A GIS-based Regional Scale Analysis of Urban Water Balance with an Aquifer-based Water Supply

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Abstract
A significant challenge in urban development is balancing water demand and supply given a growing population. In an aquifer-based water supply system, addressing water scarcity must consider urban hydrology, including maintaining groundwater levels and the interactions among elements of the water cycle.

A Geographical Information System-based Python simulation of urban water balance was created to estimate the components of the water cycle in a region over time. The analysis includes changing land cover and the resulting change in the volume of aquifer extraction, wastewater treatment and disposition over time. The simulation models the basic elements of the water cycle, e.g., evapotranspiration, infiltration, and runoff, which are used to estimate impact as well as evaluate alternative water specific strategies.

The simulation uses readily available water supply and treatment volumes, land cover and weather data, and pervious surface analysis to calculate outcome variables. The simulation spatial unit of analysis is a parcel, typically over a scale of a county, and the time step is daily, over multiple years. Parcel level data used includes metered water use, soil characteristics, and impervious surface area; weather input data includes precipitation and variables needed to calculate potential evapotranspiration; and regional-level data includes wastewater treatment and waste water disposition.

Key Innovations
- Provide data from a scalable water balance model to help evaluate changes in impervious surface when development occurs relative to water partitioning in the environment and its effect on water resources.
- Provide data to estimate potable and rain water input, water uses, and piped and other water output flows at the parcel level.
- Establish the relationship between water demand and supply at the parcel level.
- Establish the relative role increased impervious surfaces and water use play in water partitioning, at the parcel level.
- Evaluate the relationship between water use in an undeveloped or pristine environment and in a developed environment.

Practical Implications
The simulation tool analyses the impact of urbanism on the hydrologic cycle by evaluating the components of the water balance on both developed and undeveloped land cover over time. The study focuses on residential water use unlike many land use and land cover change studies. The study does not only evaluate potable water use at the parcel level but also considers wastewater distribution and importantly, the disposition of wastewater. The analysis includes both natural and artificial aquifer recharge such as treated wastewater discharged to wetlands and direct injection of treated wastewater into the aquifer, and the use of reclaimed water for irrigation.

Parcel-level aquifer withdrawal volume for potable water use is metered by the utility. The analysis evaluates groundwater recharge from infiltration by estimating parcel-level water flows such as precipitation and irrigation and parcel-level water outflows such as evapotranspiration, runoff, and wastewater.

The use of a Python application programming interface with a Geographical Information System (GIS) for simulation facilitates the incorporation of spatial data from various sources such as land cover, parcels, hydrologic soil and meteorological zone classifications, impervious surfaces, and metered water use. Python integrated with GIS automates the analysis and makes it more versatile such that the spatial scale and time step across data types can be managed and do not become a challenge.

Introduction
Groundwater is an essential water resource although it is underutilized probably due to the cost in tapping water from the ground. In 2015, about 26 percent of U.S water use was from groundwater and between 1950 and 2015, the use of surface water has consistently been more than twice that of groundwater. However, for states like Florida, Texas and California that heavily depend on the aquifer, the quantity and quality of the aquifer is of great concern. To ensure the continuous supply of the water in an urban environment given the increasing demand on water by the ever-growing urban population, the withdrawal, treatment and disposition of potable water needs to be understood. The components of the water balance also must be carefully studied. To analyse water extraction and recharge of groundwater and also to estimate the components of the water balance over time in
an aquifer-based urban environment, a GIS-based python urban water balance simulation was created. The model looked at change in land cover over time resulting in change in impervious surface cover and its associating change in the water cycle and water use.

Methods
The GIS Python based urban water balance simulation is designed to evaluate the water cycle implications of new or existing urban development. Urban development is broadly defined as buildings, roads, and infrastructure. Municipal potable water supply, municipal wastewater treatment, and storm water management infrastructures are included within urban development. The impact of development is evaluated using a comparison between infiltration, evapotranspiration, and runoff simulations of the same spatial extent under conditions when a given area is developed and when the same area is in a natural or undeveloped state. Development in a given area is associated with changes to potable water input and its disposition as treated waste water and irrigation and the change in impervious surface from buildings and infrastructure. Simulation of both developed and undeveloped conditions over time is used to assess the impact of these changes from development relative to the natural or undeveloped condition.

The model is implemented in ArcGIS Pro. ArcGIS Pro is a raster and vector GIS software with an Application Programming Interface (API) and programming language. The program uses a combination of native GIS functions and programmed functions, executed through a user interface.

