Chapter 6. Freshwater Inflows

By Gerold Morrison (AMEC–BCI) and Holly Greening (Tampa Bay Estuary Program)

Estuaries are areas where freshwater discharged from the land mixes with saltwater from the sea. Variations in the quality, quantity, timing and location of freshwater inflows, therefore, have fundamental effects on their physical, chemical, and ecological characteristics. The watersheds of estuaries contain inland freshwater habitats — such as wetlands, lakes and rivers — that provide valuable environmental services, such as water-quality enhancement, wildlife habitat, and floodwater storage. Freshwater is also a resource that is necessary for human survival, and is used by human society to support a number of economically important urban, agricultural, and industrial activities. Policy makers are, thus, faced with the difficult task of developing and implementing management programs that allocate freshwater resources between natural ecosystem functions and other societal needs in a sustainable manner (Pielou, 1998; Baron and others, 2002; National Research Council, 2005).

Globally, the current human population is estimated to use more than 50 percent of the readily available freshwater runoff, causing substantial effects on the planetary water cycle (Montagna and others, 2002). Locally, use of fresh ground and surface water in the three counties (Hillsborough, Manatee, and Pinellas) on the immediate shoreline of Tampa Bay increased by a factor of 1.5 between 1965 and 2000, from 297 to 525 Mgal/d (Marella, 2004). Following this use, an estimated 225 Mgal/d of treated effluent was discharged from municipal wastewater-treatment plants in the three-county area in 2000 (Marella, 2004). Substantial withdrawals and discharges also occur in nearby Pasco and Polk Counties. Only parts of these counties lie within the Tampa Bay watershed, however, and withdrawal and discharge volume estimates have not been developed for those areas.

Figure 6–1. Summer thunderstorm forming over the Tampa Bay watershed. Photo by Holly Greening, Tampa Bay Estuary Program.

As noted in Chapter 2, annual freshwater inputs to the bay vary a great deal from year to year, depending on variations in rainfall and other factors (Schmidt and others, 2001; Schmidt and Luther, 2002). Based on several studies (summarized by Zarbock and others, 1995), average annual inputs have been estimated to range between 1,200 to 2,200 Mgal/d in recent decades. Rainfall (fig. 6–1) falling directly on the bay surface, which averages 42.6 percent of the annual total, and a combination of gaged streamflow and ungaged runoff (41.3 percent), are the largest estimated sources of freshwater inflow (Zarbock and others, 1995). The remainder consists of domestic point source discharges (5.9 percent), groundwater (4.3 percent), spring discharges (3.4 percent) and industrial point sources (2.4 percent) (Zarbock and others, 1995). These values involve considerable uncertainty. Groundwater inputs have traditionally been difficult to estimate (Culbreth and others, 1982), for example, and recent research suggests that some components of the groundwater budget, such as submarine groundwater discharge, may not yet be adequately quantified on an annual, bay-wide basis (Kroeger and others, 2007; Swarzenski and others, 2007a; see Chapter 5, box 5–1).

As the human population continues to grow in the Tampa Bay region, the importance of environmentally protective freshwater management programs will continue to increase. For resource managers in coastal areas it will be important to maintain appropriate instream flow levels in the freshwater segments of rivers and streams (Postel and Richter, 2003; Instream Flow Council, 2004) and appropriate freshwater inflows to estuarine and marine areas (Sklar and Browder, 1998; Montagna and others, 2002) to protect important ecosystem functions and living resources through the full range of freshwater to marine habitat systems.

In freshwater rivers and streams, management of instream flows normally focuses on a key set of hydrologic, biological and ecological factors — such as maintaining functional riparian zones, stream channel morphologies and sediment transport patterns, and providing appropriate life history cues and levels of connectivity between stream systems and their floodplains — that have been identified as critical elements in the protection of living resources (Richter and others, 1996, 1997; Poff and others, 1997; Postel and Richter, 2003). Appropriate goals for instream flow management programs have been identified as "maintaining the ecological integrity of unregulated rivers and restoring regulated rivers to the ecological conditions that more nearly approximate their natural form and function" (Instream Flow Council, 2004). The most important manmade changes in freshwater inflows to estuaries are ones that impact physical and chemical habitat conditions in ways that have significant impacts on the species composition and productivity of the estuarine biota (Jassby and others, 1995; Sklar and Browder, 1998; Alber, 2002; Estevez, 2002), as shown conceptually in fig. 6–2.

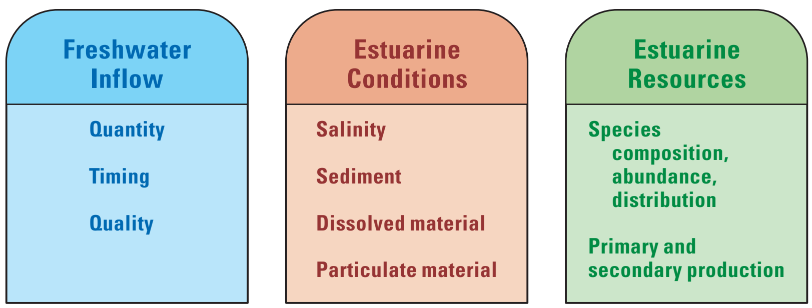


Figure 6–2. Conceptual overview of effects of freshwater inflow on estuaries. Based on Alber (2002).

In the case of Tampa Bay's biotic resources, numerous studies have noted the importance of low-salinity habitats in the tidal reaches of rivers and streams as nursery areas for a large number of fish and invertebrate species (Lewis and Estevez, 1988; McMichael and Peters, 1989; McMichael and others, 1989; Edwards, 1991; Peebles and Flannery, 1992; Zarbock and others, 1995; Matheson and others, 2005; Peebles, 2005; PBS&J, 2006; Krebs and others, 2007; Yeager and others, 2007; TBTTRT, 2008). Browder and Moore (1981) and Browder (1991) emphasized the importance of spatial overlap between favorable "dynamic" (such as salinity-based) and "stationary" (such as bottom type or shoreline plant community) habitats, during appropriate seasonal periods, to support the productivity of many estuarine-dependent organisms (fig. 6–3).

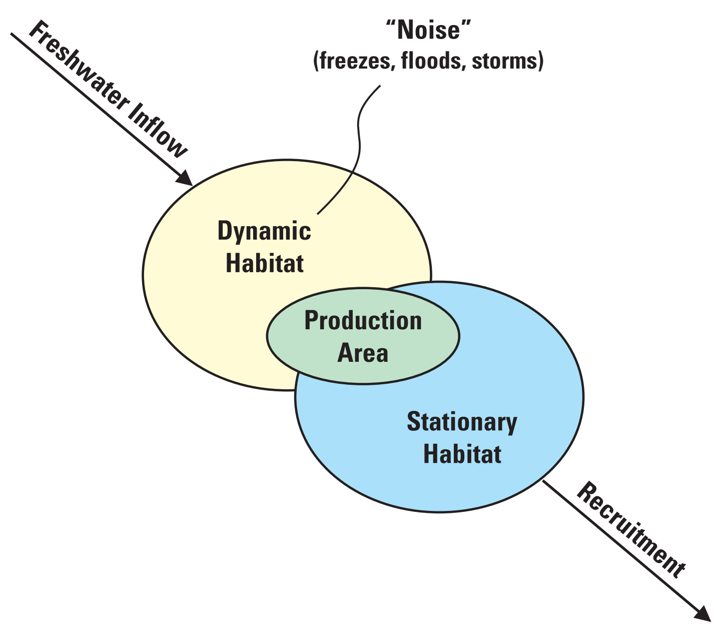


Figure 6–3. Suggested relationship of freshwater inflow to fisheries production through effects on areas of overlap of dynamic and stationary habitats in tidal tributaries. Based on Browder and Moore (1981) and Browder (1991).

Because of their importance as nursery areas for estuarine dependent species, and the fact that their acreage has declined substantially in Tampa Bay in recent decades, low-salinity or “oligohaline” habitats (fig. 6–4) have been identified by the TBEP as a priority target for protection and restoration (TBEP, 2006; see also box 8–4). Within the bay system tidal streams, and the parts of tidal rivers where channel width and volume begin to decline rapidly as one moves upstream, appear to be the low-salinity habitat areas that are most vulnerable to reductions in freshwater inflows (Estevez and others, 1991; Estevez and Marshall, 1997; SWFWMD, 2007). The volume of aquatic habitat is small in such areas, and relationships between salinity and freshwater inflow tend to be nonlinear. As a result, relatively small changes in freshwater inflows can produce large changes in salinity, potentially causing dislocations between favorable salinity regimes and benthic and shoreline habitat characteristics (Browder, 1991; Estevez and others, 1991; Zarbock and others, 1995). Changes in freshwater inflow that affect salinity regimes may, therefore, have disproportionate effects on the juvenile stages of many important species that use these areas as nursery habitat (Browder, 1991; Estevez and others, 1991; Zarbock and others, 1995). Targeted efforts to maintain or restore appropriate salinity regimes and habitats in these areas, therefore, can have enhanced environmental benefits. Habitats in the open bay appear to be better buffered against ecologically significant salinity fluctuations resulting from changes in freshwater inflows (Zarbock and others, 1995).

Figure 6–4. Oligohaline habitat in Cockroach Bay Aquatic Preserve. Photo by Nanette O’Hara, Tampa Bay Estuary Program.

In addition to changes in their salinity regimes, small tidal tributaries in Tampa Bay also appear sensitive to other forms of hydrologic modification. Freshwater inflows from their contributing watersheds can regulate productivity in these habitats by affecting fluxes of nutrients and other water-quality constituents that impact water clarity (TBTTRT, 2008; see also box 6–1). Benthic microalgae, which provide much of the primary production in small tidal tributaries that have not been overly altered by urbanization or eutrophication, require adequate light for photosynthesis. Due to their relative shallowness, these systems provide favorable areas for benthic microalgae growth when hydrologic and physico-chemical conditions are favorable. Sudden peak inflows, such as concentrated bursts of stormwater runoff, can “flush” juvenile fish and invertebrates, remove sediments, deepen and channelize the systems, and lead to unsuitable water-quality conditions, thereby reducing or eliminating benthic microalgae production and altering biotic communities (TBTTRT, 2008).

Similarly, low or no freshwater flow can result in lengthy hydraulic residence times, high concentrations of water column algae, and episodic hypoxic conditions (low or no DO), which in turn can also reduce the production of benthic microalgae. This can cause a cascading effect on benthic and fishery resources. In terms of sustained ecological production, it appears that Tampa Bay tidal tributaries with minimally altered, natural flow regimes exhibit the greatest estuarine value to fisheries resources through sustained benthic microalgae production (TBTTRT, 2008).

Anthropogenic Hydrologic Modifications

In the Tampa Bay region, as elsewhere, human population growth has led to changes in the quantity, quality, location and timing of instream flows in rivers and freshwater inflows to the coastal zone. Fortunately, a network of stream-gaging stations has been maintained on the larger tributaries in the watershed since the early to mid-20th century, allowing managers to document a number of the hydrologic changes that have occurred since that time. About 57 percent of the Tampa Bay watershed is gaged (Greening and Janicki 2006) (fig. 6–5). Anthropogenic activities that have altered some of the hydrologic characteristics of the watershed include:

- Urban development, which increases the amount of impervious surface (roads, parking lots, rooftops, etc.), thus altering the timing and magnitude of stormwater runoff and aquifer recharge (for example, NRC, 2008);
- Other physical changes, such as straightening, deepening, and hardening of stream banks (fig. 6–6) in the drainage network that carries surface-water runoff to the bay;
- Diversions and withdrawals of surface water and groundwater for human use, and the construction of dams and reservoirs (fig. 6–7) as part of the water-supply infrastructure system, which alter surface-water flow regimes and water levels in the surficial and Floridan aquifer systems; and
- Discharges of municipal and industrial wastewater, and agricultural irrigation water, which alter the timing, location, and quality of freshwater flows in streams and freshwater inflows to the bay.

Figure 6–5. Gaged and ungaged areas of the Tampa Bay watershed. Data from U.S. Geological Survey.

These activities have contributed to flow reductions in some hydrologic subbasins and increases in others, as well as altering the quality and timing of freshwater discharges in many localized areas within the watershed. As noted above, such alterations have the potential to adversely impact native plant and animal species, which are adapted to natural, climatically driven flow and salinity regimes.

Figure 6–6. Hardened streambanks increase the delivery rate of stormwater to the bay.; Booker Creek, St. Petersburg. Photo by Pinellas County Department of Environmental Management.

Figure 6–7. Lake Manatee and Manatee River Dam, 2003. Photo by Neal Parker, Manatee County.

Urban Development and Increased Imperviousness

In undeveloped parts of the watershed, upland soils are usually sandy and highly permeable, allowing rapid percolation of rainfall to the surficial (water table) aquifer and generating relatively small amounts of overland stormwater runoff under most hydrologic conditions. In contrast, urbanized areas contain large amounts of impervious surface, which reduce percolation and result in rapid transport of stormwater flows to receiving waterbodies (Schueler and Holland, 2000; NRC, 2008). As noted in Chapter 3, urban areas that were developed prior to the implementation of the stormwater treatment regulations, which were initially adopted in Florida in 1979 and substantially revised in the mid-1980s, tend to discharge particularly large volumes of untreated or inadequately treated stormwater runoff. Due to historical development patterns, these areas are concentrated near the bay shoreline within cities, such as Tampa, St. Petersburg, Clearwater, and Bradenton and their associated suburbs, and produce large stormwater discharges to the bay and the tidal reaches of rivers and streams in these areas (Xian and Crane, 2005; Xian and others, 2007).

Changes to Surface-Water Conveyance Systems

For management purposes the Tampa Bay watershed has been divided into 11 major surface-water basins (Pribble and others, 2001), whose locations are shown in Chapter 1, fig.1–3. Substantial anthropogenic modifications to the drainage network have occurred in each of these basins, initially for agricultural purposes and later to meet urban stormwater conveyance and water-supply needs (FDEP, 2003, 2005). Brief summaries of these modifications are provided below.

Coastal Old Tampa Bay Basin

The western part of this 248-mi^2 area drains a highly urbanized area of Pinellas County, including parts of the cities of St. Petersburg, Largo, Clearwater, and Safety Harbor. Tributaries in the area include the Cross Bayou Canal (which bisects the Pinellas peninsula from Old Tampa Bay to Boca Ciega Bay), Allen Creek, Alligator Creek, and Bishop Creek. The creek systems are primarily intermittent or low-flowing urban tidal streams whose freshwater flows are supplied by surface-water runoff (Hancock and Smith, 1996).

Tributaries in the northern part of the basin include the Lake Tarpon Outfall Canal, Double Branch Creek, Rocky Creek, and Sweetwater Creek. The Lake Tarpon area has a particularly interesting history from a resource-management perspective. The lake was used as a source of potable water supply during a 4-year period between March 1926 and May 1930, but that use was discontinued because of frequent inflows of saline water which entered the lake through a sinkhole on its western shoreline (Hunn, 1973). The sink is connected to the estuarine reach of the Anclote River, which lies outside the Tampa Bay watershed (Wolfe and Drew, 1990; SWFWMD, 2002a). To prevent saline inflows, an earthen ring dike was constructed around the sinkhole in May 1969. Freshwater inflows continued, both from the Brooker Creek catchment and as direct stormwater runoff from the urbanized area immediately adjacent to the lake. A manmade canal leading south to Old Tampa Bay was completed as a flood control outlet in July 1967, as an element of the Four River Basin Project of the SWFWMD and the U.S. Army Corps of Engineers. An earthen dam in the canal was partially removed in 1969 to allow discharge during high water. In 1971, the earthen dam was replaced and gated culverts were constructed in the dam (Hunn, 1973). During 1953–1971, chloride concentrations in the lake varied with inflows of fresh and saline water, ranging from near zero to nearly 5,000 mg/L (Hunn, 1973). Currently Lake Tarpon is managed as a freshwater lake, under the auspices of the SWFWMD Surface Water Improvement and Management Program (SWFWMD, 2001, 2002a).

In addition to modifications of the Lake Tarpon hydrologic system, the catchments of several streams in the central part of the Coastal Old Tampa Bay Basin have experienced major land use changes in recent decades, shifting from primarily rural to primarily urban uses. Also, in response to the flat topography and naturally slow drainage of the area, several stream reaches have been channelized and a number of manmade canals constructed to convey stormwater flows more quickly to the bay (fig. 6–8). Manmade canals, constructed primarily in the 1960s and 1970s, divert stormwater flows from the Curiosity Creek catchment (in the Hillsborough River watershed) to Sweetwater Creek, and from Sweetwater Creek to the Rocky/Brushy Creek system in the Coastal Old Tampa Bay Basin (Hancock and Smith, 1996). Manmade structures in the lower reaches of several of these creeks and canals regulate water levels and discharges from the upstream (freshwater) side and prevent upstream movements of brackish bay water.

