

# Engineered Impacts to the Natural Water Cycle

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Water is one of our most important natural resources, since without it there would be no viable life on earth. The natural water cycle transfers water from the atmosphere to the land as liquid water and then back into the atmosphere again as water vapor. Although there is plenty of water on earth, it is not always in the right place, at the right time, and in the right quality (USGS, 2001).

## ***The Natural Water Cycle***

The natural water cycle is depicted in Figure 1. Water reaches the earth's surface as precipitation in the form of rain or snow. Some of the precipitation runs off to enter streams quickly as storm flow. Some is stored in depressions, and a significant fraction infiltrates into the ground and is stored in the soil for plant growth. Some water percolates below the plant's roots and recharges underground storage called groundwater. Stored groundwater feeds streams with a slow supply of water called baseflow. Storm flow and base flow comprise the streamflow that makes its way downstream to the nearest ocean. Transpiration from plants and evaporation from soil, water bodies, and the oceans returns water to the atmosphere and cools the earth.

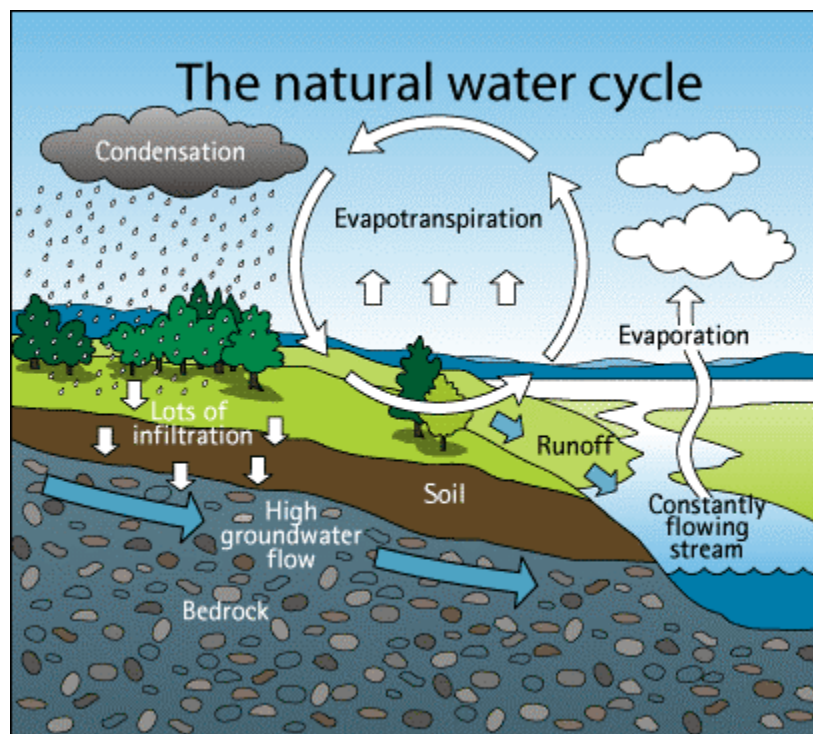


Figure 1: The natural water cycle (Auckland City Council, New Zealand)

In Massachusetts, the average annual precipitation is about 45 inches. Under natural conditions in a watershed, about 22 inches per year evaporates, another 5 inches per year is lost as runoff, leaving only 18 inches of water to recharge the groundwater. In the summer, however, there is little runoff and only about 0.5 inches of the 3.8 inches per month of precipitation is recharged. During dry summer periods there is almost no recharge. Streamflow is therefore naturally low in the summer with recharge and streamflow in a delicate balance.

### ***The Engineered Water Cycle***

Man has re-engineered the natural water cycle over two centuries and dramatically impacted the water environment. Large areas of land have been built on, converted to agriculture, and significantly altered. In metropolitan areas, soils have been compacted and paved over. Large volumes of ocean and fresh water are used for cooling in power plants. Water suppliers withdraw fresh water from surface and ground sources for residential and commercial use, and then the used water is discharged as wastewater, generally far from where the drinking water was obtained. Water distribution systems distribute water to facilitate its use, but move the water many miles from its source. Water is also consumed when it is lost to the atmosphere from agricultural or lawn irrigation and evaporation.

