The Effects of Urbanization on Water Supply

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Increased water supply demands associated with urban and suburban growth can pose a serious challenge to water planners and utility providers. In particular, East-Central Florida's rapid growth over the past 30 years has resulted in considerable attention toward and concern for the predominantly groundwater-based water supply.

In response to this concern, detailed groundwater flow analyses and numerical models have been developed to assess the potential impact of increased groundwater withdrawals on the environment and to estimate the "safe yield" of the groundwater supply in the region. The numerical models created to date generally involve a detailed analysis of the hydrogeology of the region, existing and projected groundwater withdrawals, existing and projected land-application (irrigation and aquifer recharge) projects, and existing hydrologic conditions (estimates of stormwater runoff); however, very few of these analyses have attempted to estimate the projected changes in land use and stormwater runoff and how these changes may impact water supply in the region.

As land develops, the percentage of impervious area in a watershed generally increases. This increase is associated with construction of homes, businesses, parking lots, roads, etc., and reduces the ability of precipitation to percolate into the subsurface and ultimately the groundwater system. In addition, the annual evapotranspiration (ET) in these impervious areas is reduced.

The increase in impervious area and decrease in ET thereby increase the quantity of stormwater runoff generated within the watershed, which flows downhill to low-lying lakes, wetlands, and streams. Respecting the mass balance of the surficial aquifer groundwater and surface-water systems, in which precipitation remains constant and applied irrigation typically increases due to development (water budget inflows), this increase in stormwater runoff results in a greater amount of water being available in the watershed. This increased amount of available water could be used as beneficial recharge to enhance water supply.

Water Balance

As part of the water-supply planning and permitting processes that have occurred in central Florida over the past several years, the St. Johns River Water Management District (SJRWMD) (2001) and PB Water (1999) have developed regional numerical groundwater flow models utilizing the USGS MODFLOW (McDonald and Harbaugh, 1988) code. These two models were created for water-supply planning purposes and to assess potential impacts to the hydrologic system due to regional groundwater withdrawals. As part of the conceptual and physical development of both of these numerical models, a water-budget analysis was performed to represent the hydrology of the area and determine the quantity of recharge that is applied to the local hydrologic system on an annual average basis. The water budget can be represented by the following general equation:

$$Re = P + Ra - ET + Q_{ro} + Q_{gw}$$

where:

- Re is effective (net) recharge, [Unit length per unit time (L/T)];
- P is precipitation, [L/T];
- Ra is artificial recharge, [L/T], which is a combination or sum of rapid infiltration basin (RIB) recharge, reclaimed water irrigation, alternate application site recharge, non-reclaimed water irrigation, and septic tank recharge;
- ET is evapotranspiration, [L/T];
- Q_{ro} is flow out of (or into) an area due to surface-water runoff [L/T]; and
- Q_{gw} is groundwater flow out (or in) [L/T].

Stream discharge (including upland surface-water runoff, runoff from wetlands or streams, and baseflow from streams) was not included in the calculation of applied surficial aquifer net recharge because MODFLOW does not have a surface-water modeling component. The MODFLOW Drain Package or River Package, which allow runoff and stream discharge from low-lying areas to be simulated directly, or an external calculation, can be used to simulate this component of the water budget.

Urbanization has generally been represented in these groundwater flow models as follows:

- Increased groundwater withdrawals resulting in regional drawdowns in the Floridan aquifer potentiometric surface and surficial aquifer water table; and
- Increased reclaimed and non-reclaimed water irrigation (if known), represented as an increase in artificial recharge in the hydrologic water budget.

To date, two changes that occur to the hydrologic system as a result of development have not been taken into account as part of these efforts: 1) decreased ET and 2) increased stormwater runoff.

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As a drainage basin or watershed is urbanized, upland areas are paved and the imperviousness of the basin increases. This increased imperviousness causes the ET rate to decrease and the quantity of stormwater runoff in the basin to increase, resulting in a greater amount of water being available in the watershed. This assumes that the annual average precipitation in the basin does not change and that applied irrigation will typically increase as a result of development. This increased quantity of water could potentially be used to enhance the region's water supply. A more detailed description of how the reduction in ET and increase in runoff associated with development may be estimated is provided below.