The eastern part of the Coastal Old Tampa Bay Basin drains the western side of the heavily urbanized Interbay Peninsula, which includes a part of the City of Tampa. Like many of the older urban centers around the bay, this area was developed prior to the adoption of modern stormwater management regulations and, therefore, tends to generate larger volumes of stormwater runoff at higher rates and of poorer quality in comparison to areas of similar land use intensity that were developed more recently. Large (> 0.1 Mgal/d) wastewater discharges in the basin include twelve domestic and two industrial facilities, seven of which have permitted capacities greater than 1 Mgal/d (FDEP, 2003). But, not all of these are freshwater discharges.

Figure 6–8. Northern Old Tampa Bay, 2002. The Courtney Campbell Causeway is at the bottom of the photo. From left to right, Double Branch Creek, the straightened and dredged Channel A, and the Rocky Creek tidal streams. Photo by South Florida Water Management District.

One of the industrial facilities is a thermoelectric power generating station located on the western shoreline of Old Tampa Bay, which withdraws and discharges several hundred million gallons of once-through cooling water to and from the bay on a daily basis (FDEP, 2003; Marella, 2004).

Hillsborough River Basin

This approximately 675-mi^2 watershed originates in the southwestern part of the Green Swamp, an area of poorly defined drainage that also includes the headwaters of the Withlacoochee River. Named tributaries in upper parts of the Hillsborough River Basin include Big Ditch, Flint Creek, Indian Creek, New River, Two Hole Branch, Basset Branch, Hollomans Branch, Clay Gully, Trout Creek, Itchepackesassa Creek, Blackwater Creek, and Cypress Creek, several of which exhibit seasonally intermittent flows. During low-rainfall periods, Blackwater Creek is dry upstream from its confluence with Itchepackesassa Creek, and all downstream flow is from Itchepackesassa Creek (Trommer and others, 2007). Much of the dry season flow in Itchepackesassa Creek is treated municipal wastewater effluent (Trommer and others, 2007).

Cypress Creek receives groundwater discharges from the Upper Floridan aquifer system, which in earlier decades was estimated to contribute about 20 percent of the total flow in the stream's middle reaches (Cherry and others, 1970). Along the main stem of the Hillsborough River, Crystal Springs (fig. 6–9), a second magnitude spring, also contributes discharges of Upper Floridan groundwater, which provide 85 percent to 100 percent of river flow during dry periods (Hancock and Smith, 1996; Trommer and others, 2007). Groundwater discharges in both of these areas have declined in recent decades, apparently in response to a combination of anthropogenic and natural factors (Hancock and Smith, 1996; Weber and Perry, 2001, 2006; Trommer and others, 2007).

In the middle reaches of the river, potential floodwaters generated by tropical cyclones, strong El Niño episodes and other large rain events are diverted from the river to the manmade Tampa Bypass Canal (historically a part of the Sixmile Creek/Palm River watershed), and then to McKay Bay to provide flood protection for the cities of Tampa and Temple Terrace (Knutilla and Corral, 1984; SWFWMD, 1999, 2005a). Construction of the Bypass Canal, a Federal flood control project, extended the historical Sixmile Creek drainage northward

Figure 6–9. Crystal Springs, a second magnitude spring, discharges into the upper Hillsborough River. Photo by Karen Pate, Crystal Springs Preserve.

and westward and created additional hydrologic connections with the Hillsborough River at several points, including the confluence of Trout Creek and through the Harney Canal near the midpoint of the Hillsborough River Reservoir (SWFWMD, 1999, 2005a). The reservoir is the primary source of drinking water for the City of Tampa. Since the mid-1980s, during drought conditions, water has been pumped from the Tampa Bypass Canal to the Hillsborough River Reservoir to augment the reservoir and allow water-supply withdrawals from the reservoir to be maintained (SWFWMD, 1999).

Freshwater inflows to the most downstream (tidal) reach of the Hillsborough River were intermittently regulated by dams as early as the late 1890s (SWFWMD, 1999, 2006b). A hydroelectric dam was constructed about 10 mi upstream from the river mouth in 1924 (Stoker and others, 1996). That dam failed during a flood in 1933, and the river was unregulated until 1945 when a new dam was completed to create the City of Tampa water-supply reservoir (Pride, 1962; Stoker and others, 1996). In recent decades, withdrawals for municipal supply have removed essentially 100 percent of the daily river flow from the reservoir during periods of low natural flow, leaving minimal leakage (<0.65 Mgal/d) at the dam as the only source of freshwater flow from the reservoir to the tidal reach of the river (Stoker and others, 1996; SWFWMD, 1999, 2006b). The numbers of these "zero-flow" (<0.65 Mgal/d) days per year showed dramatic increases beginning in the 1970s (fig. 6–10), presumably due to a combination of increased withdrawals, below-average rainfall, and changes in surface-water and groundwater inflows to the reservoir (SWFWMD, 1999).

Since 2003, during periods of moderate to high natural flows, additional withdrawals of up to 194 Mgal/d have been permitted from the Hillsborough River to provide water for the regional potable supply system (SWFWMD, 2007). These additional withdrawals are linked to the rate of flow from the reservoir, with no withdrawals allowed unless flows from the reservoir exceed 65 Mgal/d. The maximum rate of withdrawal is permitted when flows from the reservoir exceed 485 Mgal/d.

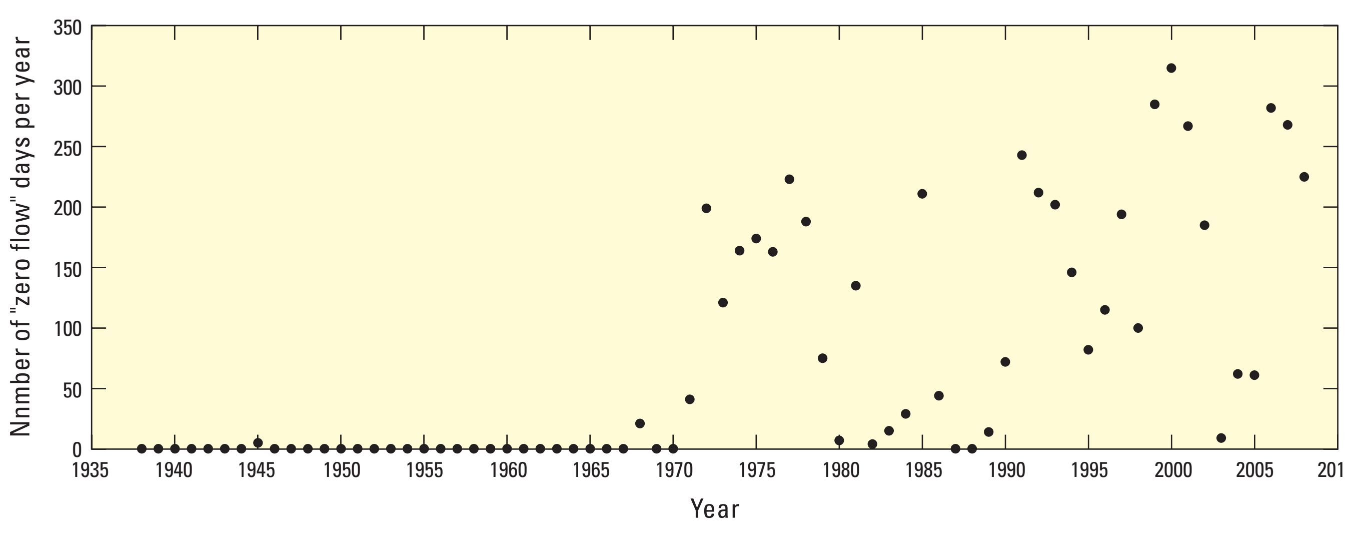


Figure 6–10. Number of "zero flow" days per year recorded at the Hillsborough River dam, October 1938 through July 2009. Data from U.S. Geological Survey.

Sulphur Springs, a second magnitude spring that is hydrologically connected to the karstic Curiosity Creek system via a series of sinks and conduits, discharges to the tidal reach of the river about 2.2 mi downstream from the dam (fig. 6–11). The long-term discharge of the spring is about 26 Mgal/d, but has shown declining trends in recent decades (Stoker and others, 1996; SWFWMD, 2004). During dry periods, some of the spring flow is pumped to the Hillsborough River Reservoir to augment water supplies for the City of Tampa, and some is pumped to the base of the Hillsborough River dam to provide freshwater inflows to that part of the river's tidal reach (SWFWMD, 1999, 2005a, 2006b).

Of the water that is withdrawn from the reservoir, about 60 Mgal/d is eventually discharged in northern Hillsborough Bay in the form of highly treated municipal effluent, providing an estimated 15 percent of the freshwater inflow to this bay segment during periods of low rainfall (Zarbock and others, 1995). Overall, the Hillsborough River watershed contains 127 domestic and industrial facilities with permitted wastewater discharges, 13 of which discharge ≥0.1 Mgal/d through surface-water discharges or by land application of the effluent (FDEP, 2003, 2005).

Coastal Hillsborough Bay Basin

This 166-mi^2 area conveys surface runoff from the heavily urbanized eastern side of the Interbay Peninsula, from the northeastern part of Hillsborough Bay between the Hillsborough and Alafia Rivers, and from small coastal drainage systems located south of the Alafia River watershed. Tributaries in the area include the Palm River/Tampa Bypass Canal, Delaney Creek, Archie Creek, and Bullfrog Creek.

The Tampa Bypass Canal, as noted above, was constructed as a Federal flood control project between the mid-1960s and early 1980s. A manmade structure at the downstream limit of the canal controls water elevations on its upstream side and regulates freshwater discharges to the tidal Palm River, as well as preventing upstream movement of saltwater (and aquatic organisms) from the bay to the canal (SWFWMD, 1999). Dredging during construction of the canal breached the Upper Floridan aquifer, leading to increased discharges (about 20 Mgal/d) of groundwater to the canal and reducing or eliminating groundwater discharges from several springs in the vicinity of the canal (Knutilla and Corral, 1984).

Figure 6–11. The Sulphur Springs spring run discharges to the lower Hillsborough River. Photo by Holly Greening, Tampa Bay Estuary Program.

Since 1984 a large amount of the resulting base flows in the canal have been withdrawn for water-supply purposes (SWFWMD, 1999, 2005a). Since 2002, under a water-use permit issued to Tampa Bay Water by the SWFWMD, moderate and high flows have also been withdrawn for regional water-supply purposes (PBS&J, 2006).

Primary land uses in the basin are urban (48 percent) and agricultural (22 percent), with most of the agricultural lands located in the southern (Bullfrog Creek) area. The basin contains more than 100 domestic and industrial wastewater facilities with permitted effluent discharges (FDEP, 2003).

Alafia River Basin

This is an approximately 410-mi^2 watershed whose upper section consists of two major branches (the North and South Prongs) that originate in western Polk County and converge in eastern Hillsborough County to form the Alafia River. The river receives flow from numerous small tributary streams, two named springs (Lithia and Buckhorn Springs) that provide discharges from the Floridan aquifer, and several smaller groundwater springs and seeps. Due to elevated nitrate levels in local groundwater, caused by a combination of agricultural and residential land uses, the two spring systems contribute disproportionately large N loads to the lower river and Hillsborough Bay (Jones and Upchurch, 1993). Although some reduction in the average nitrate concentrations is expected to occur over time, due to conversions from agricultural to residential land uses and decreasing residual groundwater concentrations, the continued loading of N from septic tanks in this area will likely keep N concentrations in the springs well above background levels (SDI Environmental Services, 2005).

Since 1977 water has been withdrawn from the springs for industrial use, averaging about 4.5 Mgal/d for 1998–2003 (SWFWMD, 2008a). Water is also withdrawn from the Alafia River for potable supply purposes. The intake site is located near Bell Shoals, just upstream from the river's tidal reach. A pipeline transports withdrawals to a 1,000 acre offstream reservoir located about 6 mi southeast of the intake facility. This offstream reservoir, which is part of the regional water-supply system operated by Tampa Bay Water, was completed in 2005 and receives water from the Alafia River, the Hillsborough River, and the Tampa Bypass Canal (SWFWMD, 2008a).

Phosphate surface mining has affected much of the headwater area of the Alafia River watershed, with the construction of numerous mine pits and clay settling areas, and several processing plants. Sixty-two permitted wastewater discharges are present, four of which discharge >0.1 Mgal/d (FDEP, 2003). Twenty of the permitted facilities, primarily phosphate mining and processing operations and municipal wastewater-treatment plants, discharge to surface waters (FDEP, 2003, 2005). Several phosphogypsum stacks located in the upper part of the watershed are planned for closure in the near future, which will require the treatment and disposal of large volumes of industrial wastewater (PBS&J, 2007). Trend analyses presented by SWFWMD (2008a) indicate that industrial discharges to the river have decreased in recent decades, largely due to more efficient water use by the phosphate industry. Predominant land uses in the watershed are phosphate mining (28 percent of the surface area) and agriculture (about 27 percent of the surface area) (FDEP, 2005). Urban land uses make up about 17 percent of the area and are increasing in coverage in both coastal and inland areas.

Box 6–1. Regional Drinking-Water Supply — Groundwater, Surface Water, and Desalination

By Robert McConnell (Tampa Bay Water)

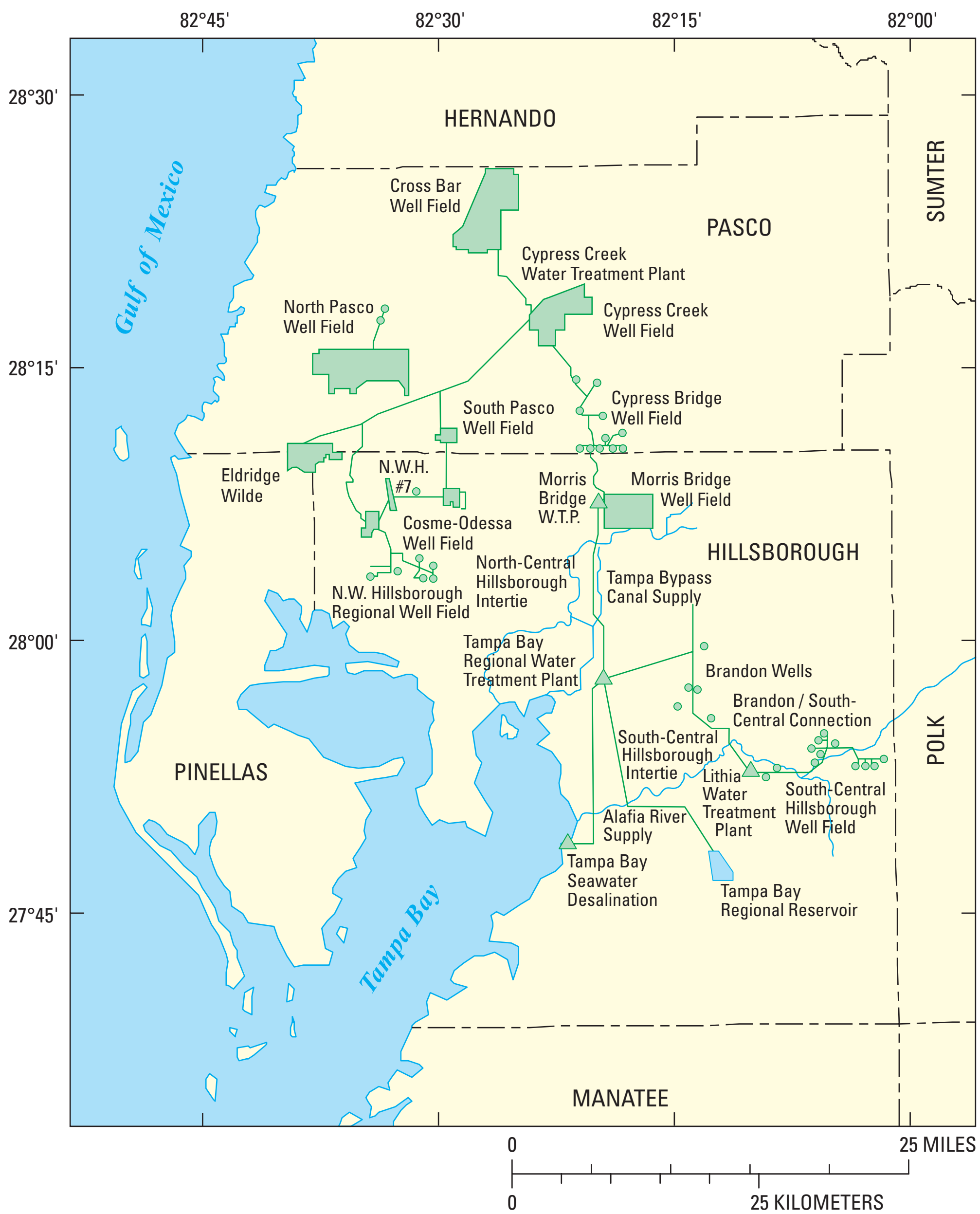
An important aspect of resource-based management for Tampa Bay includes drinking-water supply. About 244 Mgal/d of drinking water were provided to more than 2.5 million residents in the region during 2008 by Tampa Bay Water and its member governments. Drinking water is supplied through a diverse water-supply system that minimizes environmental impacts by avoiding over-reliance on individual groundwater or surface-water-supply sources.