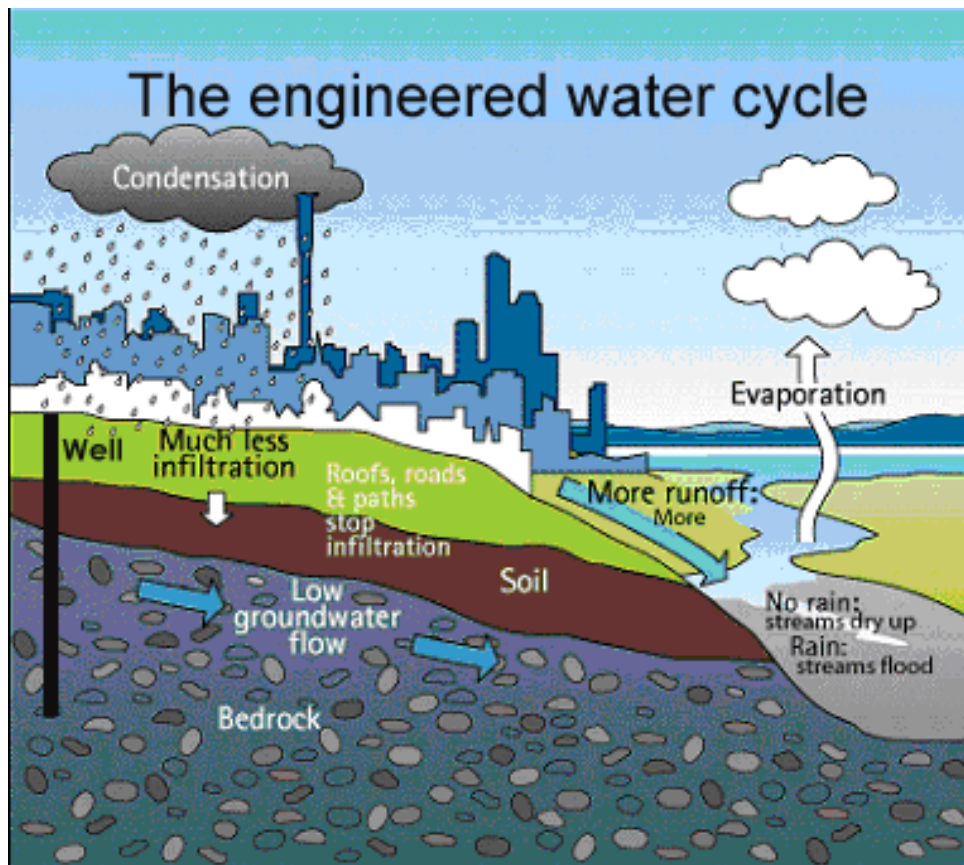


Figure 2. The engineered water cycle (Auckland City Council, New Zealand)

## Land Development

Land clearing and drainage of wetlands can actually augment recharge and baseflow because forests and wetlands have higher evaporation rates than grasslands or lawns. However, this effect is usually short-lived as the land becomes more developed. Land development does result in the loss of quality contiguous terrestrial habitat and subsequently affects both the numbers and diversity of terrestrial species.

## Impervious Areas

As impervious surfaces like rooftops, driveways, parking lots and roads proliferate, they reduce evaporation, recharge, and groundwater travel times. The double-edged effect of impervious surfaces are that they disconnect rainfall from groundwater, thus creating larger peak runoff volumes while reducing recharge and baseflow. The result is more storm flow with less baseflow, in other words, more of the wrong kind of water. Figure 3 illustrates the increase in peak flows using modeled results, while Figure 4 shows the classic divergence in total flow and base flow on the Neponset River, at Norwood, MA. The minimum 7-day flow used in Figure 4 is a measure of the lowest base flow during the year. There are also factors, including water withdrawals and the wastewater collection systems, that affect Neponset River flows in this example.