Estimation of these two components of the water budget, the reduction in ET and the increase in runoff, can be difficult on a regional scale. This is likely the reason they have been neglected in many of the current groundwater flow models; however, neglecting these components of the water budget may result in the overestimation of impacts associated with future groundwater withdrawals by the current groundwater flow models. The concepts presented herein can be used to refine current groundwater flow models or used in development of future groundwater flow models.

Decreased Evapotranspiration Due to Urbanization Effects

ET rates vary across the region depending on multiple factors, including depth to water table, soil type, land use, and active irrigation amounts. To estimate ET values, the region can be divided into multiple coverage areas based on estimated depth to water table and land use.

The primary divisions developed as part of this study consist of general areas of high upland (water table six feet below land surface or deeper), low upland (water table with-

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in six feet of ground surface), and lowland (saturated wetlands, streams, and open-water bodies). The upland coverages were further divided into developed (urban) and undeveloped land. The urban land was finally subdivided into estimated areas of high-density and low-density development.

In the Orange County engineering report submitted in support of the CUP renewal process (PB Water, 1999), urban areas of high-density development were assumed to be 45-percent impervious and urban areas of low-density development were assumed to be 30-percent impervious. Further refinement for a study performed in support of the Phase 2B expansion of the Orange County Eastern Regional Water Supply Facility (ERWSF) (PB Water, 2000) subdivided urban land into estimated areas of high-density (52-percent imperviousness), medium-density (39-percent imperviousness), and low-density (10-percent imperviousness) development.

These refined levels of development were estimated from aerial photography of the Little Econlockhatchee watershed basin provided by the Orange County Stormwater Management Division (OCSWMD). Percent imperviousness was calculated based on a representative sample of the actual percent impervious area observed in the aerial photos for typical land-use types. High-density development was typically classified as areas primarily consisting of apartment complexes and multi-family residences. Medium-density development was typically classified as single-family housing subdivisions, while low-density development was typically classified as sporadic housing or other sparse development. Commercial development, which primarily consists of shopping malls, industrial areas, and dense business districts with parking facilities, was assumed to be 80-percent impervious for this study.

These percent directly connected impervious area (DCIA) assumptions are similar to those found in other hydrology references. For example, the textbook Applied Hydrology (Chow, et al., 1988) lists the DCIA for commercial, 1/8-acre residential, 1/4-acre residential, and 1/3-acre residential developments as 85-, 65-, 38-, and 30-percent DCIA, respectively. Based on these data, the DCIA assumptions herein were considered reasonable.

Based on a study by Sumner (1996), the following hydrologic parameters were assumed:

- an undeveloped high upland area ET rate of 27 in/yr
- a saturated lowlands/open water bodies ET rate equal to the potential evapotranspiration (PET) for the area, or approximately 47 in/yr

Though variable, PB Water has found that the ET rate for undeveloped low upland areas is approximately 37 in/yr.

For the portions of high and low upland coverages that were identified as developed, the ET rates stated above for undeveloped lands were reduced according to the assumed percent of imperviousness, based on an estimated ET rate for 100-percent impervious urban land of 14 in/yr. This ET rate is an annual average rate for impervious area based on a recent stormwater runoff study (Pandit and Gopalakrishnan, 1996). The study utilized long-term continuous numerical simulations and field observations to estimate average annual storm runoff coefficients.

Long-term runoff should be lower than single-event storm runoff quantities. On an annual average basis, rainfall on impervious areas that did not run off was conservatively assumed to be lost as evaporation. It should be noted that an adjustment must be made for irrigated areas. The assumed ET rate for well-irrigated agriculture or urban pervious area was 45 in/yr for this study.