Tampa Bay Water is a regional water-supply authority created in 1998 by inter-local agreement among six member governments: Hillsborough County, Pasco County, Pinellas County, New Port Richey, St. Petersburg and Tampa. Tampa Bay Water owns and operates interconnected water-supply facilities to meet drinking water demands. These facilities include groundwater well fields, river and canal surface-water intakes, a seawater desalination facility, treatment facilities, storage facilities including a large off-stream reservoir, pumping stations, and transmission mains (box 6–1, fig. 1).

For all current and future drinking water supplies, detailed environmental assess-ments are conducted to determine if projects are environmentally sustainable as well as technically feasible. Typical environmental protection activities include: impact assessment and permitting, evaluation of minimum flows and levels requirements, and development of environmental monitoring programs. Environmental monitoring is coordinated with Tampa Bay Water's Optimized Regional Operations Plan system that utilizes monitoring data and sophisticated computer models to analyze and forecast conditions to rotate and adjust production activities to ensure environmental impacts are minimized.

Groundwater

Major regional groundwater supplies include the 11 Central System Well fields, the South-Central Hillsborough Regional Well field and the Brandon Urban Dispersed Wells (box 6–1, fig. 1). Tampa Bay Water has been able to reduce groundwater pumping



Box 6–1, Figure 1. Tampa Bay Water regional drinking-water supply system.

from historical levels to allow aquifer levels and associated wetlands to recover through development of new alternative surface-water-supply sources. The average annual production permitted from the 11 well fields was 158 Mgal/d from 1995–2002. However, with development of alternative sources, annual average production was below 90 Mgal/d by the end of 2008. Water use permits for well field areas include comprehensive environmental management plans to monitor the status of wetlands, lakes and other natural systems in these areas for any changes associated with groundwater withdrawals including recovery in areas of reduced pumping.

Surface Water

Tampa Bay Water's Enhanced Surface Water System includes withdrawals from major surface waters including the Tampa Bypass Canal, the Hillsborough River and the Alafia River that have been part of the regional system since 2002–2003. About 42 Mgal/d of treated surface water was supplied to the regional system in 2008. For each source, water-use permits specify a withdrawal schedule that varies with available flows, and includes minimum and maximum flow limits to minimize environmental impacts. These permits also require implementation of hydrobiological monitoring programs that include extensive sampling and analysis of water-quality and biological data (fish, plankton, benthos and vegetation) to ensure these estuarine systems are not adversely impacted. Water not treated and used immediately in the regional system is stored in the 15 billion gallon C.W. Bill Young Regional Reservoir added to the system in 2005 to help meet drinking water demand during dry periods.

Desalination

The Tampa Bay Seawater Desalination Facility is located on Hillsborough Bay in the southeastern part of Tampa Bay. This facility initially went online in 2003, was off-line in 2005–2007 for repairs and improvements, and in 2008 contributed an average of 20.1 Mgal/d or about 11 percent of regional supply. The desalination facility uses reverse osmosis, a mechanical process that forces seawater through semipermeable membranes under high pressure, squeezes freshwater from saltwater and leaves salts and minerals behind in a concentrated seawater solution. The facility is co-located with Tampa Electric's Big Bend Power Plant and is designed to withdraw up to 44 Mgal/d from powerplant cooling water yielding up to 25 Mgal/d of potable water along with about 19 Mgal/d of concentrate discharged back into the cooling water conduits. The withdrawal is a small fraction of the 1.4 billion gallons of cooling water used by the powerplant, and the concentrate is typically diluted about 70:1 with cooling water before discharge so salinity is about the same as Tampa Bay.

Development of the desalination facility included extensive modeling and assessment of potential impacts to water-quality and biological components of the Tampa Bay ecosystem (fish, benthos, and seagrass). Based on results from water-quality and biological monitoring through 2008, there has been no indication that discharge from the desalination facility has had an adverse impact on Tampa Bay (R. McConnell, Tampa Bay Water, personal commun., 2009).

Supply Planning and Protection

Tampa Bay Water's regional supply system also includes long-term planning to ensure that regional water supplies are sufficient to meet future demands. It takes up to 10 years to plan, permit, design and build drinking water facilities. Therefore, planning for the future ensures the region's supply can meet demand in an environmentally sound and cost-effective manner. Tampa Bay Water's Board of Directors has selected potential new supply sources for further study, including brackish groundwater, seawater desalination, additional well field and surface-water withdrawals, and use of reclaimed water for augmentation or aquifer recharge to meet anticipated demands over the next 20 years.

Another critical aspect of regional drinking-water supply and resource-based management includes source water protection. Maintaining a diverse regional water-supply system to minimize environmental impacts requires maintaining source water quality so that all sources can be used reliably. Protection of groundwater supplies has been accomplished in the past through adoption of wellhead protection programs with associated regulations and ordinances to limit land use activities that could pollute aquifers. Although protection of drinking water has environmental benefits, source water protection has become increasingly complex with the development of new surface-water-supply sources due to potentially conflicting uses such as industrial or municipal wastewater disposal and uncertain future land use changes. Tampa Bay Water is working with State and local governments, private stakeholders, and the public to evaluate and implement actions to ensure water-quality protection for the future.

Coastal Middle Tampa Bay Basin

This approximately 80-mi^2 area includes an urban center (part of the City of St. Petersburg) located on the west side of the bay, and a predominately agricultural area on the east side. Six large (permitted effluent discharges >0.1 Mgal/d) municipal wastewater and industrial facilities are present in the basin (FDEP, 2003). Some of the industrial facilities discharge brackish rather than freshwater, such as the TECO Big Bend Power Station which circulates more than 1,000 Mgal/d of once-through cooling water to and from the northeastern shoreline of Old Tampa Bay. A desalination facility that is part of the regional potable water-supply system has recently been built adjacent to the power station. It is currently designed to withdraw 44 Mgal/d of surface water from Tampa Bay, producing 25 Mgal/d of potable water for regional distribution and discharging 19.5 Mgal/d of brine concentrate into the Big Bend Power Station's cooling water discharge conduits (FDEP, 2003).

Little Manatee River Basin

This is an approximately 220-mi^2 watershed with headwaters near Fort Lonesome in southeastern Hillsborough County. The Little Manatee River has two major branches (the North and South Forks) and numerous smaller tributaries. The watershed includes a 4,000 acre offstream reservoir that provides cooling water for a power generating station. The water supply for the reservoir is withdrawn from the river, primarily during higher-flow periods (Flannery, 1989). Land uses are predominantly (>50 percent) agricultural, which along with large holdings of publicly owned conservation lands make this watershed one of the least-urbanized in the Tampa Bay region (Flannery and others, 1991; FDEP, 2003, 2005). However, surface discharges of groundwater used for agricultural irrigation have produced measurably increased dry season flows and hydrologic impacts to area wetlands in recent decades (Flannery and others, 1991). Fourteen domestic and industrial facilities have permitted discharges in the watershed, all less than 0.1 Mgal/d (FDEP, 2003, 2005).

Coastal Lower Tampa Bay and Terra Ceia Bay Basins

These basins include an area of about 56 mi^2, most of which is located on the eastern side of Lower Tampa Bay in northern Manatee County. Predominant land uses are agricultural (35 percent, primarily inland) and urban (25 percent, primarily on or near the bay shoreline). Facilities with permitted effluent discharges greater than 0.1 Mgal/d include a municipal wastewater-treatment plant and a former phosphate processing facility. In 2001, the owner of the phosphate plant filed for bankruptcy and turned operation of the facility over to the State of Florida. The FDEP has since closed the facility, which holds large volumes of acidic industrial wastewater in phosphogypsum stacks. These have the potential to contaminate surface water and groundwater along the bay shoreline if not properly managed (FDEP, 2003).

Manatee River Basin

This approximately 360-mi^2 watershed lies primarily in Manatee County and contains numerous coastal lowlands, hardwood swamps, marshes, and mesic flatwoods. Major tributaries include the Braden River, Gamble Creek, and Gilley Creek (FDEP, 2005). During 1966–1967, the Manatee River was dammed about 24 mi upstream from Tampa Bay, creating a 1,900 acre instream reservoir (Lake Manatee) that is the principal water supply for Manatee County (fig 6–7). The river is tidally influenced from its mouth to the dam. The Braden River, which was dammed in 1939 and expanded in 1985 to create a 1.4-billion gallon instream water-supply reservoir for the City of Bradenton, discharges to the estuarine reach of the Manatee River. Tidally influenced brackish waters now extend upstream to the Braden River dam under most flow conditions.

Land uses in the Manatee River watershed include agricultural (about 40 percent), rangeland (14 percent), urban (14 percent), wetlands (13 percent) and upland forest (11 percent). Most of the urban lands occur near the river mouth, in the cities of Bradenton and Palmetto and their associated suburbs (FDEP, 2003). The watershed contains 14 domestic and industrial facilities with effluent discharge permits, three of which discharge >0.1 Mgal/d of treated wastewater to surface waters or via land application (FDEP, 2003).

Boca Ciega Bay Basin

This 92-mi^2 area is highly (83 percent) urbanized, consisting primarily of high density residential, commercial, and industrial land uses located within the municipalities of Gulfport, St. Petersburg, St. Pete Beach, and South Pasadena. Much of the urbanization occurred prior to the adoption of modern stormwater management regulations. The basin contains Lake Seminole, the second largest lake in Pinellas County (with a surface area of 680 acres), which was once an estuarine waterbody. The lake was isolated from direct tidal influence by a manmade salinity barrier and weir structure built in the 1940s. The lake now discharges over the weir to Long Bayou, which flows to Boca Ciega Bay (SWFWMD, 2002a).

Changes in Groundwater Systems

Surface- and groundwater resources are highly interconnected in the Tampa Bay watershed, and anthropogenic modifications to one often affect the other. As noted, several rivers and streams receive discharges from the Upper Floridan aquifer, which contribute a large percentage of the dry-season baseflow in some surface-water systems. Groundwater discharges to Tampa Bay itself have not received extensive study, and remain an incompletely resolved component of the bay's water budget (Culbreth and others, 1982; Kroeger and others, 2007; Swarzenski and others, 2007a, 2007b).

Several reports have summarized the hydrogeology and groundwater resources of the Tampa Bay region (for example, Hancock and Smith, 1996; Miller, 1997; Fernald and Purdum, 1998). Briefly, the bay's surface watershed overlies parts of three groundwater basins (the northern, central and southern west-central Florida basins), whose locations are shown in

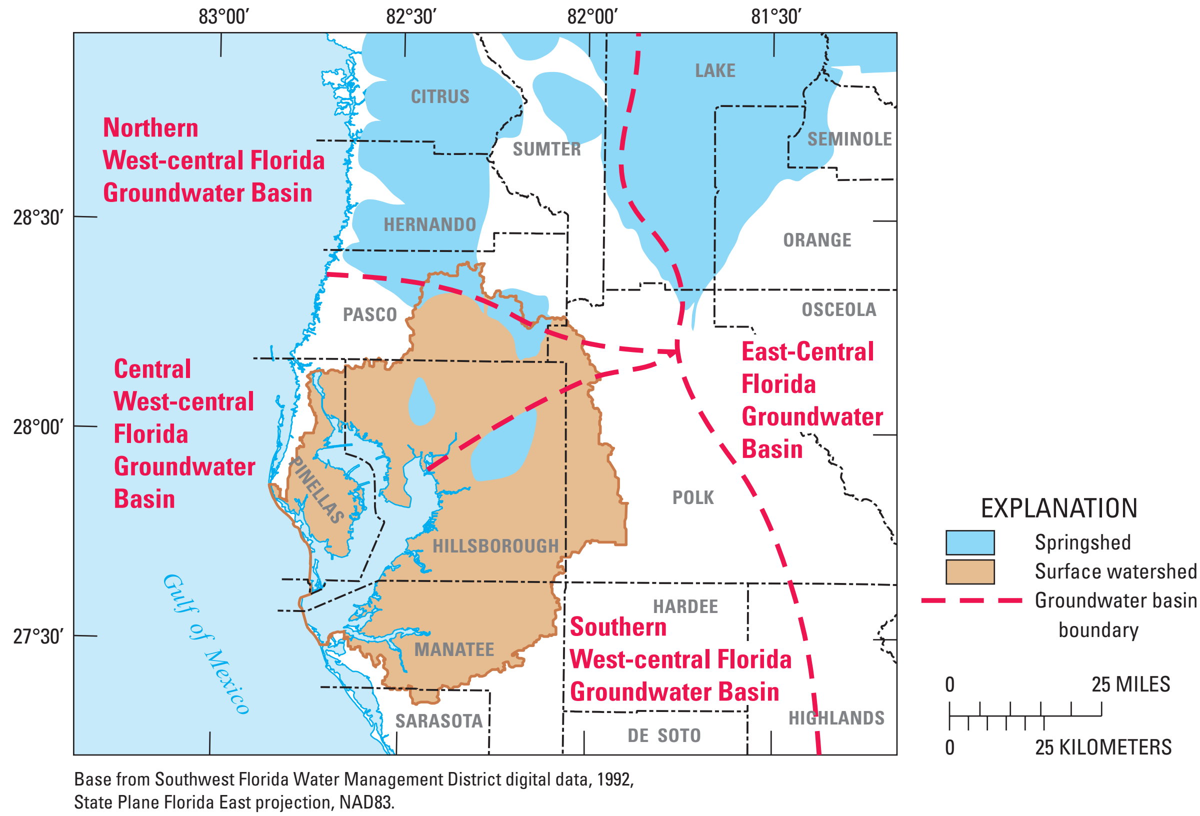


Figure 6–12. Groundwater basins in west-central Florida. From Southwest Florida Water Management District (2006c).

fig. 6–12. The southern basin differs from the other two in possessing a well-developed intermediate aquifer system, which is lacking in the northern basins. The intermediate aquifer is not used as a major source of water supply in the Tampa Bay region. However, its presence in the southern part of the watershed, and absence in the northern part, produces different types of interactions between groundwater and surface waters in the two areas, and makes them respond differently to groundwater withdrawals (Hancock and Smith, 1996).

Northern Groundwater Basins

The northern part of the Tampa Bay watershed, which includes much of the central west-central and a part of the northern west-central groundwater basins (fig. 6–12), is a karst area that contains few large river systems but numerous surface depressions and sinkholes, many of which contain lakes or wetlands (Hancock and Smith, 1996; Fernald and Purdum, 1998). The surficial aquifer in this area occurs within an unconsolidated mantle of sand, silt, and clay whose thickness is highly variable depending on local topography, but averages 6 to 15 m. In some areas this unconsolidated material overlies a semiconfining zone made up of clay, silt, and sandy clay that retards vertical water movement, whereas in others it directly overlies the thick deposits of carbonate (limestone and dolomite) rocks that make up the highly productive Upper Floridan aquifer (Hancock and Smith, 1996; Miller, 1997;

Marella and Berndt, 2005). Depth to the water table varies from at or near land surface in wetland areas to more than 4.5 m in uplands, with average depths between 0.5 and 1.5 m (Hancock and Smith, 1996; Trommer and others, 2007).

On average the thickness of the clay semiconfining layer tends to be greater in southern than in northern parts of the area, but this pattern includes considerable variability. The clay layer is thin, fractured, breached, or missing in many localized areas, greatly increasing hydraulic connectivity between the Upper Floridan and surficial aquifers in those locations. The elevation of the water table, therefore, is highly variable, both spatially and temporally, and strongly affected by changes in the potentiometric surface of the underlying Upper Floridan aquifer (Hancock and Smith, 1996; Trommer and others, 2007).

