The Relationship Between Land Change and Water Resources Vulnerability: A Review of Existing Literature

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1. Introduction

“To all those involved in hydrology and water resources, land-use change is the problem which will not go away” (Sahin & Hall, 1996; p. 293)

The relationship between land change and hydrology is complex, with linkages existing at a wide variety of spatial and temporal scales; however, land change unquestionably has a strong influence on global water yield. Land cover and use directly impact the amount of evaporation, groundwater infiltration and overland runoff that occurs during and after precipitation events. These factors control the water yields of surface streams and groundwater aquifers and thus the amount of water available for both ecosystem function and human use (Mustard & Fisher, 2004). Changes in land cover and use alter both runoff behavior and the balance that exists between evaporation, groundwater recharge and stream discharge in specific areas and in entire watersheds, with considerable consequence for all water users (Sahin & Hall, 1996; DeFries & Eshleman, 2004). Climate models have even shown that land change affects global precipitation and temperature patterns, which drive the global hydrological cycle in the most fundamental ways (Chase, et al., 2000). River discharge worldwide has increased noticeably since 1900, and studies suggest that land change may be directly responsible for as much as 50% of this increase (Piao, et al., 2007).

While land change is clearly a forcing factor in water supply, it is also an important driver of human water demand and overall water quality (DeFries & Eshleman, 2004). The conversion of native land cover to irrigated agriculture has been a critical factor in our ability to
feed a human population growing at an exponential rate. By some estimates, 40% of the world’s population relies on irrigated crops (Vorosmarty, et al., 2000) and irrigation accounts for as much as two-thirds of all human water usage (Malmqvist & Rundle, 2002). Deforestation, afforestation, and urban development have lesser though not insubstantial effects on water demand and supply as well. The consequences of all of types of land changes have profound impacts on water quality. Sewage and industrial pollution are widespread in most urban areas, and agricultural runoff almost universally results in elevated nitrate levels in both surface and groundwater supplies. By one estimate, a mere 10% of the world’s rivers can be considered ‘pristine’ (Malmqvist & Rundle, 2002).

Anthropogenic alteration of global water supply and quality, along with continued population growth, has resulted in a considerable percentage of people being forced to live in ‘water-stressed’ environments. Recent estimates suggest that 10-15% of all annual fresh water runoff is exploited for human use. However, because only 31% of global fresh water supplies are reasonably accessible, 54% of the water that could potentially be developed is already allocated (Vorosmarty & Sahagian, 2000). By 2025, it is projected that 70-90% of globally accessible water supplies will be exploited (Sophocleous, 2004). Because water is not equally distributed worldwide, some areas have a surplus of water resources while others have a deficit. Problematically, some deficit areas are among the most densely populated. Vorosmarty & Sahagian’s landmark study (2000) estimates that as many as 1.5 billion people already live in high water-stress areas and that by 2025, this number will approach 2.2 billion (with another 2.7 billion living in medium-high water-stress areas; Figure 1).

Water vulnerability is a critical issue facing humanity in the decades ahead, and because land change plays such a significant role in water quality and quantity, there is a great need to
integrate land change science, hydrology and water resources management in future research initiatives (DeFries & Eshleman, 2004). At this point, while methods for modeling the hydrological impacts of land change are still in their infancy (Bevan, 2000), an expanding body of literature has analyzed the specific hydrological responses of various types of land change. This paper reviews some of this literature, with an emphasis on the hydrologic consequences associated with deforestation/afforestation, increased agricultural land use and irrigation and increased urbanization. The goal of this review is to highlight the potential for increased water vulnerability resulting from common land use and land cover alterations.

2. Deforestation/Afforestation and Water Vulnerability

The amount and type of vegetative land cover is one determinant of the water yield of a drainage basin. Forests produce higher rates of evapotranspiration and interception (the storage of water on leaf surfaces) than do grass or shrublands, all of which influence the amount of water that is available for direct drainage into streams or for aquifer recharge (Farley, et al., 2005). The adjustment in evapotranspiration in deforestation/afforestation land change is particularly acute.
Trees generally have lower surface albedo, higher surface aerodynamic roughness, higher leaf surface area, and deeper roots than other types of vegetation, with each characteristic tending towards an increase in evapotranspiration of water and a decrease in streamflow discharge (Costa, et al., 2003). A study from Mount Kenya (Africa) illustrates this behavior (MacMillan & Liniger, 2005). Comparing two grassland sample plots, one in a more arid area and one partially forested, researchers found that the treed plot produced only half the runoff despite receiving nearly twice as much precipitation.