The average ET of a study area can be aerially weighted, based on the percentage of developed versus undeveloped land. For example, if a theoretical study area is 30-percent high-density development (pervious areas irrigated) and 70-percent undeveloped, irrigated high upland (farmland), the resulting effective ET for the study area would be 40.8 in/yr calculated as:

0.30 x (0.45 x 14 in/yr + 0.55 x 45 in/yr)
+ 0.70 x 45 in/yr = 40.8 in/yr

As land is developed, the effective ET rate for the impervious area is reduced. Using the same example study area and increasing the high-density development (with pervious areas irrigated) to 70 percent and undeveloped, irrigated high upland to 30 percent, the effective ET would reduce to 30.8 in/yr. As ET is reduced, the quantity of water available for recharge to the hydrologic system is increased.

Increased Surface Water Runoff Due to Urbanization Effects

Increased runoff due to development has been analyzed, included in designs, and permitted for many decades. In Florida, environmental resource permits must be obtained from the water management districts as part of the permitting process for any site development or design project which alters a parcel of land. This process typically involves estimating the quantity of stormwater runoff generated for pre- and post-development conditions and designing a method to treat and manage this runoff in accordance with state and local regulations.

Though stormwater runoff is a standard part of engineering design, it has been addressed primarily on an individual project basis and typically has not been related to or incorporated into regional water-supply planning efforts. Individual stormwater analyses associated with site development or roadway projects generally are performed on a local scale (parcel or project level), and on a single-storm-event basis. Water-supply planning efforts generally are performed on a regional scale for a long-term or annual average timeframe. Due to this disparity in physical and temporal scale, a method of calculating annual average stormwater generation was utilized for this study.

Average annual storm runoff coefficients (ASRCs) were used in this study to calculate annual average stormwater generation. This technique is a Soil Conservation Service (SCS) based method, which is a standard and widely accepted technique to estimate stormwater runoff. Annual runoff depth is estimated by multiplying an ASRC by the annual precipitation depth.

The first step in developing an ASRC for a basin is the determination of curve numbers (CNs) that will be used for the land uses in the basin. CNs were determined based on the previously identified land-type coverages used for the determination of ET. Curve numbers were related to long-term ASRCs based on a recent study (Pandit and Gopalakrishnan, 1996), as mentioned above. As described, long-term ASRC values should be lower than reported single-event storm runoff coefficients (SRCs). Upland runoff rates can then be calculated as the product of land use ASRC values and the average observed precipitation.

Developed lands with higher levels of impervious area have higher curve numbers and ASRC values, which correspond to greater volumes of stormwater runoff than that which is discharged from undeveloped land. This is primarily due to the impervious surfaces reducing the infiltration capacity of the site. The total volume of stormwater runoff from upland areas within a drainage basin will increase as the density of development within the basin increases.

Effects on Water Supply

Increased runoff resulting from the aspects of development described above flows downhill to be collected in low-lying lakes, wetlands, and streams, and eventually becomes concentrated. Depending on the drainage basin, it then either enters the groundwater system via diffuse leakance to the Floridan aquifer or discharges from the system via larger streams and rivers. In urban areas, a portion of the upland runoff also can

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be collected by street and lake drainage wells that allow water to directly recharge the Floridan aquifer.

Whether stormwater leaves the basin as streamflow or is retained and integrated into the groundwater flow system is a function of the type of drainage basin being assessed. In a closed basin or land-locked watershed, which has no discharge elevation or a discharge elevation that is too high to be regularly achieved, precipitation and runoff are either retained by a stormwater management system or routed to low-lying areas of the basin. Either way, the runoff generated eventually evaporates or recharges the aquifer via diffuse leakage. This recharge of the aquifer is the additional component of the water budget previously discussed that is currently not accounted for in the recent groundwater flow modeling efforts of the region.

Because this excess stormwater is retained in the basin, generally it does not represent a source of lost water that can be captured prior to discharge from the basin and utilized for aquifer-recharge projects. Though already beneficially enhancing recharge in the basin, this water could be redistributed though various stormwater management techniques to areas of the basin or to nearby basins that have a higher potential of being affected by groundwater withdrawals. Small additional increases in aquifer recharge can be made by reducing evaporative losses before recharging the aquifer by moving water from less leaky areas to more leaky areas.