The Upper Floridan aquifer is the primary source of groundwater withdrawals in the region (Hancock and Smith, 1996; Marella and Berndt, 2005). Groundwater withdrawals for potable and irrigation supply lower the potentiometric surface of the aquifer which, due to the absence of a consistent regional confining layer, leads to “induced recharge” of water from the surficial aquifer downward to the Upper Floridan (Hancock and Smith, 1996). The result is a lowering of the surficial water table, and local assessments suggest that in “leaky” parts of the northern Tampa Bay area a high percentage of groundwater pumped from the Upper Floridan is derived from vertical leakage downward from the surficial aquifer (Bedient and others, 1999).

Water-level fluctuations in the Upper Floridan aquifer caused by groundwater withdrawals affect water levels of the surficial aquifer and lakes and wetlands that are connected to the surficial aquifer (Bedient and others, 1999). Although varying in degree, all major well fields within the northern Tampa Bay region have exhibited drawdowns in water tables, lakes, and wetlands associated with increased groundwater withdrawals (Hancock and Smith, 1996). These environmental impacts are major factors constraining the amount of water that can be withdrawn from the Upper Florida aquifer in this region of the watershed (Hancock and Smith, 1996; Fernald and Purdum, 1998).

Such impacts can be mitigated to some extent through water reuse programs, whereby the treated effluent produced by municipal wastewater-treatment plants is reused as irrigation water for residential, recreational, and agricultural areas and other applications that provide a degree of aquifer recharge (Young and York, 1996; Fernald and Purdum, 1998). In the northern region of the Tampa Bay watershed, however, much of the water that is withdrawn for public supply from the Upper Floridan aquifer is pumped from concentrated well fields that are located in inland areas, and is then distributed regionally (Hancock and Smith, 1996). Many of the municipal wastewater-treatment facilities that produce effluent in the region are located in coastal communities. In 2000, for example, the largest withdrawals of groundwater occurred in Pasco (102.67 Mgal/d) and Hillsborough (85.51 Mgal/d) Counties, respectively, whereas the largest municipal wastewater-effluent discharges were produced in Pinellas County (106.08 Mgal/d) (Marella, 2004). Although substantial percentages of the available effluent are currently reused (48 percent in Pinellas County, 33 percent in Hillsborough County; Reuse Coordinating Committee, 2003), and effluent reuse programs are increasing on a regional and statewide basis (Young and York, 1996; Fernald and Purdum, 1998; Office of Policy Programs and Government Accountability, 2003), much of the current reuse is occurring in areas other than those from which large amounts of groundwater are being withdrawn (Hancock and Smith, 1996).

Due to the generally unconfined upper surface of the Upper Floridan aquifer, and the availability of induced recharge from the surficial aquifer, saltwater intrusion does not appear to be a critical factor limiting groundwater withdrawals for the northern Tampa Bay region (Hancock and Smith, 1996). Saltwater intrusion is an issue in other locations, however, particularly in coastal areas in the vicinity of groundwater withdrawals (Hancock and Smith, 1996). As discussed below, saltwater intrusion is an important management issue for the southern region of the Tampa Bay watershed and adjacent areas in west-central and southwestern Florida (Fernald and Purdum, 1998; SWFWMD, 2002b).

Southern Groundwater Basin

In the southern region of the Tampa Bay watershed, in areas overlying the southern west-central Florida groundwater basin (fig. 6–12), three recognized aquifer systems are present. The unconfined surficial aquifer system is at the surface, extending several meters deep, and generally consists of unconsolidated sediments. It is underlain by the intermediate aquifer system, which is made up of a series of thin, interbedded limestone and phosphatic clays of generally low permeability. Although permeable water-yielding units are present in the intermediate aquifer system, it is often categorized as a confining unit that separates the surficial and Upper Floridan aquifers (SWFWMD, 2002b). The third aquifer system, which underlies the intermediate aquifer, is the Floridan. Confined by the overlying low-permeability rock, it is composed of a series of limestone and dolomite formations that can yield in excess of 3 Mgal/d from large diameter wells (SWFWMD, 2002b).

The Floridan aquifer system is divided into upper and lower aquifers, which are separated by a middle confining unit. The Lower Floridan aquifer, which is hydraulically isolated from the upper aquifer, contains highly brackish water and is not currently used as a water-supply source. The Upper Floridan aquifer is, therefore, the principal source of groundwater in the southern Tampa Bay watershed and elsewhere in west-central Florida (SWFWMD, 2002b).

Estimated annual groundwater withdrawals from the Upper Floridan aquifer in the southern west-central groundwater basin increased substantially between 1950 and the mid-1970s, more than doubling during that period (fig. 6–13) (SWFWMD, 2002b). In response, the “potentiometric surface” of the Upper Floridan aquifer (the level to which water would rise in a well tapping the aquifer) exhibited regional declines, dropping by 3 to 15 m below predevelopment levels in some areas (SWFWMD, 2002b). During the dry season of 2009 the potentiometric surface elevation ranged between -3 m and +30 m relative to the land surface in the Tampa Bay region (fig. 6–14).

In response to the regional declines in groundwater levels, the SWFWMD in 1989 identified several water-use caution areas where additional regulatory and management actions were needed to protect water resources (fig. 6–15). A “most impacted area” (fig. 6–15) was also

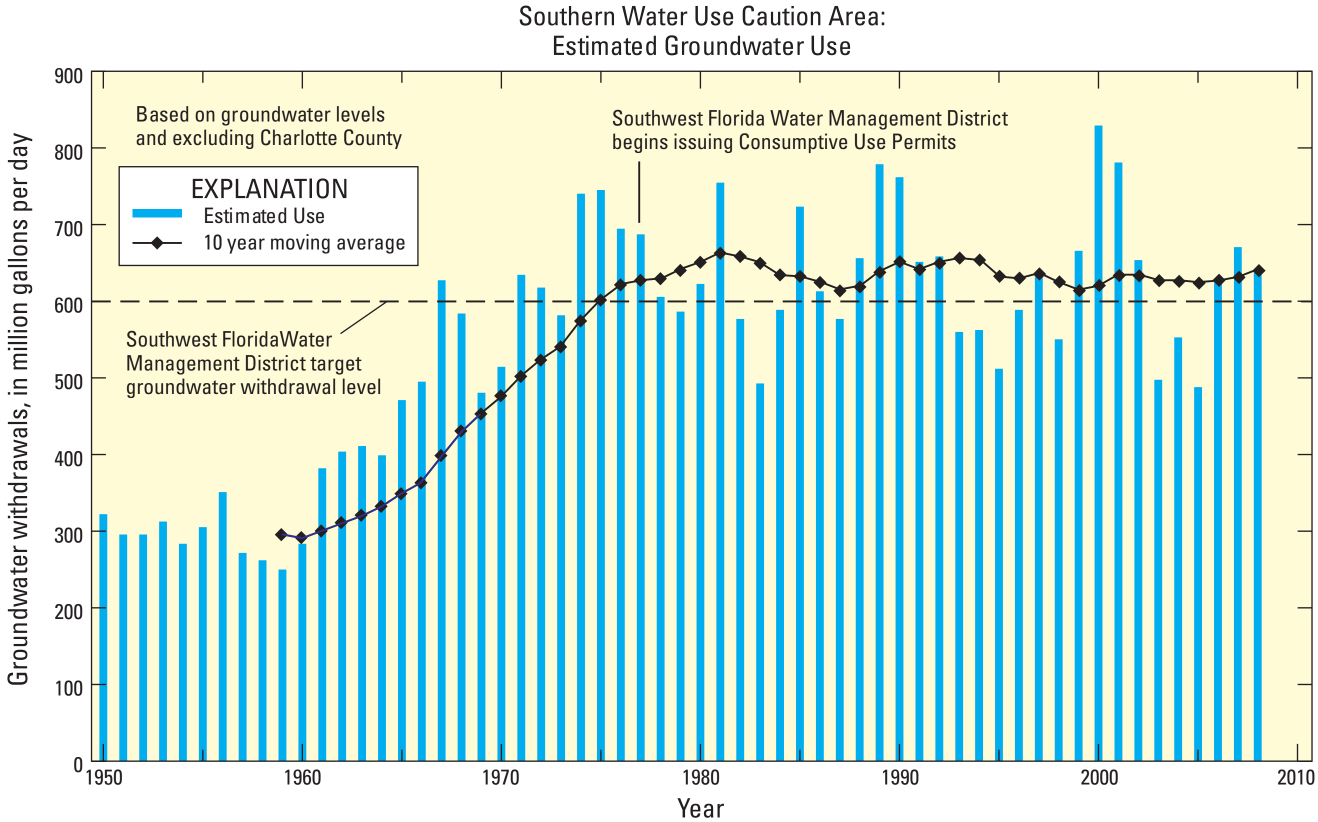


Figure 6–13. Estimated groundwater use in the Southern Water Use Caution Area, 1950–2008. The Southwest Florida Water Management District began issuing Consumptive Use Permits (CUPs) in the late 1970s. Groundwater withdrawal values were estimated using a regression analysis that was developed using groundwater levels and water use estimates prepared by Southwest Florida Water Management District over the last 15 years. Historic groundwater levels were then added to the regression equation to estimate historic water use. Data from M. Beach, Southwest Florida Water Management District, personal commun., July 7, 2009.

designated, which is an area of about 708 mi^2 located along the coast of southern Hillsborough, Manatee and northwestern Sarasota Counties where the concern for saltwater intrusion was greatest. In 1992 the Southern Water Use Caution Area was designated, a 5,100-mi^2 area comprising most of the southern west-central groundwater basin and incorporating the earlier Eastern Tampa Bay and Highlands Ridge water-use caution areas. The Southern Water Use Caution Area covers the region of the SWFWMD generally south of Interstate Highway 4 and includes all of DeSoto, Hardee, Manatee and Sarasota Counties, and parts of Charlotte, Highlands, Hillsborough and Polk Counties (fig. 6–15) (SWFWMD, 2002b, 2006c).

In the Tampa Bay area of the Southern Water Use Caution Area, a primary management issue is the presence of an area where the closed zero potentiometric surface contour is located landward of the coast. The management concern is that if the closed zero contour were allowed to persist landward of the coast, the entire thickness of the Upper Floridan aquifer beneath the depression could eventually (for example, over a period of centuries) become saline (SWFWMD, 2002b). The long-term recovery strategy that has been adopted by the SWFWMD to address this saltwater intrusion issue (SWFWMD, 2006c) is described in more detail below.

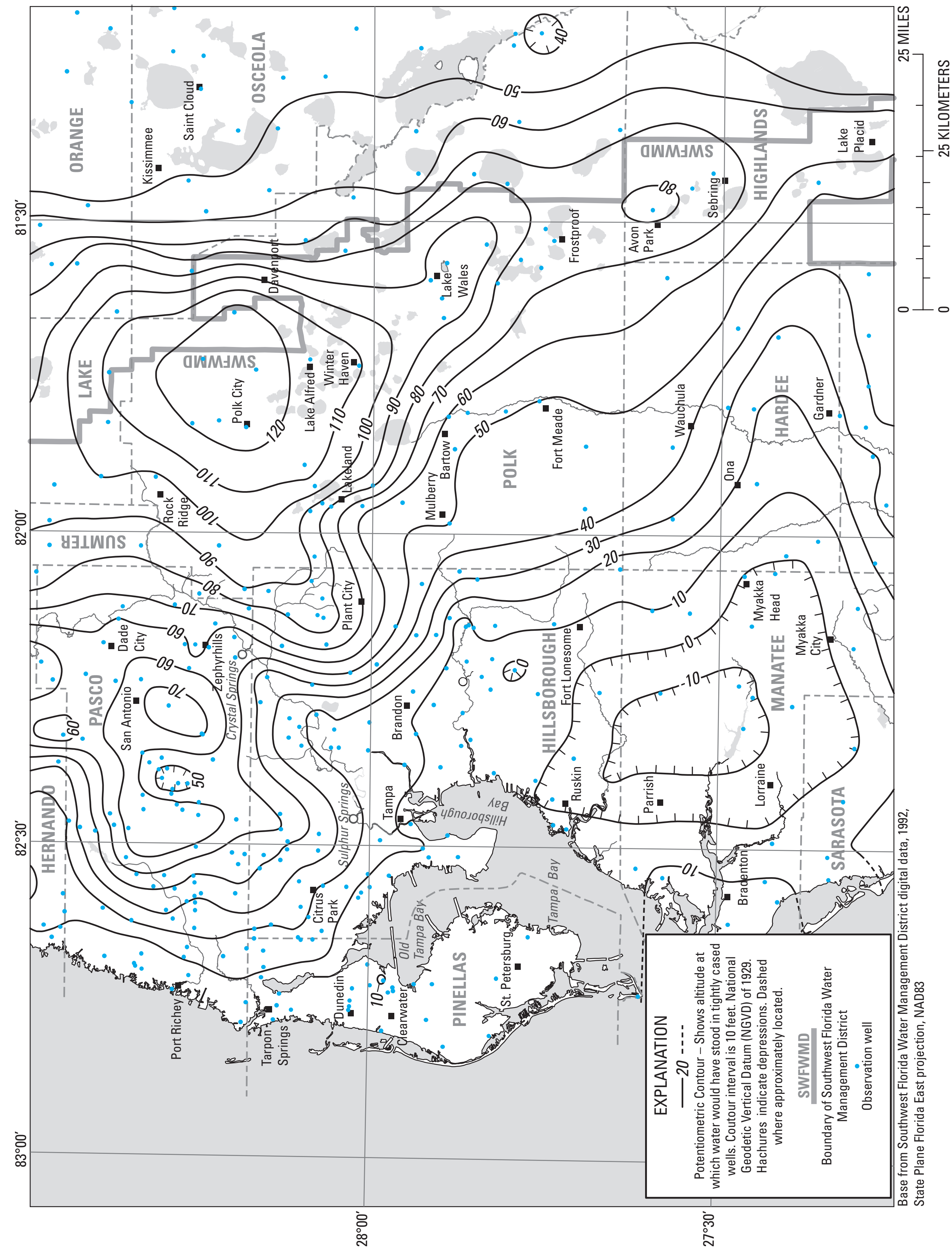
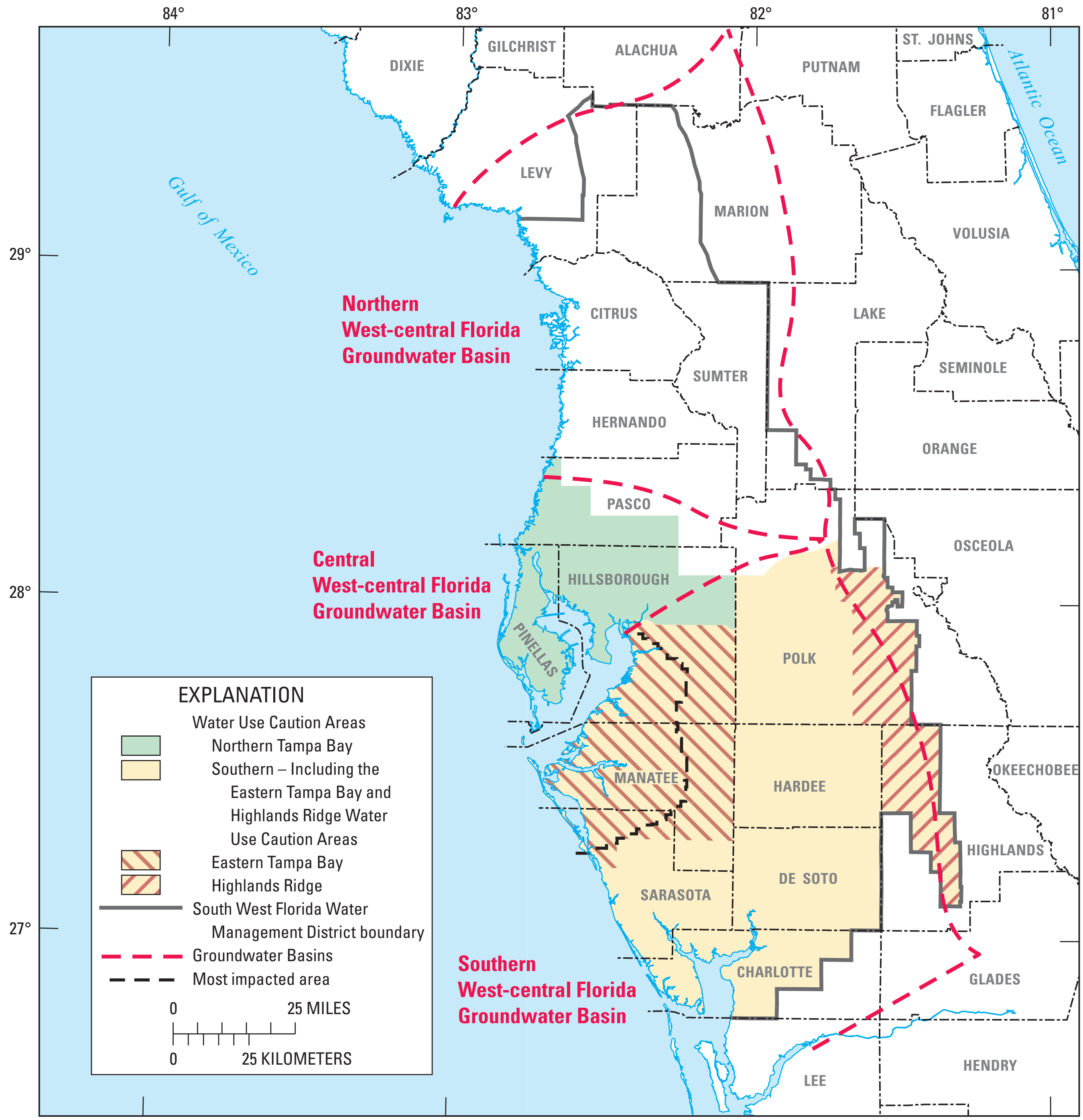


Figure 6–14. Upper Floridan aquifer potentiometric surface, May 2009. Data from Ortiz (2009).