Interception plays a more important role in water balance during precipitation events. Leaves and forest floor leaf-litter capture a considerable amount of water and thus encourage its slow infiltration into the soil. This water (termed sub-surface flow) serves two critical purposes in the hydrologic system: it recharges groundwater supplies stored in aquifers and supplies the return flow of water to stream beds during periods of dry weather (Knighton, 1998). Without these intercepting materials, water tends to immediately drain into stream channels during precipitation events. Thus, deforestation represents a hydrologic transition from sub-surface flow to overland runoff, which results in higher stream yield during precipitation events and lower yield (base flow) between precipitation events (Costa, et al., 2003).

The hydrologic impacts of deforestation have been studied in detail for many decades. In their classic analysis of 94 previous paired watershed studies, Bosch & Hewlett (1982) found a consistent relationship between forest cover and water yield: reduction in forest cover led to increased stream flow while an increase in forest cover decreased stream flow. On average, deforestation increased water yield four-fold compared to loss of grassland and by a factor of 1.6 compared to conversion of shrubland. This review also noted that changes in water yield were most pronounced in high-rainfall areas (which has ramifications for afforestation efforts as
described below), while the effect of deforestation was more long-lived in low-rainfall areas due to slow rates of reforestation.

The amount stream yield increases as a result of deforestation within a given watershed varies depending upon the local climate, geology and type of use to which the land is converted. Some studies suggest that stream discharge may increase as much as 50% as a result of deforestation (Mustard & Fisher, 2004). Bevan (2000) notes that a few studies have resulted in contradictory findings, though this may be explained by variations in the intensity and extent of soil compaction during logging operations (via road building, skid operations and the movement of heavy machinery). Most case studies originate from smaller watersheds, where water yield variations due to land change are easier to quantify as a result of more homogenous weather conditions, soil types and land use (Costa, et al., 2003). Nonetheless, a study of a meso-scale watershed in Amazonia (Costa, et al., 2003) was consistent with the findings reported by Bosch & Hewlett. Mean annual discharge and dry season discharge increased 24% and 29% respectively in the Rio Tocantins watershed when two multi-decadal time periods were compared (1949-1968 and 1979-1998), despite the fact that variation in precipitation rates was statistically insignificant. The researchers identified as the most likely explanation an increase from 30% in 1960 to 49% in 1995 in the amount of land converted from forest to agriculture within the watershed.

Though deforestation is typically viewed as a detrimental land change in the global environmental system, it is worth noting that the resulting increase in stream yield may, in some instances, be viewed as a benefit. A study modeling the effect of land change in Africa’s Lake Malawi basin found that, because forest cover decreased by 13% between 1967 and 1990, increased water
yield saved approximately 1-meter in lake-level decline during a severe drought in 1992. Without this moderation, problems associated with transport and hydroelectric generation at the 28,750 km² lake would have been worse than they actually were during the drought (Calder, et al., 1995). Indeed, in view of the increasing rate of water vulnerability worldwide, it may be worth considering how deforestation may have some benefit in some water-stressed watersheds. Of course, the apparent benefit of increased water yield may be offset by other significant system adjustments to deforestation. For example, over longer temporal scales, there is evidence to suggest that the reduction of evapotranspiration resulting from deforestation ultimately leads to decreased precipitation rates in the watershed (Gordon, et al., 2005).

In contrast to the effects of deforestation, reforestation and afforestation (the planting of trees in areas that are naturally non-forested) can be expected to result in reduced water yields. Case studies from a variety of climate zones support this hypothesis, though it should be noted that deforestation/afforestation processes are not ‘opposite and reversible’ and changes in water yield resulting from each may differ (Farley, et al., 2005). Forest regeneration following logging and natural fire in Melbourne, Australia’s water supply catchment resulted in a 50% reduction in water yield, with peak reduction occurring 25 years after the land change event had occurred (Bevan, 2000). In the Spanish Pyrenees, the widespread abandonment of hillslope farms and the subsequent regeneration of dense shrubs and forests (covering 22% of the study area) generated a 30% reduction in water yield between 1945 and 1995 (Beguería, et al., 2003). A land change model used to predict response in Scotland found a 28-30% reduction in water yield following 100% reforestation of the watershed (Eeles, 1993).