In open basins, the total runoff generated either is retained by a stormwater management system or flows out of the basin through rivers and streams. Water that is retained in a stormwater management system such as a wet retention pond evaporates or recharges the aquifer and does not generally represent a source of lost water that can be used for aquifer-recharge projects; however, the excess stormwater that flows out of the basin through rivers and streams and ultimately is routed to the ocean is a source of lost water that could be used to significantly increase recharge if it were captured and distributed to lakes and wetlands that may be potentially impacted by groundwater withdrawals.

Central Florida Case Study

The quantity of increased recharge due to development was estimated for the Lake Sherwood drainage basin in western Orange County as part of a project for Orange County Utilities. The impetus of this project was to determine how much the current groundwater flow models were overestimating water-level drawdowns associated with future groundwater withdrawals in this region of the county. Though not specifically used to develop an aquifer-recharge project designed to enhance regional groundwater supplies in this case, the same methodology could be applied to such a project.

To determine the quantity of aquifer recharge achieved due to increased development, a detailed Geographic Information Systems (GIS) analysis of the study area was performed. For this project, the study area was designated as a portion of the land within Orange County's West Water Service Area (WSA) that lies within the Wekiva River drainage basin. These limits bounded the analysis on the east and west by Orange County's jurisdictional service area boundary and on the south by the Wekiva River drainage basin boundary.

The northern boundary was chosen for convenience as follows: The Orange County WSA "bottlenecks" just north of the study area due to the city of Ocoee's service area on the west and the city of Orlando/Orlando Utility Commission's (OUC's) service area on the east. North of the bottleneck, the WSA enlarges to encompass a majority of the area between Lake Apopka on the west, to the city of Orlando on the east, and the city of Apopka on the north. Because this specific project focused on the area south of the bottleneck, the bottleneck served as a convenient northern boundary.

Information on major drainage basins or watersheds in the study area was acquired from the SJRWMD and South Florida Water Management District (SFWMD) GIS hydrologic databases. As stated, the area of interest for this study is primarily in the Wekiva River basin, in particular the southernmost extreme of the basin as typified by the SJRWMD subbasin delineation (Adamus, et. al., 1997).

It is proposed herein that even though the study area is within the larger Wekiva River watershed, most of this area is actually composed of smaller land-locked drainage basins. For example, Lake Lotta, Lake Rose, Lake Steer, Lake Olympia and Lake Sherwood are all effectively in a subcatchment of the Wekiva River generally designated as the Lake Sherwood drainage basin. Lake Sherwood has a discharge elevation that appears to be too high to achieve and a drain well which does not allow the lake to rise above a set elevation. It is generally regarded as a "land-locked" watershed (PEC, 1999); therefore, stormwater entering the lake recharges the Floridan aquifer either via vertical leakance through the lake bottom or directly via the recharge well.

The Orange County property appraiser's database as of May 2002 was obtained in GIS format to analyze the level of increased development in the study area. The database was initially divided into three categories: parcels developed before 1995, parcels developed since 1995, and parcels with no development date. These three categories were then further subdivided into the following land uses:

Agricultural (AG)
Commercial (COMM)
Commercial-vacant (COMM-V)
Single-family residential (SFR)
Single-family residential-vacant (SFR-V)
Multi-family residential (MFR)
Multi-family residential-vacant (MFR-V)
Non-developable (ND)
Vacant (VAC)

These land uses were then further classified as currently developed or undeveloped.

The following additional information was included in the GIS coverages used in this analysis:

Property owner's name
Property owner's address
Land parcel size
Land parcel value and building value (used to further determined whether a parcel was developed or undeveloped)
Government-owned parcels (such as those belonging to Orange County)
Detailed land use

The detailed land-use category provided further information such as single-family residential parcels that are primarily submerged or whether an agricultural parcel was a nursery or an ornamental grove.

The data set was then "field truthed" during a windshield survey. In general, the Orange County Property Appraiser's database was quite accurate.