The ArcGIS Pro environment is used to pre-process and geo-process data and produce a visual result regarding the water cycle implications of urban development. ArcGIS Pro’s API enables the definition of the spatial extent of the analysis, load variables and data from external sources, calculate the model, and display results graphically using maps and charts.

The ArcPy package in ArcGIS Pro provides access to the Python programming language. ArcPy can access native GIS operations as well as Python modules for mathematical functions and standard solution modules. The Python programming language was used to program the water balance model and in conjunction with ArcPy and ArcGIS Pro, utilize native geo-processing functions and tools to perform data management functions and data analysis, and produce graphical and numerical output.

Model Description
Data Sources
Data for the analysis were obtained from the following sources.

Area of Interest. The spatial scale considered under the analysis included the county scale, four individual neighborhoods from east and west sides of the county and the parcel level. Spatial extents for the analysis were obtained from United States Geological Survey (USGS) and the Florida Geographic Data Library and the county property appraisal website in the form of shapefiles.

Alachua County Property Appraisal Data. Data obtained from the Alachua county property appraisal website were GIS data for individual parcel information for the county in a parcel shapefile.

Florida Geographic Data Library (FGDL). The FGDL is a repository for GIS data relating to the state of Florida. As such, parcel and building data in the form of shapefiles were obtained from this source. The shapefiles provide useful area and location information including building footprint. For example, the parcel and building area data was used to calculate the impervious area percentage per parcel for the site.

Any parcel less than 1200 square feet were eliminated in analysis. Extremely small parcels are infrequent, generally thin slivers that represent left over areas between property lines.

Gainesville Regional Utility (GRU). GRU data in spreadsheet format consists of monthly metered utility data for potable water use, wastewater generation, metered irrigation, and metered reclaimed water, also used for irrigation in some areas of the county.

Potable water is categorized under residential regular service, general service area regular service, residential irrigation service and general service area irrigation service. Waste water or sewer service is categorized as waste water general service area regular service, waste water residential regular service, waste water residential irrigation and waste residential reclaimed water.

GRU data in a monthly time step was converted to a daily time step by dividing the monthly data equally per each day over the number of days in the month. In addition to rainfall, if any, the daily potable water data for each parcel was used as the input water for the parcel each day. The simulation used the daily parcel data to calculate the water partitioning as infiltration, evapotranspiration, and runoff given the weather-related variables and parcel characteristics. Daily time step results were also aggregated to monthly and yearly time steps for use in analysis and graphics depending upon the individual analysis.

GRU provides several options for water service. A household can either irrigate with potable water or with reclaimed water. A household can either have one meter for all water use; thus, same meter for indoor water use and for irrigation. Alternatively, a household can have two separate meters, one for potable water use and one for irrigation. Irrigation can however be from potable water or reclaimed water. Hence a household can either have a potable water regular use meter and a potable water irrigation meter or a potable water regular use meter and a reclaimed water irrigation meter. The most common meter arrangement is one meter per parcel for all potable water followed by one potable water meter and one reclaimed meter for irrigation and then, lastly, one meter for potable water and one for irrigation.

Parcel-level metered potable water irrigation data from GRU is limited to parcels that have separate irrigation meters. For the remaining parcels, the potable water for irrigation is estimated using various landscape irrigation
estimations and calculations. GRU estimates that sixty percent of potable water delivered is irrigation based on previous studies and facility operations.

Weather data. Weather data on a daily time step was used. Daily data were obtained from the National Weather Service Forecast Office, NOWData or NOAA Online Weather Data. Daily precipitation, minimum, maximum, and average temperatures were obtained from this source and used to calculate the weather dependent water balance variables. NOAA weather data is available by county, city, zip code and other location definitions. Initially, Alachua County was selected as the location. The weather data was refined to be more specific by using zip codes for the individual neighborhoods where parcels were located. Solar radiation was obtained from National Solar Radiation Database (NSRDB) and National Renewable Energy Laboratory (NREL).

In general, the data were cleaned and stored in MS Excel *.csv files. A python sub-program was created to add data to the ArcGIS Pro geodatabase by converting the *.csv data files to geodatabase tables using the ArcGIS Pro python programming interface.