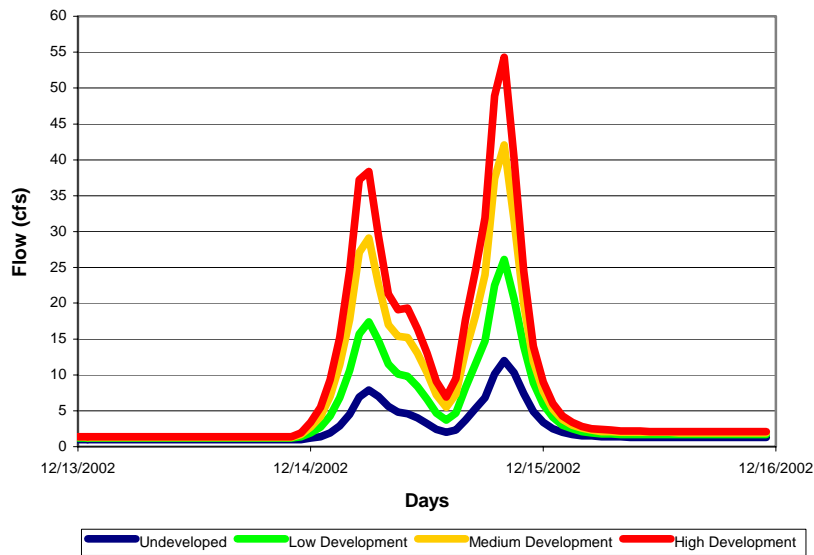
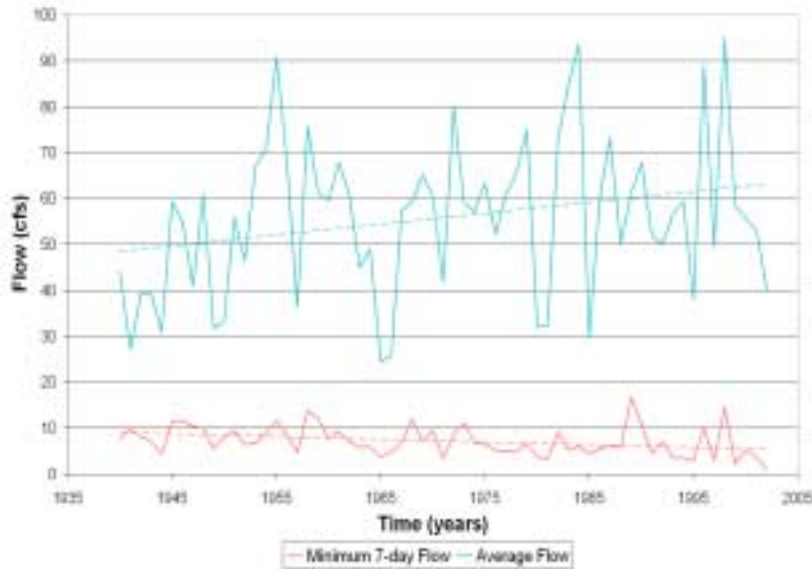


Figure 3: Modeled increase in stream flow peaks with increasing impervious area



**Figure 4: Annual total and minimum flows for the Neponset River, Norwood, MA**

Runoff from land surfaces to streams, or storm flow, often causes visible adverse effects on the watershed. High storm flow can also have adverse physical and chemical impacts. It raises water temperatures since runoff from impervious surfaces is often warm, increases sediment and nutrient loadings since there is increased transport and erosion capacity, raises stream levels to augment flooding, and can increase the frequency of combined sewer overflows (raw sewage spills into waterways during large rain events).