The next step in the analysis was to determine which land parcels would be used to estimate the stormwater recharge capacity in the study area. Based on a detailed review of the database, the following land parcels were removed from the analysis and were not considered in the calculations to determine the quantity of increased recharge in the study area:

- Parcels developed before 1995 (1995 is considered the baseline year that the SJRWMD utilizes to assess water supply planning needs in the region with their groundwater flow model);
- Agricultural parcels developed since 1995 or without a set date of development (percent impervious area and changes in ET assumed to be negligible);
- Stormwater utility sites developed since 1995 or without a set date of development (sites were assumed to have no directly connected impervious area (DCIA));
- Non-developable sites (includes environmentally sensitive areas, parks, and conservation areas); and

- Single- and multi-family residential parcels designated as “vacant water” sites (typically wetlands, lakes, or stormwater ponds);

Based on current trends in Central Florida, the agricultural parcels could be developed in the future; however; the future land use and development dates of these parcels could not be determined and therefore were not included in the analysis.

Land parcels without development dates required a more detailed analysis. It was determined during the field survey that some parcels listed as undeveloped (without development dates), particularly those zoned as single-family residential, currently were being developed. This situation was also true for some parcels designated as vacant in the GIS coverage, representing a lag between the time a parcel is developed and the time its information is updated in Orange County’s database.

Parcels of this nature that could be identified during the field survey were converted to “parcels developed since 1995” in the GIS database. Once these changes in the database were made, two primary data sets remained in the analysis:

- Commercial, single-family, and multi-family residential parcels developed since 1995 including parcels currently being developed
- Parcels without a development date that could not be identified during the field survey as being currently developed

The parcels in the second category were then further subdivided into parcels that will likely develop within the timeframe of this project and parcels without enough data to determine a development classification. Parcels without development dates but zoned as single-family, multi-family, or commercial were considered parcels that would likely develop within the timeframe of this project (through July 2005). The 2005 timeframe was dictated by special condition in Orange County Utilities’ consumptive use permit through the SJRWMD. This assumes that if a parcel has been zoned for a particular land use, it will likely be converted to that intended use in the near future.

All remaining parcels did not have enough data to determine a development classification and were removed from the analysis. Although it is likely that a portion of these parcels will be developed, the future land-use zoning and possible development dates could not be determined.

It was assumed that the parcels within the final coverage were originally undeveloped high upland areas. This was considered a reasonable assumption for this area of Orange County because most developable areas are classified as high uplands except lands immediately surrounding the depressional lakes in the region. The low-upland areas adjacent to the lakes are generally non-developable or have steep slopes and result in a small-enough quantity of low-upland area to be neglected.

Since ET rates decrease as land is developed, it should be noted that this decrease in ET is strictly in the impervious areas of the development. The change in ET in pervious areas differs, depending on irrigation practices. If the pervious area of a new development is not irrigated, ET rates do not significantly change from the pre-development condition. If the pervious area changes from being non-irrigated to being irrigated, ET increases; however, this increase in ET is generally satisfied by recharge attributed to the irrigation, which is accounted for in current groundwater flow models.

Most new developments have irrigation systems; therefore, it is reasonable to assume the pervious areas within a development will be irrigated. In reality, it is common for residents and businesses to over-irrigate pervious areas (that is, apply an irrigation rate that exceeds the increase in ET). It was assumed for this study that pervious areas within new developments are either not irrigated or are irrigated efficiently (application rate equals the increase in ET) in the post-development condition. In either case, the change in ET due to development is negligible. In addition, because people generally over-irrigate, assuming efficient irrigation of the pervious areas is conservative.

The final rainfall, ET, and stormwater runoff characteristics and assumptions utilized herein to determine the net increase in recharge to the study area from 1995 to present conditions are presented in **Table 1**.