Base from Southwest Florida Water Management District digital data, 1992,
State Plane Florida East projection, NAD83.

Figure 6–15. Location of Water Use Caution Areas and groundwater basins within the Southwest Florida Water Management District. From Southwest Florida Water Management District (2006c).

These changes in the regional aquifer system have apparently caused substantial reductions in discharges of fresh groundwater to the coastal zone. Beach (2003) noted that under predevelopment conditions (in the early 1900s), the Upper Floridan aquifer in the southern basin discharged about 140 Mgal/d of freshwater to the Gulf of Mexico and Tampa Bay along 90 mi of coastline. By May of 2000, the inland area where the potentiometric surface of the Upper Floridan aquifer had dropped below sea level covered about 950 mi^2 (Beach, 2003), presumably eliminating a large percentage of this historical discharge. Along the eastern shoreline of Tampa Bay, inland groundwater withdrawals are estimated to have reduced fresh groundwater discharges from 63 Mgal/d under predevelopment conditions to 2 Mgal/d in 1989 (SWFWMD, 1993).

Potential effects of these changes in aquifer levels on instream flows in rivers and streams within the Tampa Bay watershed and the larger Southern Water Use Caution Area have been topics of active investigation and discussion among resource managers (for example, Stoker and others, 1996; Hickey, 1998; Lewelling and others, 1998; Basso and Schultz, 2003; Kelly, 2004; Metz and Lewelling, 2009).

Rainfall and Streamflow Patterns

As noted in Chapter 2 the Tampa Bay region has a humid subtropical climate with an average annual temperature of about 72 °F and average annual rainfall ranging between 50 to 55 in. in different areas of the watershed (Lewis and Estevez, 1988; Wolfe and Drew, 1990). About 60 percent of the annual rainfall generally occurs during the summer (mid-June through September) rainy season, in the form of localized thunderstorms and occasional tropical storms and hurricanes. During the dry season, which on average extends from October through early June, rainfall is usually associated with the passage of large-scale frontal systems. Rain events associated with frontal passages are most common during the January-through-March period, producing a period of somewhat elevated rainfall during an otherwise dry season (Flannery, 1989). The months of lowest rainfall are usually November, December, and April. Mean monthly rainfall for the 60-year period extending from 1947–2006 is shown in fig.6–16. Seasonal and annual rainfall amounts are highly variable from year to year, and the west-central Florida region experiences frequent periods of substantially above- and below-average rainfall (Fernald and Purdum, 1998).

In addition to rainfall, instream flows and freshwater discharge are also influenced by other meteorological and biological factors — such as temperature and humidity levels, and evapotranspiration rates — which affect the amount of precipitated water that discharges via runoff to the surface-water system, percolates through the soil to the groundwater system, or is returned to the atmosphere as water vapor. Evapotranspiration rates are generally high in Florida due to relatively high annual mean temperatures and the fact that water is available at or near the land surface at many times and locations (Miller, 1997). In the Tampa Bay watershed evapotranspiration rates have been estimated at 30 to 48 in/yr (Wolfe and Drew, 1990). Evaporation rates from open surface-waterbodies have been estimated at 48 to 52 in/yr — values that are only slightly less than average annual precipitation — and tend to be highest in April and May due to the high insolation levels and

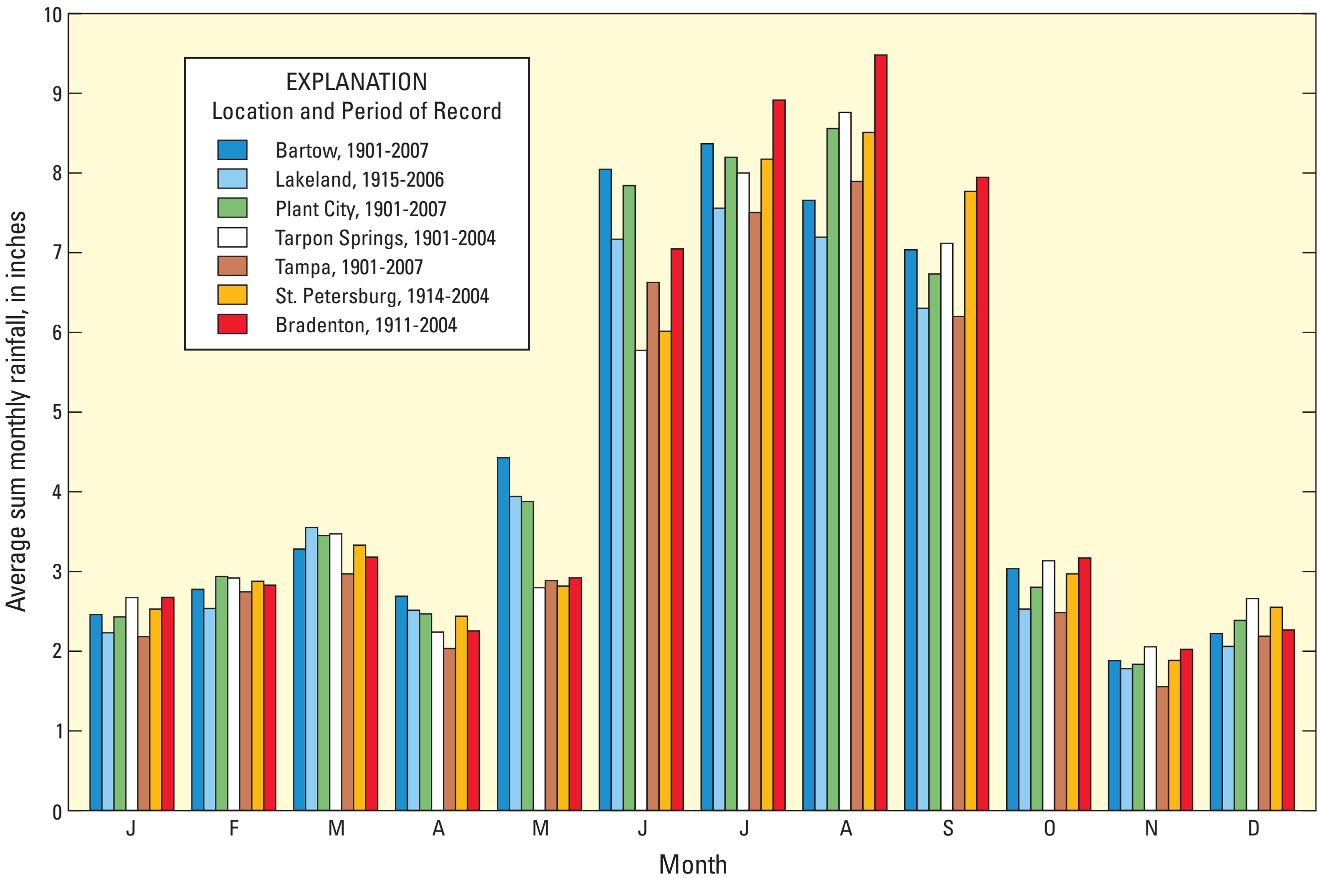


Figure 6–16. Average monthly rainfall measured at seven rainfall recording stations over specified periods of record. Data from National Weather Service.

reduced cloud cover that typically occur during those months (Wolfe and Drew, 1990). For some waterbodies and years, evaporation rates may exceed annual precipitation levels (Swancar and others, 2000).

Some of the precipitation that falls on the land surface is directly transported as runoff to lakes, rivers, and streams. An additional amount infiltrates through the soil to the surficial aquifer, where it may be discharged to streams as baseflow or percolate downward to recharge deeper aquifers (Miller, 1997). Areas and average annual quantities of recharge to and discharge from the Floridan aquifer are shown in fig. 6–17. The sum of direct runoff and baseflow is termed "total runoff," which for the Tampa Bay region during 1951–1980 is estimated to average between 9 and 15 in/yr (Gebert and others, 1987; Miller, 1997).

Solar insolation and pan evaporation rates tend to be highest in the spring (April, May, and early June), which are also periods of relatively low rainfall in most years (Flannery, 1989; Wolfe and Drew, 1990). Month-to-month variations in streamflow in most Tampa Bay tributaries reflect these meteorological factors, with highest average monthly flows occurring during and immediately following the summer rainy season, and lowest flows occurring during the spring and fall (Flannery, 1989; fig. 6–18). These typical patterns are strongly affected by the El Niño/Southern Oscillation cycle, however, and monthly rainfall values are highly variable from year to year (for example, Schmidt and others, 2001; Morrison and others, 2006).

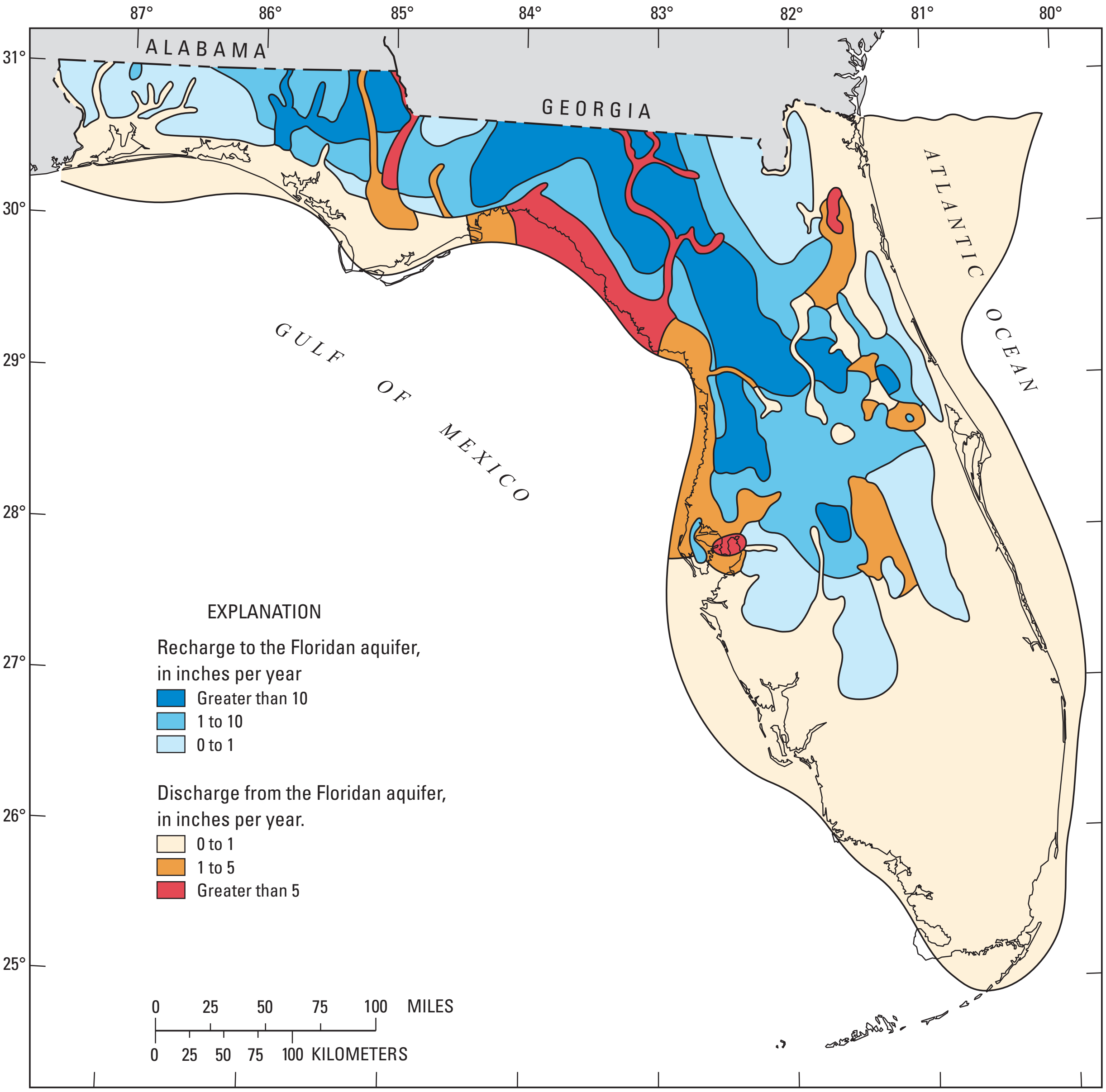


Figure 6–17. Areas of Floridan aquifer discharge and recharge. Data from Southwest Florida Water Management District.

Long-Term Trends in Spring Discharge and Instream Flows

The availability of long-term discharge records for the rivers and larger springs in the Tampa Bay watershed allows trends in streamflow and spring discharge to be tracked over periods of several decades. Stoker and others (1996) investigated flow trends in the Hillsborough and Alafia River watersheds, and documented declining annual flows in several locations, including:

- Sulphur Springs, 1960–1992;
- Hillsborough River at the Tampa Dam, 1939–1992;
- North Prong Alafia River, 1951–1992;
- South Prong Alafia River, 1963–1992; and
- Alafia River at Lithia, 1933–1992.

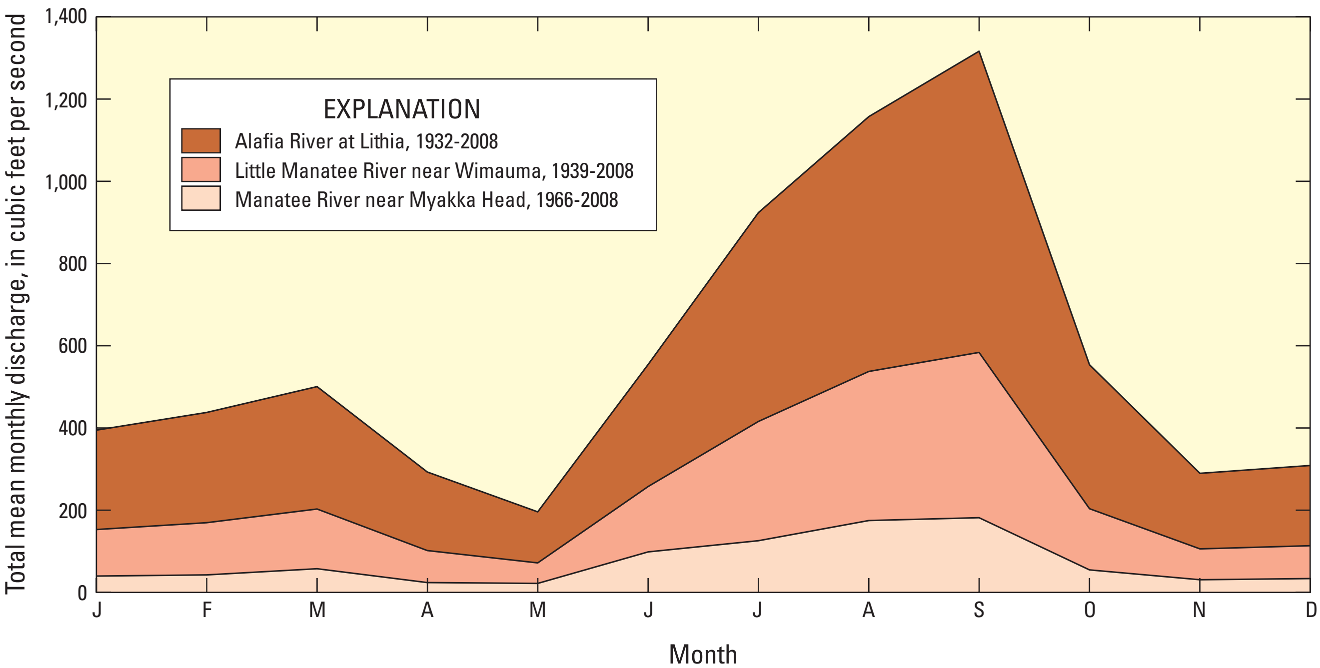


Figure 6–18. Average monthly streamflow of several Tampa bay tributaries. Data from U.S. Geological Survey.