Flow of water from groundwater to streams, or baseflow, is the lifeblood of streams since it feeds the streams with cool clean water during periods when there is no precipitation. Impervious surfaces reduce recharge and groundwater storage thus decreasing baseflow. Low baseflow can have adverse physical and chemical impacts: it raises water temperatures in the summer since groundwater temperatures are naturally low, decreases water quality since there is less good quality water for dilution, and lowers stream levels.

The biological impacts of these changes in the flow regime reduces fish and macro invertebrate habitat, diversity and numbers, and promotes the undesirable growth of algae and aquatic plants.

### **Water Supply Withdrawals**

Water is withdrawn for human use from surface water, groundwater, or the ocean and used in power generation, agriculture, commerce and industry, and residences. Water withdrawals for 2005 in the United States were estimated at approximately 408 billion gallons per day (Bgd) (USGS, 2001). Thermoelectric power is the largest single use category (196 Bgd, 48%) followed by irrigation (137 Bgd, 34%). Public water supplies are the third largest category (43 Bgd, 11%) followed by commercial and industrial uses (29 Bgd, 7%). Private water withdrawals constitute only 4 Bgd, or 1% of total use.

Total water withdrawals have varied less than 3 percent since 1985 as the largest uses have stabilized. Public water withdrawals, however, have increased in proportion to the increasing population. About 60 percent of water withdrawals for irrigation and public water supply are from surface water bodies, though since 1985 there has been a shift towards using more groundwater. Almost all the saline water withdrawals (63 Bgd, 98%) are for thermoelectric power plants. About 85 percent of the US population obtains drinking water from public suppliers compared to 62 percent in 1950. Almost all private water withdrawals are from groundwater.

In Massachusetts, water withdrawals for 2005 were estimated to be about 4,661 million gallons per day (Mgd) (USGS, 2001). Thermoelectric power uses the most (3,718 Mgd, 80%) followed by public water supplies (739 Mgd, 16%). Irrigation for agriculture and landscapes (126 Mgd, 3%) is the third largest category, followed by commercial and industrial uses (36 Mgd, 1%). Private water withdrawals constitute only 42 Mgd or 1 percent of the total.

The water use picture for the whole United States differs sharply from Massachusetts. In many parts of the rest of the country, water withdrawals are dominated by thermoelectric and irrigation needs while in Massachusetts the largest users are public water suppliers.

***Water withdrawals impact streamflow.*** The degree of the impact of water withdrawals depends on many factors. A gallon of water withdrawn normally results in a gallon less streamflow unless the water withdrawn is returned to its source. This is particularly true in the east and in Massachusetts because surface water is connected to groundwater. In the Ipswich River watershed, the USGS found that water withdrawals in the upper watershed reduce flows by an order of magnitude.<sup>1</sup>

Generally, the larger the withdrawal, the larger the ***volumetric*** impact on the stream. The smaller the stream, the larger the ***relative*** impact on the stream. Distance from the stream and type of groundwater strata do not affect the ***magnitude*** of the effect, but might affect the ***timing*** of the impact. For example, high seasonal human water use in the summer could have a more muted effect on streamflow in the summer if the water supply well were located far from the stream, or in a confined aquifer. **Not only does each well withdrawal have a local effect on the nearest stream, water withdrawal impacts are accumulated over entire watersheds, affecting streamflow throughout the watershed.**

In eastern Massachusetts, towns use about 2 to 4 inches per year of water, expressed as a depth, per year, compared to 23 inches (groundwater recharge plus surface water runoff) of total streamflow. From an annual perspective, the numbers indicate that there is plenty of water available for water supply in most rivers. In the summer, however, towns use about 0.5 inches per month for water supply while there is only about 0.5 inches per

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<sup>1</sup> P.J. Zarriello and K.G. Ries, 2000, *A Precipitation-Runoff Model for Analysis of the Effects of Water Withdrawals on Streamflow, Ipswich River Basin, Massachusetts*, Water-Resources Investigations Report 00-4029, 99 pp.