Applying the hydrologic characteristics in Table 1 and assumptions to the property parcel areas database results in a total net increase in recharge of 0.477 mgd annual average daily flow (AADF) within the Lake Lotta study area. This can be subdivided into the following two categories:

1) Net change in recharge from 1995 through May 2002: 0.399 mgd AADF
2) Net change in recharge between May 2002 and July 2005: 0.078 mgd AADF

A sensitivity analysis of the stormwater recharge calculations was performed to determine the recharge capacity’s sensitivity to varying rainfall and DCIA assumptions. This was done to determine if the quantity of recharge to the basin would significantly change if the rainfall amount or the percent imperviousness assigned to certain land uses were greater or less than initially assumed.

It was determined that the assumed rainfall rate had a negligible impact on the calculated recharge amount because the change in rainfall is offset by the correspon-

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Table 1. Assumed Hydrologic Parameters for Stormwater Augmentation Analysis

Land Use	Rainfall (in/yr)	DCIA	Pre-Dev. ET (in/yr)	Post-Dev. ET (in/yr)	Pre-Dev. ASRC	Pre-Dev. CN	Post-Dev. ASRC	Post-Dev. CN	Pre-Dev. Runoff (in/yr)	Post-Dev. Runoff (in/yr)
High Upland, Single-Family Residential	51.5	39%	27	21.9	0.01	41	0.30	73	0.52	15.5
High Upland, Multi-Family Residential	51.5	52%	27	20.2	0.01	41	0.39	78	0.52	20.1
High Upland, Commercial	51.5	80%	27	16.5	0.01	41	0.59	90	0.52	30.4

In/yr = inches per year
ASRC = Annual Storm Runoff Coefficient
Post-Dev. = Post-Development.
ET = Evapotranspiration
Pre-Dev. = Pre-development.
DCIA = Directly Connected Impervious Area
CN = Curve Number

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ding change in runoff and ET. The percent imperviousness of the different major land uses (commercial, single-family residential, etc.) was then varied to determine the recharge rate's sensitivity to the assumed DCIA. It was found that this parameter did vary the quantity of net recharge applied to the basin, but by less than 20 percent depending on the assumption. It was also determined that the assumptions made herein tended to fall in the lower portion of the range of potential values and are therefore conservative and may underestimate the actual recharge amounts.

From this analysis, it was found that net recharge in the study area increased by approximately 0.3 million gallons per day per square mile (mgd/mi2) of developed land within the approximately 5,400-acre study area. This initial study is a strong indicator that increased stormwater runoff associated with development could result in a significant quantity of increased recharge to the region.

An example of a project that utilizes excess stormwater within a closed basin to increase recharge in the region is the Sawmill Pond project. Sawmill Pond is a small, isolated lake (no surface discharge) in western Orange County that periodically floods the adjacent land parcels and road during wet-weather events. To prevent this flooding, Orange County Public Works is constructing a project to pump excess stormwater via a pipeline from Sawmill Pond to nearby Crooked Lake when water levels in Sawmill Pond reach a specific discharge elevation. Because Crooked Lake has a higher apparent connection to the underlying Floridan aquifer than Sawmill Pond, this project enhances recharge in the area.

An example of a project that utilizes excess stormwater within an open basin has been proposed for Lake Orlando, which is in the Little Wekiva River basin in western Orange County. As development has occurred over the years, the quantity of stormwater discharged from Lake Orlando into the Little Wekiva River basin has increased. This increase in stormwater routed through tributaries has created problems with sedimentation and erosion in the Little Wekiva River Basin.

To alleviate this problem, it has been proposed to capture and redirect increased stormwater discharged from Lake Orlando to Horseshoe Lake to the west. This could be done by raising the invert elevation of the discharge structure of Lake Orlando and pumping the stormwater captured in the increased permanent pool through a pipeline to Horseshoe Lake. Because this water was once lost as surface discharge through the Little Wekiva River to the St. Johns River, and because Horseshoe Lake is in a closed basin with high apparent leakance characteristics, implementating this project could serve to increase recharge in the region.

The Sawmill Pond and Lake Orlando projects are examples of the utilization of this increased stormwater runoff to enhance water supply. Closer analysis and better management of increased runoff (through projects such as those described herein) could result in an increase in the sustainability of the groundwater supply in the region and is an example of the need for an integrated water-resources approach to the region's water-supply issues.

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