In the upper part of the Hillsborough River watershed, Weber and Perry (2001) reported an approximately 32 percent decline in discharge from Crystal Springs during 1933–1999, and noted that flow declines had also occurred at two gaging stations located on Cypress Creek. The causes of the observed declines have been a topic of debate, but have been generally attributed to a combination of groundwater withdrawals, changes in water-use practices by the phosphate industry (in parts of the Alafia River Basin), and fluctuations in rainfall (Stoker and others, 1996; Hickey, 1998; Weber and Perry, 2001, 2006; Kelly, 2004; SWFWMD, 2004, 2005a, 2005b, 2006b, 2007, 2008a,b; Trommer and others, 2007).

In the Little Manatee River watershed, Flannery and others (1991) detected increasing flow trends during the dry season months of April and May from about 1976 to 1989. This trend was attributed to streamflow augmentation in the river due to agricultural irrigation runoff (Flannery and others, 1991). No published reports on long-term flow trends in the Manatee or Braden Rivers were found during the literature searches performed for this report, but total withdrawals from the instream reservoirs located on those two rivers have increased from 2.6 to 36.05 Mgal/d between 1965 and 2000 (Marella and Berndt, 2005), presumably altering their annual freshwater discharges to the tidal reach of the Manatee River. Trommer and others (1999) reported a number of localized hydrologic and environmental impacts associated with the Braden River Reservoir, including the change of the middle reach of the river from a brackish water estuary ecosystem to a freshwater lake, an increase in water levels in the surficial aquifer system adjacent to the river, changes in water quality, and reduced freshwater flow to the estuary during periods of low flow. Flow to the estuary was decreased by an average of 13.6 percent by evaporation from the lake and by pumpage for water supply during the 1993–1997 study period (Trommer and others, 1999).

Seasonal and annual freshwater inflows to the tidal reach of the Hillsborough River, another tributary with an instream water-supply reservoir, have been increasingly reduced by reservoir withdrawals since the 1970s (SWFWMD, 1999; fig. 6–10). Freshwater inflows to the tidal reach of the Palm River were initially increased by the construction of the Tampa Bypass Canal, which breached the Upper Floridan aquifer in some areas (Knutilla and Corral, 1984), but in recent years much of that water has been withdrawn to augment local and regional public supplies (SWFWMD, 1999).

As noted, water budgets that have been developed to date for Tampa Bay include a number of uncertainties (Culbreth and others, 1982; Zarbock and others, 1995; Kroeger and others, 2007; Swarzenski and others, 2007a). Due to the relatively flat topography of the watershed, for example, tidal influence extends 10 mi or more inland in many tributaries (Flannery, 1989). Recent use of broad-band acoustic Doppler current profilers has made flow measurements in tidally influenced rivers more feasible (Stoker and others, 1996), but the large amount of tidal exchange near the mouths of some rivers can make the measurement of small rates of net freshwater flow difficult. Because net freshwater flow is difficult to measure in tidally influenced areas using standard stream gaging techniques, the long-term gaging stations have been located above head of tide. As a result, more than 40 percent of the total watershed currently remains ungaged (Greening and Janicki, 2006). Much of the oldest and highest-density urban development that has occurred in the watershed has taken place in the coastal, ungaged region. Because no direct measurements of freshwater inflow are currently available from the ungaged areas, flows from these areas — which presumably make up a substantial percentage of the total annual overland runoff (for example, Zarbock and others, 1995) — must be estimated using indirect methods that contain numerous sources of uncertainty (Flannery, 1989, 2007; Zarbock and others, 1995). Using surface-water models, efforts have been made to estimate ungaged flows in the Alafia (Tara and others, 2001), Little Manatee (Intera, 2006), Manatee (Dynamic Solutions, 2006) and Hillsborough River (SWFWMD, 2006b) basins for different time periods. Still, much of the ungaged flow to Tampa Bay remains poorly quantified. The development of a comprehensive water budget containing less uncertainty, and covering both predevelopment and currently existing land and water-use conditions, would be useful for resource managers, who rely on such quantitative information as the basis for technically sound decisionmaking.

During the mid-1990s the TBEP used currently available data to develop comparative bay-wide estimates of monthly freshwater inflows for an older benchmark (1938–1940) period and a more recent (1985–1991) period, and comparative estimates of freshwater inflow-salinity relationships for the open waters of the four largest bay segments during those periods (Zarbock and others, 1995). A regression-based technique was used to estimate monthly flows from ungaged basins, as a function of rainfall and land use/land cover. The analyses produced no evidence of significant changes in total monthly inflows or inflow-salinity relationships between the two periods. Estimated total inflows to the bay (which included wastewater and stormwater discharges) were most similar during low-flow months between the two periods, and diverged during high-flow months. This was particularly evident in urban basins, suggesting that larger volumes of stormwater runoff (and decreased surface storage and infiltration) were occurring in urban impervious areas during the more recent period (Zarbock and others, 1995). The study did not address long-term changes in freshwater inflow or salinity regimes in the tidal reaches of rivers and streams, which are the areas of Tampa Bay that historically contained much of the ecologically important low-salinity habitat in the estuary (Zarbock and others, 1995).

Management Responses to Anthropogenic Alterations

It appears that four types of human activities have had the strongest effects on the hydrology of the Tampa Bay watershed: urban development; physical alteration of the surface drainage network; impoundments, diversions and withdrawals of freshwater for human uses; and discharges of wastewater and return flows of irrigation water. These activities have been the subject of a number of resource-management programs that have sought to reduce or mitigate their environmental impacts.

Stormwater Management

Florida's existing stormwater management regulations (Chap. 62–25, Florida Administrative Code) follow a technology-based approach that relies on the implementation of approved best management practices, such as wet detention ponds or vegetated swales, which are designed to meet a specific treatment level or performance standard. Following a review of the performance and cost-effectiveness characteristics of a number of urban stormwater best management practices, the performance standard for most discharges was defined as an 80 percent reduction of the average annual loading of total suspended solids (Livingston, 1997). A more stringent 95 percent TSS reduction standard was adopted for direct stormwater discharges to sensitive waterbodies, such as those designated as Outstanding Florida Waters due to their outstanding water quality or other environmental attributes. In addition, the State's water management districts and local governments have established performance standards to minimize flooding by limiting the post-development stormwater peak discharge rate and, for some flood-prone closed basins, the stormwater volume.

Implementation of these regulations has helped to reduce the negative hydrologic and water-quality impacts of urbanization in recently developed areas, but has not eliminated them (Livingston, 1997). Currently, an updated statewide stormwater rule is being drafted by FDEP and the water management districts in an effort to address several known shortcomings of the existing regulatory system (Livingston, 2008) to:

- Update the water management districts' environmental resource permit water-quality treatment rules to increase the effectiveness of new stormwater-treatment systems in removing nutrients and reducing nutrient loads, and in decreasing the movement of nutrients into groundwaters;
- Reduce the number of waterbodies that become impaired by nutrients from future development (about 45 percent of Florida's current verified impaired waters are nutrient related);

- Meet the goal of the State's existing water resource implementation rule (Chap. 62–40, Florida Administrative Code), which is to assure that post-development stormwater discharges do not exceed predevelopment conditions in terms of peak discharge rates, overall volumes or pollutant loads; and
- Streamline stormwater permitting and make stormwater regulatory requirements more consistent throughout the State.

Regulatory activities at the Federal and State levels in recent decades, including the expansion of the National Pollutant Discharge Elimination System permitting program to include many types of municipal and industrial stormwater management systems, and increased implementation of the national Total Maximum Daily Load (TMDL) program, are expected to provide additional reductions in impact levels (FDEP, 2003, 2005). A number of improved development practices have also been identified in recent years that have the potential to further reduce the hydrologic and water-quality impacts of ongoing urbanization (for example, Schueler and Holland, 2000).

Water Withdrawals for Human Use

As noted above, since the early 1950s steadily increasing amounts of groundwater and surface water have been withdrawn to provide potable supplies and support agricultural and industrial uses. Together with fluctuations in rainfall that have caused variations in water availability, these withdrawals have caused hydrologic and environmental impacts in several parts of the Tampa Bay watershed (Flannery, 1989; Hancock and Smith, 1996; Fernald and Purdum, 1998; SWFWMD, 1999, 2006b; Weber and Perry, 2001, 2006; Kelly, 2004). In response to those impacts, and similar ones seen in other rapidly growing areas, the Florida legislature passed the Florida Water Resources Act (Chap. 373, Florida Statutes), which requires the water management districts to establish minimum flows and levels for surface-waterbodies and aquifers to protect aquatic resources. The statute also requires the water management districts to develop regional water-supply plans for areas where existing and anticipated water sources are projected to be inadequate to meet demand over a 20-year planning horizon (FDEP, 2007b). The State-mandated regional water-supply plans identify water-supply sources and water resource development projects that will be implemented to meet anticipated demands while sustaining water resources and related natural systems.

The SWFWMD identified the Tampa Bay watershed as a region of two larger groundwater basins where projected demands would outstrip supply during the 2005 through 2025 planning period, and developed management strategies for these two water-use caution areas that were designated the Northern Tampa Bay Water Use Caution Area and the Southern Water-Use Caution Area (fig. 6–15) (SWFWMD, 2006a).

In the Southern Water Use Caution Area, groundwater withdrawals that exceeded sustainable yields had contributed to coastal saltwater intrusion in the Tampa Bay area and, farther inland, to flow reductions in the upper Peace River and lowered lake levels on the Lake Wales Ridge (SWFWMD, 2002b; FDEP, 2007a; Metz and Lewelling, 2009). In 2006, the SWFWMD began implementing a multicomponent recovery strategy for the Southern Water

Use Caution Area. Over time, groundwater withdrawals are to be reduced by up to 50 Mgal/d through the development of alternative water supplies and other management actions. Construction of additional reservoir volume for added surface-water storage capacity, increased re-use of treated effluents for irrigation and industrial uses, and implementation of aquifer storage and recovery technologies to provide more consistent year-round water supplies are viewed as important alternatives in this area (SWFWMD, 2002b, 2006a,c; FDEP, 2007a,b). For the Tampa Bay area the chief environmental objective of the recovery strategy is to reduce the rate of saltwater intrusion in coastal Hillsborough, Manatee and Sarasota Counties by achieving a proposed minimum aquifer level for saltwater intrusion by 2025. Once the target aquifer level is achieved, future efforts will seek further reductions in the rate of saltwater intrusion and the ultimate stabilization of the saltwater-freshwater interface (SWFWMD, 2006c).

In the Northern Tampa Bay Water Use Caution Area, groundwater and surface-water withdrawals for public supply purposes increased by more than 400 percent (from about 60 to 250 Mgal/d) between 1960 and 1993, causing hydrologic and environmental impacts to a number of wetlands, lakes, and streams (Hancock and Smith, 1996; Weber and Perry, 2006). To address the observed and anticipated hydrologic impacts in the basin, the SWFWMD entered into a partnership agreement with Tampa Bay Water (the regional water-supply utility) and its member local governments in the late 1990s. The agreement called for a reduction in pumping at 11 well fields from about 160 to 90 Mgal/d by the end of 2007, as well as the development of at least 85 Mgal/d of alternative water supplies. The strategy has been implemented through the construction of a new surface-water treatment facility, a regional reservoir located in the Alafia River watershed, and a surface-water desalination plant with an initial production capacity of 25 Mgal/d that is located on the eastern shoreline of Tampa Bay (SWFWMD, 2006a; see box 6–1).

The surface-water component of the Florida Water Resources Act requires each of the State's water management districts to establish minimum flows and levels for the watercourses within their jurisdiction. For this purpose, the term "minimum flow" is defined as "the limit at which further withdrawals would be significantly harmful to water resources or ecology of the area" (Sect. 373.042, Florida Statutes). In recent years, the SWFWMD has established a number of minimum levels for lakes and minimum flows for rivers within the Tampa Bay watershed. These minimum flows and levels are typically peer-reviewed by external teams of scientists (for example, Bedient and others, 1999; Powell and others, 2005, 2008).

In the case of unimpounded rivers, the SWFWMD has sought to apply a percent-of-flow approach, which limits withdrawals to a percentage of streamflow at the time of withdrawal to maintain a relatively natural flow regime in the contributing river (Flannery and others, 2002). In the Tampa Bay watershed, this approach has been applied to the unimpounded Alafia River, where minimum flows have been proposed that would allow a 19 percent reduction of the current daily gaged flow, which is equivalent to about a 15 percent reduction of the total daily flow to the lower river (SWFWMD, 2008a). Withdrawals would be subject to a low-flow threshold that prohibits any withdrawals when the gaged daily flow is below 78 Mgal/d, which currently occurs (on average) on about 18 percent of the days during the year and 33 percent of the days during the spring

(M.S. Flannery, pers. comm.). The SWFWMD is also tracking long-term fluctuations in rainfall, in order to take such fluctuations into account when setting or revising minimum flows (Kelly, 2004; SWFWMD, 2005b).

An alternative approach has been used for impounded tributaries, such as the Hillsborough, Tampa Bypass Canal/Palm, Braden, and Manatee Rivers, which cumulatively drain a large percentage of the overall Tampa Bay watershed. During 2007, the SWFWMD set minimum flows from the Tampa Bypass Canal to the Palm River and McKay Bay at 0 Mgal/d (Ch. 40D-8.041, Florida Administrative Code). At the same time, the minimum flow from the Hillsborough River Reservoir to the tidal reach of the Hillsborough River was set as a range of values, which vary on a seasonal basis from 12.9 to 15.5 Mgal/d, to help maintain oligohaline habitats in the tidal segment of the river below the dam during periods when there would otherwise be no flow from the reservoir (SWFWMD, 2006b).

From a multidecadal perspective, daily flows as low as the recently established minimum flows were rare occurrences in the lower Hillsborough River prior to 1970. During 1939–1969, for example, daily flows recorded at the USGS gage located at the reservoir dam exceeded 14 Mgal/d about 95 percent of the time, and the median daily flow was 365.3 Mgal/d. During the 10-year period 1998–2007, in contrast, the median daily flow measured at the dam had fallen to 1.2 Mgal/d and flows less than 14 Mgal/d occurred more than 50 percent of the time.

Under the regulations issued by the SWFWMD (2006b) the minimum flow to the tidal reach of the Hillsborough River may consist of water pumped from Sulphur Springs and the Tampa Bypass Canal, in addition to flow from the Hillsborough River Reservoir. The minimum flow for Sulphur Springs was set at a range of 6.5 to 11.6 Mgal/d (SWFWMD, 2004), values that are about 17 to 46 percent of the spring's long-term (1960–1992) annual median flow as reported by Stoker and others (1996). These regulatory minimum flow values, which fluctuate between low and high tides, were selected to prevent incursions of brackish water from the Lower Hillsborough River into the spring run. It is anticipated that spring discharges exceeding these regulatory levels will be diverted to the base of the Hillsborough River dam to help meet the new minimum flow requirements that have been established there. Similarly, by setting the minimum flow of the Tampa Bypass Canal at zero (SWFWMD, 2005a), water from that source becomes available for the same purpose. Minimum flows for the Little Manatee, and Braden Rivers have been scheduled for development by 2012 (SWFWMD, 2008b).