### Water Balance Variable Calculations

Evapotranspiration. Potential Evapotranspiration (PET) is calculated using the Turc Method (Turc, 196; Lu et al. 2005). This method estimates evapotranspiration using maximum and minimum air temperature and solar radiation of the area in question.

\[
ET_{0} = 0.40 \left( \frac{T_{\text{mean}} + 15}{T_{\text{mean}} + 2} \right) (R_s + 50) \quad (1)
\]

where:

- \( ET_{0} \) = PET (mm • day\(^{-1}\))
- \( R_s \) = solar radiation (MJ • m\(^{-2}\) • day)
- \( T_{\text{mean}} \) = mean air temperature in degrees Celsius (°C)

Solar radiation is as per the National Solar Radiation Database (NSRDB) and the National Renewable Energy Laboratory (NREL) (Technical Report NREL 2012)

\( T_{\text{mean}} \) is calculated from maximum (\( T_{\text{max}} \)) and minimum (\( T_{\text{min}} \)) temperatures:

\[
T_{\text{mean}} = \frac{T_{\text{max}} + T_{\text{min}}}{2} \quad (2)
\]

Actual Evapotranspiration (AET) is calculated from PET using the following equation (Pike, 1964; Zhang et al., 2001).

\[
AET = \frac{P}{1 + \left( \frac{PET}{P} \right) ^{0.5}} \quad (3)
\]

where:

- \( AET \) = Actual Evapotranspiration

The Soil Conversion Service (SCS) Curve Number (CN) method (Harper and Baker 2007) is used to calculate runoff from a parcel. This method categorizes impervious areas as Directly Connected Impervious Areas (DCIA), where runoff flows directly into drainage conveyance system or runoff is on a concentrated shallow flow that runs through a pervious area; and non-Directly Connected Impervious Areas (nDCIA) where runoff is not directly connected to drainage conveyance system and also other pervious areas. The SCS curve number method uses soil type and land use characteristics to determine runoff potential of a given area.

According to the Natural Resources Conservation Service (NRCS) TR-55 published by the United States Department of Agriculture (USDA 1986) and Harper and Baker 2007, runoff quantity from stormwater management structures can be evaluated using the equations below given the following assumptions: a) pervious areas are covered by lawn in good condition; b) the CN is determined by the soil classification; and c) for impervious areas such as buildings and driveways, the CN is 98 (Harper and Baker 2007).

\[
Q_{nDCIA} = \frac{(P - 0.25)^2}{(P + 0.85)} \quad (4)
\]

where:

- \( Q_{nDCIA} \) = Excess rainfall (runoff) for nDCIA for each rainfall event
- \( P \) = Precipitation, in inches
- \( S \) = Soil storage, in inches

Soil storage in inches is calculated by:

\[
S = \left( \frac{1000}{nDCIA \ CN} - 10 \right) \quad (5)
\]

where:

- \( nDCIA \ CN \) = Curve Number for nDCIA areas

Curve numbers for nDCIA are calculated as:

\[
nDCIA \ CN = \frac{CN \cdot (100 - Imp) + 98 \cdot (Imp - DCIA)}{(100 - DCIA)} \quad (6)
\]

or

\[
nDCIA \ CN = (Imp \cdot 98) + ((1 - Imp) \cdot CN) \quad (7)
\]

where:

- \( CN \) = Curve Number for pervious area based on soil group classification type.
- \( Imp \) = Percent impervious area

Percent impervious area is calculated as:

\[
Imp = \frac{TI\text{IA}}{PA} \quad (8)
\]

Where:

- \( TI\text{IA} \) = Total Impervious Area, in square feet
- \( PA \) = Parcel Area, in square feet

The percent impervious area per parcel is calculated from parcel and building data included in GIS shapefiles for the area under analysis.

### Model Execution

The simulation analysis is run using the Python language in ArcGIS Pro and using the ArcGIS Python API. After external data previously described is loaded, the simulation program can be run. For the developed simulation case, the spatial, utility, and weather data tables and field names for the spatial extent and the results table are specified. For the hypothetical undeveloped state, spatial extent and weather data are required. In both cases, simulation start and end dates are specified by
entering start and end months, days, and years in the Python program.

Before simulation begins, the program cleans the base spatial data table by removing any fields not needed for the analysis. This is done by specifying the attribute table fields to retain. Required fields for calculating evapotranspiration, runoff, infiltration, precipitation, potable water and irrigation per parcel are retained. Unwanted fields are deleted to keep only the required data in the attribute tables.

The parcel-level potable water and irrigation utility meter data are then added to the attribute table using the parcel identification number to join the tables.