month of streamflow (see Figure 5). In stressed watersheds, where demand is high and the impacts of development are also high, and in drier summers, water withdrawals and streamflow are in direct competition for a finite supply of groundwater. **Consequently, water supply withdrawals are directly related to stream drawdown, increased water temperatures, concentrated pollution in rivers and streams, algae growth, and causing tributaries and rivers to run dry (see Figure 6).**

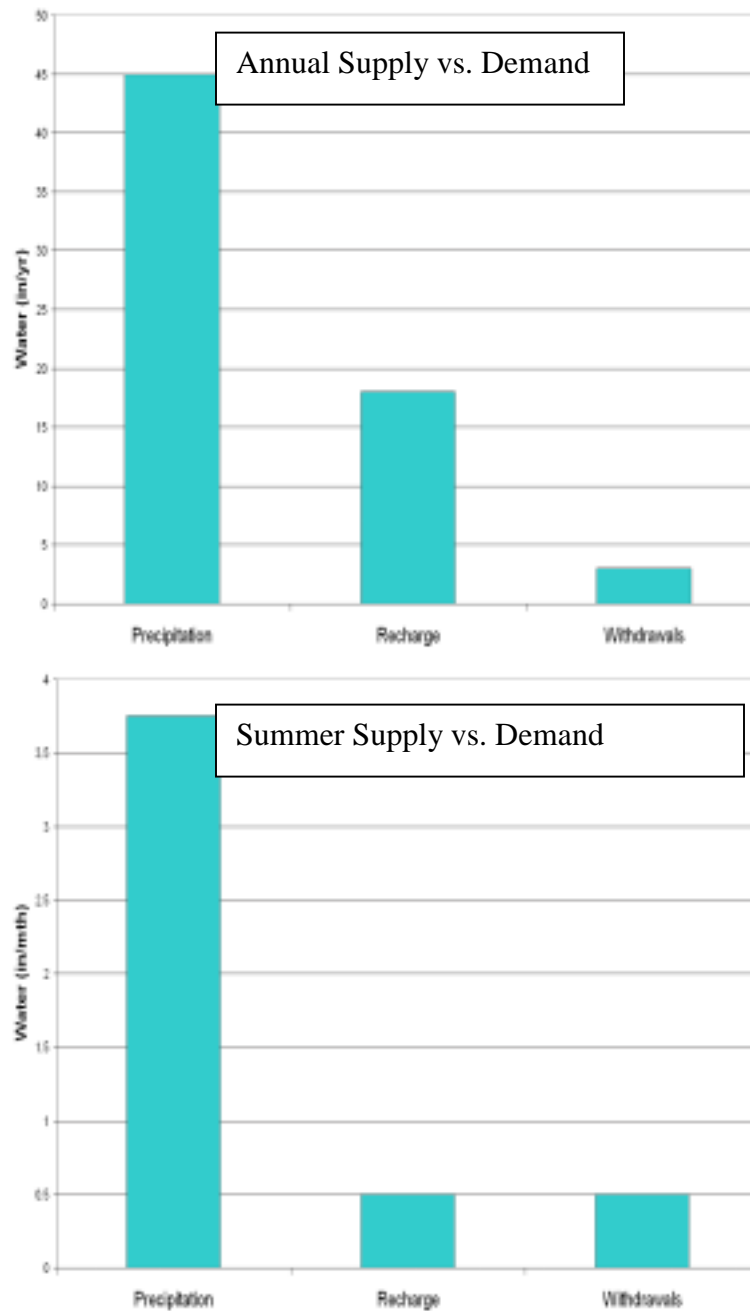


Figure 5: Annual and Summer Supply vs. Demand

Reduced water withdrawals, on a gallon for gallon basis, result in greater instream flow. Since the Massachusetts Water Management Act, G.L. c. 21G, requires the Massachusetts Department of Environmental Protection (DEP) to strike a balance between human demand, natural resource need and instream uses in its water withdrawal permits. That legal requirement, until its new water withdrawal policy was developed in 2004, had been ignored for rivers and streams in eastern Massachusetts.