Discharges of Treated Effluent and Irrigation Water

The freshwater that is withdrawn from the environment for human use is ultimately discharged in some form, and the amount that does not evaporate returns to the groundwater or surface-water systems (although not always in the same watershed). Treated effluents from municipal sewage-treatment plants and industrial facilities that are discharged directly to surface waters must be permitted under the Federal National Pollutant Discharge Elimination System, which is administered nationally by the USEPA and at the State level by the FDEP. Facilities that dispose of their effluent through land application, percolation ponds or deep-well injections must be permitted by the FDEP. Permits that are issued contain requirements involving the quality and quantity of effluent discharges, which are intended to ensure that the discharges have minimal negative impact on receiving waters and aquifers (FDEP, 2003, 2005). The locations and volumes of permitted discharges are documented, and can be tracked over time. Information on the larger facilities (those discharging >0.1 Mgal/d) in the Tampa Bay watershed has been summarized recently by the FDEP (2003, 2005).

Other types of anthropogenic discharges are more diffuse and difficult to quantify. This includes waters used for agricultural or landscape irrigation, and domestic (sewage) effluent that is treated through on-site septic systems or small wastewater-treatment plants and then discharged to the groundwater system via percolation ponds. In some situations, the hydrologic effects of these discharges can be detected in regional monitoring programs. As noted earlier, this is the case for increasing dry-season discharges of agricultural irrigation water in the Little Manatee River watershed, whose effects are evident as increased dry-season flow trends in long-term streamflow records (Flannery and others, 1991). The hydrologic effects of these diffuse discharges have not yet been characterized for the larger Tampa Bay watershed.

Agricultural use of fresh surface water and groundwater in the three counties (Hillsborough, Manatee and Pinellas) immediately adjacent to Tampa Bay increased by about 80 percent between 1965 and 2000, from about 107 to 193 Mgal/d (Marella, 2004). A variety of primarily incentive-based management programs has been implemented in recent years in an effort to encourage agricultural operations to minimize their water use and make their irrigation practices as efficient as possible (Florida Department of Agriculture and Consumer Services (FDACS), 2003).

Future Challenges

Hydrologists and ecologists studying instream flows have emphasized the importance of maintaining natural flow regimes in rivers to address several key factors — such as riparian zone condition, stream channel morphology, sediment transport patterns, appropriate life history cues for native aquatic organisms, and linkages between river systems and their floodplains — that have been identified as critical elements in the protection of living resources (Poff and others, 1997; Richter and others, 1997; Postel and Richter, 2003). As noted earlier, appropriate goals for instream flow programs have been identified as “maintaining the ecological integrity of unregulated rivers and restoring regulated rivers to the ecological conditions that more nearly approximate their natural form and function” (IFC, 2004).

There is also evidence that naturally occurring patterns of freshwater inflow are important for maintaining the structure and productivity of estuarine ecosystems (for example, Estevez, 2002). As noted by Flannery and others (2002), “sediments transported by periodic pulses of high river discharge are a major factor controlling the geomorphological structure of river deltas and bays (Kennish, 1986; Jay and Simenstad, 1996; Day and others, 1997). The productivity of coastal fisheries is positively related to freshwater inflow (Browder, 1985; Drinkwater, 1986; Day and others, 1989) and alterations to inflow regimes have caused dramatic declines and recoveries in fish stocks (Moyle and Leidy, 1992; Mann and Lazier, 1996; Sinha and others, 1996). Significant relationships have been found between fishery yields of estuarine-dependent species and preceding freshwater inflow terms calculated over 2- or 3-month intervals, indicating that the seasonality of inflow can have a significant effect on fish abundance (Browder, 1985; Longley, 1994). Wilber and Bass (1998) also found that oyster harvests were negatively correlated with the number of low flow days that occurred 2 years prior, indicating that alteration of one component of a flow regime can have an effect on a specific stage of an organism's life history."

As groundwater withdrawals have reached and exceeded sustainable levels in the Tampa Bay region in recent decades, causing substantial impacts to lakes, wetland, and other environmental resources, there has been a growing use of rivers and other surface-waterbodies as sources for water supply. Given anticipated future population increases in the region, a primary future challenge will be to ensure that demands on surface-water resources do not reach levels that allow unacceptable environmental impacts to occur. Defining "unacceptable" in this context is a social as well as a technical decision, however. From a technical perspective, some resource managers would argue that environmentally sound withdrawal levels are already being exceeded in parts of the watershed, whereas others would contest that position.

The National Research Council (NRC) recently completed a review of instream flow programs in the State of Texas (NRC, 2005), an area that, like Florida, is struggling to balance social, economic and environmental needs for water during periods of high demand and low supply. Several recommendations provided in the NRC (2005) report appear applicable to the Tampa Bay situation:

- Instream flow and freshwater inflow recommendations are developed and implemented in a complex technical, administrative, and political setting in which there are multiple and competing demands for water. Technical evaluations of hydrology, biology, physical processes, and water quality are only one aspect of the process, and a number of nontechnical considerations are also involved;
- A variety of water-resources stakeholders (State and local government agencies, water-supply utilities, nongovernmental organizations, private economic interests, and citizen groups) have interests in any watershed, and must be involved in setting goals and establishing and implementing instream flow and freshwater inflow programs;
- Because this area of environmental science is relatively new and still evolving, an adaptive management approach is necessary when developing and implementing flow recommendations over the lifetime of a management program;
- A useful working definition of adaptive management in this context is "an approach for recommending adjustments to operational plans in the event that objectives are not being achieved." Use of adaptive management allows agencies and other interested parties to test and revise management approaches by assessing the ecological responses to new flow regimes. The adaptive management approach entails a long-term commitment to environmental monitoring, and anticipates that corrections and revision will be needed over time;

- For both State and local resource-management programs, more attention should be given to the process of setting environmental goals and the means to measure progress towards achieving those goals. If currently vague legislative terms (for example, "significant harm") become more clearly defined, technically based goals can be established that will help riverine and estuarine environments avoid such "harm." State-level rule language should define goals and objectives for instream flow and freshwater inflow management programs, and should encompass the broad policy guidance expressed in relevant State legislation.

Climate change is an additional issue that is expected to affect the location, timing, and magnitude of freshwater inflows to Tampa Bay. For a number of reasons — including uncertainties regarding future emissions of greenhouse gases, and limitations in the ability of existing climate models to predict long-term responses to those emissions — quantitative predictions regarding the future impacts of climate change on freshwater resources are highly uncertain (Bates and others, 2008). Effects are also expected to vary between and within geographic regions (IPCC, 2007), further complicating efforts to predict impacts at the scale of individual waterbodies or watersheds.

Using information from published IPCC reports and other sources, the FOCC (2009) has identified the following hydrological changes likely to occur in Florida's coastal waters over the next century as a result of climate change:

- Altered rainfall and runoff patterns, due to factors such as increases in air temperature and evaporative demand, increases in atmospheric water vapor, increases in the frequency of extreme rainfall events, and possible changes in regional rainfall levels. (Although annual rainfall amounts in subtropical regions are generally predicted to decline as a result of climate change, existing climate models do not provide consistent predictions of changes that may occur on the Florida Peninsula);
- Continued increases in sea level, as a result of thermal expansion of seawater and melting of land-based glaciers and ice sheets. (Model-based projections of global mean sea-level rise between the late 20th century and the end of the 21st century are on the order of 0.18 to 0.59 m. These projections do not address several uncertainties, however, and the upper values of the ranges should not be considered upper bounds for sea-level rise);
- Reduced availability of freshwater for ecosystems and human populations in coastal areas, due to sea-level rise and its effects on saltwater intrusion in coastal aquifers.

In addition to these potential effects, the IPCC (2007) and Bates and others (2008) have noted the following issues that may affect the future management of freshwater resources as a result of climate change:

- Past hydrological experience may serve as a less reliable guide to future conditions, as climate change alters the reliability of current water management systems and water-related infrastructure. Although predicted changes in precipitation, river flows, and water levels at the river basin scale are uncertain, it appears very likely that hydrological conditions will change in many geographic areas;

- An adaptive management approach would address these and other climate-related issues. To support such an approach, monitoring networks tracking changes in surface-water and groundwater hydrology, water quality, and aquatic ecosystems would need to be maintained and, in some areas, expanded to ensure that adequate information is available regarding the water-related impacts of climate change;
- The available monitoring data, and other technical information, can be used to improve understanding of the effects of climate changes on the hydrological cycle, focusing on the spatial and temporal scales that are most relevant to decision making. Additional tools that allow decision makers to conduct integrated evaluations of adaptation and mitigation options would also need to be developed and improved.

References Cited

Alber, M., 2002, A conceptual model of estuarine freshwater inflow management: Estuaries, v. 25, p. 1246–1261.

Baron, J.S., Poff, N.L., Angermeier, P.L., and others, 2002, Meeting ecological and societal needs for freshwater: Ecological Applications, v. 12, p. 1247–1260.

Basso, R., and Schultz, R., 2003, Long-term variation in rainfall and its effect on Peace River flow in west-central Florida: Brooksville, Southwest Florida Water Management District, 33 p.

Bates, B.C., Kundzewicz, Z.W., Wu, S., and Palutikof, J.P., eds., 2008, Climate change and water — Technical paper of the Intergovernmental Panel on Climate Change: Geneva, IPCC Secretariat, 210 p.

Beach, M., 2003, Characterization of saltwater intrusion into the Upper Floridan aquifer of the southern west-central Florida groundwater basin [abs.]: Second International Conference on Saltwater Intrusion and Coastal Aquifers — Monitoring, Modeling, and Management, March 30–April 4, 2003, in Merida, Yucatan, Mexico.

Bedient, P., Brinson, M., Dierberg, F., and others, 1999, Report of the scientific peer review panel on the data, theories and methodologies supporting the minimum flows and levels rule for the northern Tampa Bay area, Florida: Brooksville, Southwest Florida Water Management District, 170 p.

Browder, J. A., 1985, Relationship between pink shrimp production on the Tortugas grounds and water flow patterns in the Florida Everglades: Bulletin of Marine Science, v. 37, p. 839–856.

Browder, J.A., 1991, Watershed management and the importance of fresh-water flows to estuaries, *in* Treat, S.F., and Clark, P.S., eds., Proceedings: Tampa Bay Area Scientific Information Symposium 2, Tampa, Fla., TEXT, p. 7–22.

Browder, J. A., and Moore, D., 1981, A new approach to determining the quantitative relationship between fishery production and the flow of freshwater to estuaries, *in* Cross, R., and Williams, D., eds., Proceedings of a National Symposium on Freshwater Inflow to Estuaries: U.S. Fish and Wildlife Service Report FWS/OBS-81/04, p. 403–430.

Cherry, R.N., Stewart, J.W., and Mann, J.A., 1970, General hydrology of the middle Gulf area: Tallahassee, Florida Bureau of Geology, Report of Investigations 56, 96 p.

Culbreth, M.A., Bretnall, R.E., and Stewart, M.T., 1982, Structural framework and movement of regional groundwaters, *in* Treat, S.F., and others, eds., Proceedings, Tampa Bay Area Scientific Information Symposium: Edina, Minn., Bellweather Press, p. 65–86.

Day, J.W., Jr., Hall, C.A.S., Kemp, W.M., and Yáñez-Arancibia, A., 1989, Estuarine ecology: New York, Wiley-Interscience, 558 p.

Day, J.W., Jr., Martin, J.F., Cardoch, L., and Templet, P.H., 1997, System functioning as a basis for sustainable management of deltaic ecosystems: Coastal Management, v. 25, p.115–153.

Drinkwater, K.F., 1986, On the role of freshwater outflow on coastal marine ecosystems — A workshop summary, *in* Skreslet, S., ed., The role of freshwater outflow in coastal marine ecosystems: Berlin, Springer-Verlag, p. 429–438.

Dynamic Solutions, 2006, HSPF hydrologic watershed model of the Manatee River Basin: Brooksville, Southwest Florida Water Management District, 186 p.

Edwards, R.E., 1991, Nursery habitats of important early-juvenile fishes in the Manatee River estuary system of Tampa Bay, *in* Treat, S.F., and Clark, P.A., eds., Proceedings, Tampa Bay Area Scientific Information Symposium 2. TEXT, Tampa, Fla., p. 237–252.

Estevez. E.D., 2002, Review and assessment of biotic variables and analytical methods used in estuarine inflow studies: Estuaries, v. 25, p.1291–1303.

Estevez, E.D., Edwards, R.E., and Hayward, D.M., 1991, An ecological overview of Tampa Bay's tidal rivers, *in* Treat, S.F., and Clark, P.A., eds., Proceedings, Tampa Bay Area Scientific Information Symposium 2. TEXT, Tampa, Fla., p. 263–275.

Estevez, E.D., and Marshall, M.J., 1997, A landscape-level method to assess estuarine impacts of freshwater inflow alterations, *in* Treat, S.F., ed., Proceedings, Tampa Bay Scientific Information Symposium 3: St. Petersburg, Tampa Bay National Estuary Program and Tampa Bay Regional Planning Council, p. 217–236.

Fernald, E.A., and Purdum, E.D., eds., 1998, Water resources atlas of Florida: Tallahassee, Florida State University, Institute of Science and Public Affairs, 312 p.

Flannery, M.S., 1989, Tampa and Sarasota Bay's watersheds and tributaries, *in* Estevez, E.D., ed., Tampa and Sarasota Bays — Issues, resources, status, and management: National Oceanic and Atmospheric Administration Estuary-of-the-Month Seminar Series 11, p. 18–48.

Flannery, M.S., 2007, Overview of freshwater inflow to Tampa Bay: Presentation at Workshop for Monitoring and Modeling Needs for Tampa Bay and its Watershed — What are the next steps, St. Petersburg, University of South Florida Center for Science and Policy Applications for the Coastal Environment (C-SPACE), accessed at *http://www.stpt.usf.edu/cspace/workshopi.asp*

Flannery, M.S., Downing, H.D, McGarry, G.A., and Walters, M.O., 1991, Increased nutrient loading and baseflow supplementation in the Little Manatee River watershed, *in* Treat, S.F., and Clark, P.A., eds., Proceedings, Tampa Bay Area Scientific Information Symposium 2. TEXT, Tampa, Fla, p. 369–395 p.

Flannery, M.S., Peebles, E.B., and Montgomery, R.T., 2002, A percentage-of-streamflow approach for managing reductions of freshwater inflows from un-impounded rivers to southwest Florida estuaries: Estuaries, v. 25, p. 1318–1332.

Florida Department of Agriculture and Consumer Services (FDACS), 2003, Florida's agricultural water policy: Tallahassee, Florida Department of Agriculture and Consumer Services, 40 p.

Florida Department of Environmental Protection (FDEP), 2003, Water quality assessment report — Tampa Bay: Tallahassee, 402 p.

Florida Department of Environmental Protection (FDEP), 2005, Water quality assessment report — Tampa Bay tributaries: Tallahassee, 584 p.

Florida Department of Environmental Protection (FDEP), 2007a, Peace River basin resource management plan: Tallahassee, 102 p.

Florida Department of Environmental Protection (FDEP), 2007b, Tapping new sources — Meeting 2025 water supply needs: Tallahassee, 48 p.

Florida Oceans and Coastal Council, 2009, The effects of climate change on Florida's ocean and coastal resources — A special report to the Florida Energy and Climate Commission and the people of Florida: Tallahassee, 34 p.

Gebert, W.A., Graczyk, D.J., and Krug, W.R., 1987, Average annual runoff in the United States, 1951–80: U.S. Geological Survey Hydrologic Atlas HA-710, scale 1:7,500,000, 1 sheet.

Greening, H.S., and Janicki, A., 2006, Toward reversal of eutrophic conditions in a subtropical estuary — Water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA: Environmental Management, v. 38, p. 163–178.

Hancock, M.C., and Smith, D.A., 1996, Northern Tampa Bay water resource assessment project — Vol. 1. Surface-water/ groundwater interrelationships: Brooksville, Southwest Florida Water Management District, 468 p.

Hickey, J., 1998, Analysis of stream flow and rainfall at selected sites in west central Florida: Tampa, SDI Environmental Services, 53 p.

Hunn, J.D., 1973, Hydrology of Lake Tarpon near Tarpon Springs, Florida: Tallahassee, Florida Bureau of Geology, Open-File Report 73024, 19 p.

Instream Flow Council, 2004, Instream flows for riverine resource stewardship: Cheyenne, Wyoming, Instream Flow Council, 267 p.

Intera, 2006, Estimating ungaged inflows in the Little Manatee River basin, Florida: Brooksville, Southwest Florida Water Management District, 78 p.

Intergovernmental Panel on Climate Change (IPCC), 2007, Climate Change 2007 — The physical science basis: [Solomon, S., Qin, D., Manning, M., and others, eds.,]; Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,: Cambridge University Press, 996 p.