This hydrologic response to tree growth has important consequences for afforestation efforts. Afforestation is increasingly viewed as an environmental restorative land change
prescription and is considered to be one of the most practical carbon sequestration strategies presently available (Farley, et al., 2005). Per the findings of Bosch & Hewlett (1982), it has been suggested that arid areas might be particularly appropriate for afforestation because the impact on stream flow would be less severe than in more humid areas. In reality, considering proportional runoff reductions and the possibility that discharge reductions might be more acute during low-flow periods than during other seasons, afforestation efforts in arid areas – especially those that are already water-stressed – might be quite severe. Models suggest that in areas where stream discharge is approximately 30% of mean annual precipitation, a 50% reduction in local discharge may occur in afforested areas. Where the discharge to precipitation ratio is closer to 10%, a complete elimination of stream flow generated from afforested areas is possible (Farley, et al., 2005). Clearly, if afforestation is to be used as a carbon sequestration technique, it will have to be limited to areas where such reduction in water yield can be absorbed by local ecosystems and human communities.

3. Agriculture/Irrigation and Water Vulnerability

The conversion of native ecosystems to irrigated agricultural production is one of the most widespread land change processes and is one with profound hydrologic impacts of its own. Some researchers have estimated that irrigated land coverage has increased worldwide from 100,000 km$^2$ in 1800 to 2,700,000 km$^2$ in 2000. The rate of conversion is accelerating to match exponential population growth, with a doubling of the amount of irrigated land in just the past 50 years (Mustard & Fisher, 2004). Unfortunately, irrigation is one of the least efficient water uses, at least in terms of sustaining resources within a watershed. Research indicates that anywhere from 2400 to 3500 km$^3$ of water is irretrievably lost each year worldwide (meaning it cannot be
returned in fluid form to the watershed from which it was obtained), with irrigation accounting from 85-90% of this total. This represents 9.5% of all of the earth’s total annual fresh water supply and 30% of the fresh water than is accessible (Vorosmarty & Sahagian, 2000).

Malmqvist & Rundle (2002) highlight two of the most extreme examples of hydrologic alteration resulting from irrigation water withdrawal. Irrigation of cotton plantations in Uzbekistan’s Aral Sea basin has diverted nearly the entire discharge of the Amu Darya and Syr Darya rivers over the course of the past century. As a result, the Aral Sea (a drainage basin with no external drainage) has lost 90% of its volume (Micklin, 2007), with disastrous ecological and human consequences. Diversion of water from the Colorado River to irrigate crops in California’s Imperial Valley has led to less severe but still considerable effects in the hydrology of the river. For the majority of years between 1960 and 1980, no river flow reached the river’s delta at the Gulf of California. This too has had considerable ecological consequences and has led to political tension between the United States and Mexico.

The impact of irrigation on groundwater resources is also significant, especially in those arid and semi-arid areas where groundwater aquifers are the primary sources for both irrigation and domestic water use. Jackson, et al. (2001) describe two examples. During the 1990s, the rate of withdrawal from the Northern Sahara Basin Aquifer was twice the rate of recharge, and as a result, numerous springs – which provide the only water for wildlife and many rural human settlements – have completely dried up. The Ogallala Aquifer, which underlies the most arid portion of the Great Plains, is estimated to have lost 5% of its thickness over 20% of its total area just in the 1980s. Should such unsustainable consumption continue, the water supplies (and entire economies) of tens of thousands of people in at last a half-dozen states could be at risk.
As with deforestation, the conversion of the land surface from native cover to managed cropland has an effect on the evapotranspiration, infiltration and overland runoff characteristics of a watershed. Depending on the type of product being grown, croplands tend to have a percentage of bare ground even during the peak of the growing season, and may be completely bare prior to being planted. In both instances, most of the precipitation that lands on these denuded areas will be discharged directly into the stream channel rather than infiltrating into the soil or evaporating/transpiring from the plant surfaces. As a result, conversion to cropland tends to increase water yield compared to native vegetation (Mustard & Fisher, 2004). The same Mount Kenya study cited earlier demonstrates this behavior. MacMillan & Liniger (2005) note earlier research which suggested that while runoff from natural grasslands during precipitation events is minimal, anywhere from 20-45% of precipitation is drained via surface runoff from croplands. They then performed their own modeling scenario for a small, lower-mountain watershed whereby 100% of natural grassland was converted to cropland. The model suggested the consequence of such land change would be a 50% increase in annual water yield.