## Water Discharges

Water is discharged to surface water, groundwater, or the ocean from power plant cooling facilities, agricultural return flows, and commercial, industrial, and residential wastewater. Wastewater discharges to streams have positive *quantity* benefit but negative *quality* effect. Wastewater discharges augment streamflow and in dry periods provide a steady flow of water for the stream. However, the water quality in the stream is reduced even if the wastewater is given standard treatment from surface water discharges. In periods of low flow, stream flow can consist mostly of wastewater. In eastern Massachusetts, streamflow in the Upper Charles and in the Assabet and Sudbury Rivers during summer months consists almost entirely of wastewater effluent.

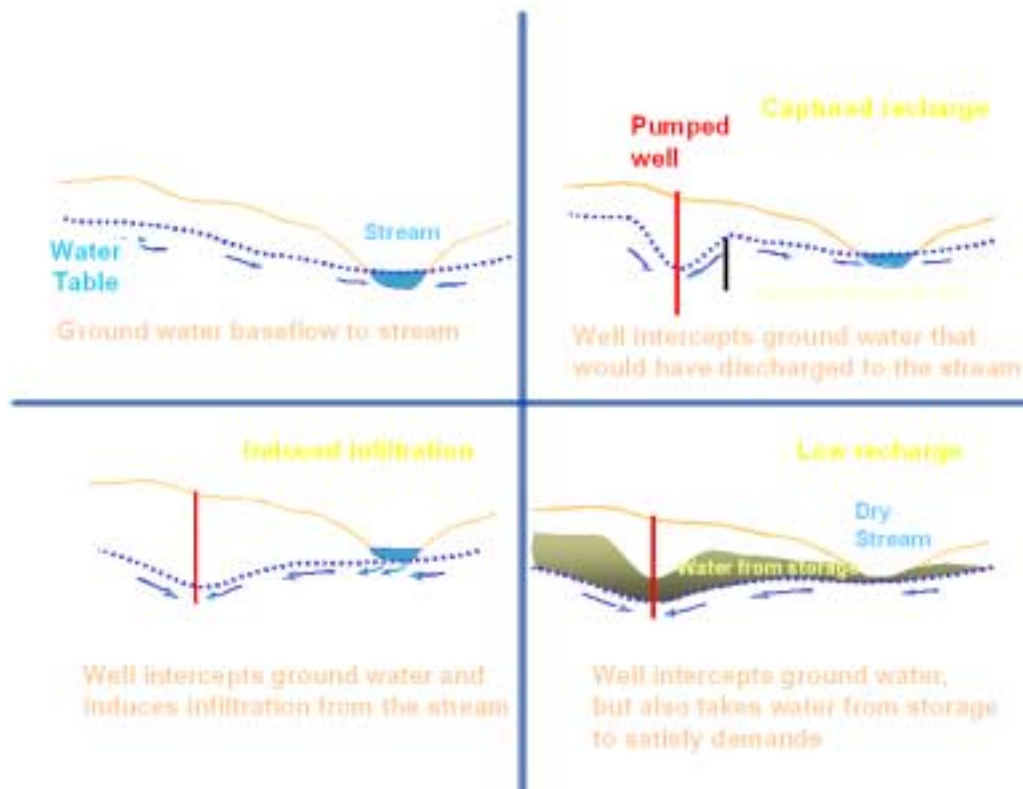


Figure 6: Effects of Water Withdrawal on Instream Flow

## **Dams**

Dams have multiple environmental effects on streams. From a water quantity perspective, they augment evaporation losses from the water surface and reduce streamflow. They can augment recharge locally but leakage around the dam into the downstream segment limits the net effect. Dam storage can also provide additional stream storage, which lowers peak flows and helps mitigate flood damage. Water supply reservoirs have a tremendous impact on downstream flows, unless downstream releases of water are programmed into reservoir operations. For a number of water supply reservoirs, 100 percent of the downstream flow is harvested for human use, leaving only dry streambeds downstream.

