especially where land-use intensity is not extreme. It is possible that 21st-century climate change will exceed the ranges observed to date during the Holocene, in which case climate change could exert equal or greater baseflow response relative to land-use change. This is particularly the case where climate fluctuations lead to major changes in the hydrologic regime, e.g. from snow- to rain-dominated systems (Barnett et al., 2008; Schneider, 2008). There is also evidence that baseflow response will vary with hydrogeologic and geomorphic setting (Tague et al., 2008; Wang et al., 2009). Watersheds with high drainage efficiency (as a result of highly permeable bedrock or high drainage density) may show exacerbated reductions in baseflow associated with higher atmospheric temperature and ET (Tague et al., 2008; van Wateren-de Hoog, 1998). Conversely, watersheds in settings that favor higher storage and baseflow proportion, and/or those underlain by large, productive aquifers will likely demonstrate mediated response (Schneider, 2008; Wang et al., 2009).

V Summary and conclusions

Understanding how land-use and climate change will affect baseflow quantity, in the context of watershed geomorphology, will aid watershed managers and stream ecologists in the protection of adequate water supply for human needs and habitat availability for stream biota. In addition to introducing challenges in meeting agricultural, municipal, and industrial water needs, reduced baseflows contribute to impairments known to affect fish, invertebrates, and algal assemblages (James et al., 2009; Kennan and Ayers, 2002; Roy et al., 2009; Wenger et al., 2009). Even in regions characterized by relatively low-intensity land-use change, there have been detectible reductions in baseflow quantity and quality, as well as impairments to aquatic species assemblages (Price and Leigh, 2006b; Roy et al., 2003; Sutherland et al., 2002; Walters et al., 2003).

This review of the literature has shown that watershed topography and geomorphology influence baseflow by affecting the storage properties and rates of water transmission within a catchment. The influence of factors of slope, relief, and drainage density are particularly noteworthy. However, it remains unclear whether these factors are themselves strong drivers of baseflow (Price et al., 2011), or whether they instead correlate to other aquifer properties that more directly control baseflow. More research is needed to understand the role of subsurface topography on baseflow, and very little is known about water storage in varied geomorphic units (e.g. colluvial deposits and alluvial bottomlands) and their linkages to baseflow.

Research investigating anthropogenic controls on baseflow has tended to disproportionately emphasize forestry experimentation and urbanization, and within these studies the natural background controls on baseflow are often downplayed or ignored. Several recent studies emphasize the importance of considering changes in soil hydrology when assessing streamflow response to land-use change (Bruijnzeel, 2004; Price et al., 2010; Woltemade, 2010). Very little is known about baseflow response to land-use change in larger, more complex systems, or in settings affected by development of moderate intensity, information which is essential for effective water resources protection and management. It is increasingly clear that the results of forestry experimentation studies demonstrating baseflow increase with forest removal should not be extrapolated to more complex systems with long-term land-use change and extensive soil disturbance.

It is difficult to draw overarching conclusions regarding the influence of watershed characteristics on baseflow from the existing body of literature, given the enormous diversity of natural background conditions, watershed parameters, and baseflow metrics among case studies. This highlights a clear need for more studies investigating the relative influences of watershed geomorphology and land use within a given natural template, and for efforts to be made toward developing consistent methodologies for watershed characterization and baseflow quantification. Few predictions can be made from the current knowledge base of how greenhouse gas-induced warming will affect baseflows, because our current modeling capabilities cannot resolve significant uncertainty in state variable projections (e.g. climate and land cover), as well as the unknown dynamics concerning the interaction of climate and land-cover change. It can be inferred from empirical and simulation-based studies that earlier spring snowmelt in high-latitude and high-altitude regions will threaten summer and fall low flows (Barnett et al., 2008).

From this review, seven key needs for future research have emerged that could broadly benefit the water resources community, and without which our understanding of watershed function will remain limited:

(1) Experimental studies specifically designed to evaluate the influence of subsurface topography on baseflow.
(2) Improvement of methods to determine distribution of shallow subsurface storage at scales relevant to policy and management.
(3) Comprehensive empirical comparisons that link soil hydrology and baseflows under land-use gradients that incorporate more detail than the broad categories of forest, agriculture, and urban land use.
(4) Modeling and empirical studies that address multiple aspects of watershed hydrology in a single study, such as a comparative watershed study in which ET, soil moisture, subsurface storage recharge, and streamflow are all evaluated. There is a clear need for enhanced understanding of watershed function, and addressing the complete system should be a high priority.
(5) Modeling and empirical studies that explore baseflow response to varied land-use change, planned growth, and mitigation strategies.
(6) Under a given experimental design, do research conclusions differ with the specific baseflow metric analyzed? Are there optimal baseflow separation methods, recession statistics, and low flow statistics?
(7) Ensemble modeling studies that explore multiple working hypotheses of atmospheric feedbacks that will accompany warming, and various interactions between land-use and climate change, in order to ensure mitigation plans are in place for any scenario that is likely to occur.

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