4. Urbanization and Water Vulnerability

Though conversion to urban land use comprises a relatively small amount of total land area, the hydrologic effects of urbanization can affect a considerable number of people and may range far beyond the boundaries of the urban area. These effects tend to fall within one of three main categories: adjustment and interruption of local groundwater supplies, pollution of local groundwater and downstream surface water, and the artificial adjustment of watershed yield via trans-basin diversion.

Hydrologically-speaking, the most important impact of urbanization is the increase of impervious surfaces within the watershed. Impervious surfaces prohibit infiltration of water to
the soil during precipitation events, thus inhibiting groundwater recharge and increasing overland runoff during precipitation events (Mustard & Fisher, 2004; Shanahan & Jacobs, 2007). The result is that urban hydrographs typically feature higher peak flows during storms, lower base flows between storms, and more rapid transition from low base flow to high stream discharge. Considering that many urban areas are highly reliant upon local aquifers for their municipal water supplies, the reduction in groundwater recharge is potentially quite problematic (Harbor, 1994). Many urban areas draw water from their aquifers at rates much higher than could be replenished by even unimpeded natural recharge, though in some instances the amount of water imported from other basins can ameliorate this effect (Shanahan & Jacobs, 2007).

In general, groundwater supplies appear to be disproportionately impacted by urbanization relative to surface water yield. Not only is the quantity of groundwater altered by high rates of withdrawal and inhibited recharge, the movement and overall quality of groundwater are altered as well. Sub-surface flow is an important part of water movement within a hydrologic system, and much of this flow occurs at relatively shallow depths. The underground infrastructure essential to any city may radically alter the configuration and direction of this flow, with consequences for aquifer recharge and return-flow recharge of surface streams (Shanahan & Jacobs, 2007). Meanwhile, urban areas are typically significant water pollution sources, with both sewage and industrial processes potentially contaminating the local ground water supply. The rapidly growing city of Hat Yai, Thailand is a case in point. The city is built above two aquifers, one quite shallow and one slightly deeper that is used for municipal water supply. Inadequate sewage treatment has greatly degraded water quality in the shallow aquifer, and is now affecting the deeper supply aquifer as well. Without adequate funds to construct
water treatment facilities and with limited alternative water supply options, the potential health consequences are substantial (Lawrence, et al., 2000).

Trans-basin water diversions may alter water yields both in the watershed from which the water is withdrawn and in the portion of the watershed downstream from the urban area. The diversion of water from California’s Owens Valley to supply the city of Los Angeles is perhaps the best known example of the former situation. Nearly all surface water and a significant quantity of groundwater (via pumping) is diverted from the watershed. Downstream of the diversion point, the Owens River is now dry and the formerly 280km² Owens Lake no longer exists. The riparian ecosystem along the river has disappeared and a once thriving agricultural community has largely been abandoned (Mustard, et al., 2004). The city of Colorado Springs, which also obtains a portion of its water via trans-basin diversion, provides an example of the latter effect. All water used in the city is discharged into Fountain Creek, either via natural and artificial channels or through the municipal water treatment system. As a result of the import of water from outside the watershed, water yield from Fountain Creek downstream from the city has increased by about 15% from what would occur naturally (Harvey & Morris, 2004).

5. Concluding Remarks

The hydrologic effects of land change can be substantial and can have both positive and negative consequences for humans at a variety of temporal and spatial scales. The increased discharge that results from many land change processes may be of benefit to people living in water-stressed areas, though the long-term hydrological effects of these same land changes are less well-understood and may ultimately be highly detrimental. The spatial complexity of land change and the operational complexity of the hydrologic cycle – especially in larger basins – make predictions difficult (Bevan, 2000; Costa, et al., 2003).
The existing literature demonstrates that progress has been made in identifying the likely consequences of various land changes, though there remains a clear need to improve the tools available to water resource planners to predict and manage the specific impacts of land change in their own watersheds (Sahin & Hall, 1996; MacMillan & Liniger, 2005). In particular, there appears to be a critical gap in research that links potential hydrological response to land change with the water resource management situation that exists in the watershed. While predicting the consequences of change is a necessary first step, understanding the resulting effect on the local politics of water usage and allocation is just as important if effective planning is to occur.

Water demand is forecast to increase worldwide, including in those areas already experiencing high water-stress (Vorosmarty, et al., 2000). Certain land use and land cover changes, some of which are occurring at an accelerating rate, have distinctly negative impacts on water resources. Other land changes may moderate water-stress. It is critical to human well-being that we better understand these effects – especially in water-stressed areas – if land use and water resource sustainability is to be achieved.

6. References