Jassby, A.D., Kimmerer, W.J., Monismith, S.G., and others, 1995, Isohaline position as a habitat indicator for estuarine populations: Ecological Applications, v. 5, p. 272–289.

Jay, D.A., and Simenstad, C.A., 1996, Downstream effects of water withdrawal in a small, high-gradient basin — Erosion and deposition of the Skokomish River Delta: Estuaries, v. 19, p. 501–517.

Jones, G.W., and Upchurch, S.B., 1993, Origin of nutrients in groundwater discharging from Lithia and Buckhorn springs: Brooksville, Southwest Florida Water Management District, 209 p.

Kelly, M., 2004, Florida river flow patterns and the Atlantic Multidecadal Oscillation, Draft — August 10, 2004: Brooksville, Southwest Florida Water Management District, 80 p.

Kennish, M.J., 1986, Ecology of estuaries — Vol. 1. Physical and chemical aspects: Boca Raton, Fla., CRC Press, 254 p.

Knutilla, R.L., and Corral, M.A., Jr., 1984, Impacts of the Tampa Bypass Canal system on the areal hydrology, Hillsborough County, Florida: U.S. Geological Survey Water-Resources Investigations Report 84–4222, 65 p.

Krebs, J.M., Brame, A.B., McIvor, C.C., 2007, Altered mangrove wetlands as habitat for estuarine nekton — Are dredged channels and tidal creeks equivalent?: Bulletin of Marine Science, v. 80, p. 839–861.

Kroeger, K.D., Swarzenski, P.W., Greenwood, W. J., and Reich, C., 2007, Submarine groundwater discharge to Tampa Bay — Nutrient fluxes and biogeochemistry of the coastal aquifer: Marine Chemistry, v. 104, p. 85–97.

Lewelling, B., Tihansky, A., and Kindinger, J., 1998, Assessment of the hydraulic connections between groundwater and the Peace River, west-central Florida: U.S. Geological Survey Water Resources Investigations Report 97–4211, 96 p.

Lewis, R.R., and Estevez, E.D., 1988, The ecology of Tampa Bay, Florida — An estuarine profile: U.S. Fish and Wildlife Service Biological Report 85, no.7.18, 132 p.

Livingston, E.H., 1997, Florida's evolving stormwater/watershed management program, *in* Roesner, M., ed., Effects of watershed development and management of aquatic ecosystems: New York, American Society of Civil Engineers, p. 567–590.

Livingston, E.H., 2008, Draft white paper — Proposed statewide stormwater rule, March 3, 2008 revision: Tallahassee, Florida Department of Environmental Protection, 3 p.

Longley, W.L., ed., 1994, Freshwater inflows to Texas Bays and estuaries: Ecological relationships and methods for determination of needs: Austin, Texas Water Development Board and Texas Parks and Wildlife Department, 386 p.

Mann, K.H., and Lazier, J.R.N., 1996, Dynamics of marine ecosystems — Biological-physical interactions in the ocean: Cambridge, Massachusetts, Blackwell Science, 394 p.

Marella, R.L., 2004, Water withdrawals, use, discharge, and trends in Florida, 2000: U.S. Geological Survey Scientific Investigations Report 2004–5151, 138 p.

Marella, R.L., and Berndt, M.P., 2005, Water withdrawals and trends from the Floridan aquifer system in the southeastern United States, 1950–2000: U.S. Geological Survey Circular 1278, 20 p.

Matheson, R.E., Greenwood, M.F.D., MacDonald, T.C., McMichael, R.H., 2005, Assessment of relationships between freshwater inflow and populations of fish and selected macroinvertebrates in the lower Alafia River, Florida: Brooksville, Southwest Florida Water Management District, 400 p.

McMichael, Jr., R.H., and Peters, K.M., 1989, Early life history of spotted seatrout, *Cynoscion nebulosus* (Pisces: Sciaenidae) in Tampa Bay, Florida: Estuaries, v. 12, p. 98–110.

McMichael, Jr., R.H., Peters, K.M., and Parsons, G.R., 1989, Early life history of the snook, *Centropomus undecimalis*, *in* Tampa Bay, Florida: Northeast Gulf Science, v. 10, p. 113–125.

Metz, P.A., and Lewelling, B.R., 2009, Hydrologic conditions that influence streamflow losses in a karst region of the upper Peace River, Polk County, Florida: U.S. Geological Survey Scientific Investigations Report 2009–5140, 82 p.

Miller, J.A., 1997, Hydrogeology of Florida, *in* Randazzo, A.F., and Jones, D.S., eds., The geology of Florida: Gainesville, University Press of Florida, p. 69–88.

Montagna, P.A., Alber, M., Doering, P., and Connor, M.S., 2002, Freshwater inflow — Science, policy, management: Estuaries, v. 25, p. 1243–1245.

Morrison, G., Sherwood, E.T., Boler, R., and Barron, J., 2006, Variations in water clarity and chlorophyll *a* in Tampa Bay, Florida, in response to annual rainfall, 1985–2004: Estuaries and Coasts, v. 29, p. 926–931.

Moyle, P.B., and Leidy, R.A., 1992, Loss of biodiversity in aquatic ecosystems — Evidence from fish faunas, *in* Fiedler, P.L., and Jain, S.K., eds., Conservation biology — The theory and practice of nature conservation, preservation, and management: New York, Chapman and Hall, p. 127–169.

National Research Council (NRC), 2005, The science of instream flows — A review of the Texas Instream Flow Program: Wash., D.C., National Academy of Sciences, 149 p.

National Research Council (NRC), 2008, Urban stormwater management in the United States: Wash., D.C., National Academy Press, 610 p.

Office of Policy Programs and Government Accountability, 2003, Wastewater reuse reduces discharges and provides alternative water supplies: Tallahassee, Fla., Office of Policy Programs and Government Accountability, 8 p.

Ortiz, A.G., 2009, Potentiometric surface of the Upper Floridan aquifer, west-central Florida, May 2009: U.S. Geological Survey Scientific Investigations Map 3093, 1 p.

PBS&J, 2006, Tampa Bypass Canal/Alafia River water supply projects, Hydrobiological monitoring program, water year 2006 — Year 6 interpretive report: Clearwater, Fla., Tampa Bay Water, 100 p.

PBS&J, 2007, A petition for the reclassification of segments of the Alafia River as class I waters: Submitted to the Florida Department of Environmental Protection, Tallahassee, by Tampa Bay Water, Clearwater, Fla., 87 p.

Peebles, E.B., 2005, An analysis of freshwater inflow effects on the early stages of fish and their invertebrate prey in the Alafia River Estuary: Brooksville, Southwest Florida Water Management District, 147 p.

Peebles, E.B., and Flannery, M.S., 1992, Fish nursery use of the Little Manatee River estuary (Florida) — Relationships with freshwater discharge: Brooksville, Southwest Florida Water Management District, 102 p.

Pielou, E.C., 1998, Freshwater: University of Chicago Press, 275 p.

Poff, N.L., Allan, J.D., Bain, M.B., and others, 1997, The natural flow regime — A paradigm for river conservation and restoration: Bioscience, v. 47, p. 769–784.

Postel, S., and Richter, B., 2003, Rivers for life — Managing water for people and nature: Wash., D.C., Island Press, 253 p.

Powell, G.L., Montagna, P.A., Walton, R., and Hu, H., 2005, Scientific peer review report: Minimum flows for the Tampa Bypass Canal, Tampa, Florida: Brooksville, Southwest Florida Water Management District, 33 p.

Powell, G.L., Alber, M., and Johnson, B.H., 2008, Review of minimum flows and levels for the lower Alafia River, Florida: Brooksville, Southwest Florida Water Management District, 40 p.

Pribble, R.J., Janicki, A.J., Zarbock, H., and others, 2001, Estimates of total nitrogen, total phosphorus, total suspended solids, and biochemical oxygen demand loadings to Tampa Bay, Florida, 1995–1998: Tampa Bay Estuary Program, Technical Publication 05–01, 227 p.

Pride, R.W., 1962, Floods at Tampa, Florida: U.S. Geological Survey Hydrologic Atlas HA-66, 2 sheets.

Reuse Coordinating Committee, 2003, Water reuse for Florida — Strategies for effective use of reclaimed water: Tallahassee, Fla., Reuse Coordinating Committee and the Conservation Initiative Water Resource Work Group. 161 p.

Richter, B.D., Baumgartner, J.V., Powell, J., and Braun, D.P., 1996, A method for assessing hydrologic alteration within ecosystems: Conservation Biology, v. 10, p. 1163–1174.

Richter, B.D., Baumgartner, J.V., Wigington, R., and Braun, D.P., 1997, How much water does a river need?: Freshwater Biology, v. 37, p. 231–249.

Schmidt, N., Lipp, E.K., Rose, J.R., and Luther, M.E., 2001, ENSO influences on seasonal rainfall and river discharge in Florida: Journal of Climate, v. 42, p. 615–628.

Schmidt, N., and Luther, M.E., 2002, ENSO impacts on salinity in Tampa Bay, Florida: Estuaries, v. 25, p. 976–984.

Schueler, T, and Holland, H.K., 2000, The practice of watershed protection: Ellicot City, Md., Center for Watershed Protection, 742 p.

SDI Environmental Services, 2005, Investigation of land use and nitrate migration potential in Lithia and Buckhorn Springs focus area: Clearwater, Fla., Tampa Bay Water, 21 p.

Sinha, M., Mukhopadhyay, M.K., Mitra, P.M., and others, 1996, Impact of Farakka barrage on the hydrology and fishery of Hooghly estuary: Estuaries, v. 19, p. 710–722.

Sklar, F.H., and Browder, J.A., 1998, Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico: Environmental Management, v. 22, p. 547–562.

Southwest Florida Water Management District (SWFWMD), 1993, Eastern Tampa Bay water resource assessment project: Brooksville, Southwest Florida Water Management District, 311 p.

Southwest Florida Water Management District (SWFWMD), 1999, An analysis of hydrologic and ecological factors related to the establishment of minimum flows for the Hillsborough River: Brooksville, Southwest Florida Water Management District, 347 p.

Southwest Florida Water Management District (SWFWMD), 2001, Lake Tarpon Surface Water Improvement and Management (SWIM) Plan: Brooksville, Southwest Florida Water Management District, 98 p.

Southwest Florida Water Management District (SWFWMD), 2002a, Tampa Bay/Anclote River comprehensive watershed management plan: Brooksville, Southwest Florida Water Management District, 117 p.

Southwest Florida Water Management District (SWFWMD), 2002b, Saltwater intrusion and the minimum aquifer level in the Southern Water Use Caution Area, Draft, August 21, 2002: Brooksville, Southwest Florida Water Management District, 47 p.

Southwest Florida Water Management District (SWFWMD), 2004, The determination of minimum flows for Sulphur Springs, Tampa, Florida: Brooksville, Southwest Florida Water Management District, 265 p.

Southwest Florida Water Management District (SWFWMD), 2005a, Minimum Flows for the Tampa Bypass Canal, Tampa, Florida: Brooksville, Southwest Florida Water Management District, 129 p.

Southwest Florida Water Management District (SWFWMD), 2005b, Alafia River minimum flows and levels, freshwater segment: Brooksville, Southwest Florida Water Management District, 235 p.

Southwest Florida Water Management District (SWFWMD), 2006a, Regional water supply plan: Brooksville, Southwest Florida Water Management District, 283 p.

Southwest Florida Water Management District (SWFWMD), 2006b, Lower Hillsborough River low flow study results and minimum flow recommendation, Draft, August 31, 2006: Brooksville, Southwest Florida Water Management District, 208 p.

Southwest Florida Water Management District (SWFWMD), 2006c, Southern Water Use Caution Area recovery strategy: Brooksville, Southwest Florida Water Management District, 305 p.

Southwest Florida Water Management District (SWFWMD), 2007, Proposed minimum flows and levels for the Upper Segment of the Hillsborough River, from Crystal Springs to Morris Bridge, and Crystal Springs: Brooksville, Southwest Florida Water Management District, 295 p.

Southwest Florida Water Management District (SWFWMD), 2008a, The determination of minimum flows for the Lower Alafia River Estuary: Brooksville, Southwest Florida Water Management District, 480 p.

Southwest Florida Water Management District (SWFWMD), 2008b, Board approved 2009 minimum flows and levels priority list and schedule: Brooksville, Southwest Florida Water Management District, 3 p.

Stoker, Y.E., Levesque, V.A., and Woodham, W.M., 1996, The effect of discharge and water quality of the Alafia River, Hillsborough River, and the Tampa Bypass Canal on nutrient loading to Hillsborough Bay, Florida: U.S. Geological Survey Water Resources Investigation Report 95–4107, 69 p.

Swancar, A., Lee, T.M., and O'Hare, T.M., 2000, Hydrogeologic setting, water budget, and preliminary analysis of groundwater exchange with Lake Starr, a seepage lake in Polk County Florida: U.S. Geological Survey Water-Resources Investigations Report 00–4030, 72 p.

Swarzenski, P.W., Reich, C., Kroeger, K.D., and Baskaran, M., 2007a, Ra and Rn isotopes as natural tracers of submarine groundwater discharge in Tampa Bay, Florida: Marine Chemistry, v. 104, p. 69–84.

Swarzenski, P.W., Yates, K., Baskaran, M., and Henderson, C.S., 2007b, Tampa Bay as a model estuary for examining the impact of human activities on biogeochemical processes: An introduction: Marine Chemistry, v. 104, p. 1–3.

Tampa Bay Estuary Program (TBEP), 2006, Charting the course — The comprehensive conservation and management plan for Tampa Bay: St. Petersburg, Tampa Bay Estuary Program, 151 p.

Tara, P.E., Rokicki, R., and Ross, M.A., 2001, Estimation of ungaged flows in the Alafia River: Brooksville, Southwest Florida Water Management District, 85 p.

Tampa Bay Tidal Tributary Research Team (Sherwood, E.T., ed.), 2008, Tampa Bay Tidal Tributary Habitat Initiative — Integrated Summary Report: Tampa Bay Estuary Program, Technical Report 02–08, 83 p.

Trommer, J.T., DelCharco, M.J., and Lewelling, B.R., 1999, Water budget and water quality of Ward Lake, flow and water-quality characteristics of the Braden River estuary, and the effects of Ward Lake on the hydrologic system, west-central Florida: U.S. Geological Survey Water-Resources Investigations Report 98–4251, 33 p.

Trommer, J.T., Sacks, L.A., and Kuniansky, E.L., 2007, Hydrology, water quality, and surface- and groundwater interactions in the Upper Hillsborough River watershed, west-central Florida: U.S. Geological Survey Scientific Investigations Report 2007–5121, 73 p.

Weber, K., and Perry, R., 2001, Impacts of groundwater withdrawals in the Hillsborough River region, Hillsborough, Pasco, and Polk Counties: Brooksville, Southwest Florida Water Management District, 51 p.

Weber, K., and Perry, R.G., 2006, Groundwater abstraction impacts on spring flow and base flow in the Hillsborough River Basin, Florida, USA: Hydrogeology Journal, v. 14, p. 1254–1266.

Wilber, D.A., and Bass, R., 1998, Effect of Colorado River diversion on Matagorda Bay epifauna: Estuarine, Coastal and Shelf Science, v. 47, p. 309–318.

Wolfe, S.H., and Drew, R.D., 1990, An ecological characterization of the Tampa Bay watershed: U.S. Fish and Wildlife Service Biological Report 90, no. 20, 334 p.

Xian, G., and Crane, M., 2005, Assessments of urban growth in the Tampa Bay watershed using remote sensing data: Remote Sensing of Environment, v. 97, p. 203–215.

Xian, G., Crane, M., and Su, J., 2007, An analysis of urban development and its environmental impact on the Tampa Bay watershed: Journal of Environmental Management, v. 85, p. 965–976.

Yeager, L.A., Krebs, J.M., McIvor, C.C., and Brame, A.B., 2007, Juvenile blue crab abundances in natural and man-made tidal channels in mangrove habitat, Tampa Bay, Florida (USA): Bulletin of Marine Science. v. 80, p. 555–565.

Young, H.W., and York, D.W., 1996, Reclaimed water reuse in Florida and the south Gulf Coast: Florida Water Resources Journal, November 1996, p. 32–36.

Zarbock, H., Janicki, A., Wade, D., Heimbuch, D., and Wilson, H., 1995, Current and historical freshwater inflows to Tampa Bay, Florida: Tampa Bay Estuary Program, Technical Publication 01–94, 202 p.