From a water quality perspective, the slow moving water behind dams enables algae and aquatic plant growth, especially in nutrient-rich streams. They also trap sediments behind dam walls, which further exacerbates plant growth. From a biological perspective, dams block the passage of migratory species of fish unless there are well-designed fish ladders that allow fish to pass. Multiple dams also promote the proliferation of warm water pond species within the resident fish population, instead of fluvial, or river fish.

## **Distribution and Collection Systems**

Water distribution systems for water supply and irrigation, and wastewater collection systems are designed to convey water from one place to another. These distribution and collection systems are usually piped. Water leaks into or out of these systems depending on whether they are pressurized and/or above the water table. Groundwater usually leaks into wastewater pipes, while water supply pipes leak water out of the system into the surrounding soils.

The result for watersheds is that water is shifted around, usually in great quantities, and often out of its basin of origin. For example, wastewater systems not only convey wastewater, they also collect inflow from cross-connections to stormwater pipes and infiltration of groundwater into the sewer pipes via cracks and fissures in the pipes. In urbanized areas, the volume of water being moved out-of-basin by wastewater systems can be equivalent to stream baseflow. For example, the Massachusetts Water Resources Authority wastewater collection system delivers, on average, 340 Mgd for treatment to Deer Island each day. Of this total, on average, approximately 180 Mgd is groundwater leaking into the system and rainwater collected and discharged into the system. The collected groundwater and rainwater treated at Deer Island as wastewater is, on an annualized basis, greater than the flow of the Charles River.

## **Irrigation**

Water withdrawals are used for irrigation of agricultural crops and residential landscapes. In the urbanized northeast United States, recent development of large lot residences with in-ground irrigation systems has promoted the irrigation of lawns and landscapes.

Irrigation is a loss of water to the atmosphere. The common misconception that most of the applied water percolates through the soil and recharges the groundwater is completely false. Depending on the type of irrigation system and degree of water management, the

water that is lost entirely to the atmosphere is 50-75 percent of the applied water. Irrigation systems with high uniformity (*i.e.*, even application of water over the desired area) and high irrigation efficiency (*i.e.*, most of the water ends up in the desired volume for the root zone) use less water but have the highest percentage loss to the atmosphere.

Irrigation demand also occurs during the late spring, summer, and early fall, when streamflows are at their lowest and competition for groundwater supply between human demand and streamflow needs are at their highest. Increased summer water withdrawals to meet irrigation demand (in some towns a doubling of use) have severe impacts on eastern Massachusetts streamflows. Many tributaries, and long reaches of rivers, such as the Ipswich and Sudbury, simply dry up as aquifers used for public water supply and private irrigation wells are pumped to provide water for landscape irrigation. Figure 6 shows how withdrawals intercept baseflow and pull water away from the stream.

### **Water Quality**

Since the 1950s, the US has made great strides in removing or minimizing industrial, commercial, and illicit discharges to rivers and streams through pipes, drains and outfalls (point source pollution). The greatest remaining threats are runoff from roads, residential areas, agricultural land uses, and urban areas (non-point sources) which carry a virtual cocktail of contaminants, such as oil grease, pet waste and sediments. The key to eliminating these environmental impacts is to reduce direct runoff from land surfaces to water bodies.

### **Overall Impacts**

The urban water cycle combines all these changes into significant impacts. Streams are flashier with higher storm flows and lower baseflows. Water withdrawals create local impacts while water is moved around in pipes creating a pattern of stress on streamflow. Water temperatures are elevated and water quality is poorer, enhancing algae and aquatic plant growth. Poorer physical and chemical conditions lower the numbers and diversity of fish and macro invertebrates.

Stream draw down to meet human demand also indicates groundwater supplies are threatened, and that demand will exceed available supply as pumping increases due to growth. Rivers and tributaries are, in effect, canaries in the coal mine, warning us that our current demand and water infrastructure is not sustainable.

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