Next, the program scans data in the attribute tables for null values, which can occur for certain types of data when values do not exist for a parcel. For example, a parcel may not have potable water service or service may begin mid-year, resulting in attributes without values. These null values are replaced with zeros.

The simulation begins by calculating the potential evapotranspiration (ET) and the actual evapotranspiration (AET) for the first day in the simulation duration, beginning with the start date specified, and using weather variables as defined in Eq. (1), (2) and (3).

At this point, the ArcGIS Pro Python programming interface is used to dynamically create results fields in the ArcGIS Pro geodatabase attribute table for seventeen variables per parcel. Fields are created with unique field names as frequently as needed, i.e., for daily, monthly, and yearly results.

The daily utility meter data and climate data for the dates specified are used to calculate potable input and rain water incident on the parcel to end point in the environment. For each parcel, the potable water use and irrigation water use is retrieved from the utility meter data. Utility meter data for potable water and irrigation are per parcel in monthly time steps. Daily water use per parcel is estimated by dividing the monthly utility meter data by the number of days in the current month. If a parcel does not have service, daily potable and irrigation water volume is zero.

Based on waste water disposition percentages obtained from GRU, the simulation partitions the potable water not used for irrigation on the parcel into the various waste water disposions. On average, sixty percent of potable water used in Florida is for irrigation. When a parcel does not have an irrigation or a reclaimed water meter, the irrigation percentage is used to estimate waste water volume.

It is also assumed that irrigation occurs only on pervious areas without runoff and as such, irrigation water end points are either infiltration or evapotranspiration.

GRU uses tertiary waste water treatment and releases treated waste water to wetlands, re-injects water into aquifers through wells, and distributes reclaimed water for irrigation. Seventy-two percent of treated waste water is deep well injected, 17% is released through wetlands, and 11% is reclaimed water distributed for irrigation.

The calculation of waste and irrigation water end points is dependent upon the water supply and meter situation at each parcel. In cases where an irrigation meter for potable water volume exists, that value is used for irrigation water use and the waste water volume is considered to be equal to the potable water volume. The disposition of irrigation water is either infiltration or evapotranspiration.

In parcels that have reclaimed water service for irrigation, the reclaimed water volume is considered to be the only irrigation source. The disposition of reclaimed water is either infiltration or evapotranspiration. The waste water volume is considered to be equal to the metered potable water volume for the parcel.

Lastly, in parcels with only a potable water utility meter, 60% of the water volume is considered to be used for irrigation. Forty percent of the metered potable water is considered returned to the waste water treatment plant and ultimately to end points in the disposition described previously.

Potable water, irrigation, and reclaimed water meters are coded in the utility data for each parcel that has service. Each parcel has a binary flag that is used to indicate whether an irrigation meter existed at the parcel. The binary value was used to determine whether a percentage of the potable water meter volume should be set aside for irrigation end points or if all volume should be considered as waste water and flow to waste water end points.

Reclaimed irrigation meter volumes were considered in the disposition upon first use instead of reuse to avoid double counting. In other words, the parcel generating the waste water, a portion of which is reclaimed, is credited with the related disposition volumes.

Utility meter data is in thousand gallons per month which is converted into inches over the parcel area. Water depth is a consistent way to assess water use and is compatible with and easily integrated with rainfall data.

Evapotranspiration associated with a parcel occurs from rainfall and from potable water used for irrigation on the parcel and from waste water treated and released to wetlands and reclaimed water reused for irrigation. Daily weather data includes precipitation water depth. Rainfall will run off and infiltrate as well as evapotranspire dependent upon impervious surface area, soil type, and weather related variables such as temperature and solar radiation. The portion of rainfall that evapotranspires is calculated using Eq. (3).

Daily irrigation volume is determined from utility meter data and only pervious areas of the parcel are considered to be irrigated. Irrigation water can either infiltrate or evapotranspire, and, as with rainfall, dependent upon soil characteristics and daily weather variables.

Infiltration from rainfall and irrigation occurs on the parcel as well from waste water disposition after treatment. Daily infiltration from irrigation on the parcel is equal to the irrigation water depth minus the evapotranspiration water depth calculated for that day. Irrigation is assumed to occur on pervious surfaces only with no runoff water volume.
Infiltration from waste water disposition after treatment occurs from deep well injection, wetlands, and reclaimed water used for irrigation. Treated waste water volume deep well injected is considered 100% infiltration. Wetlands infiltration volumes are equal to total wetlands volumes minus evapotranspiration related to wetlands. Similar to potable irrigation, reclaimed water irrigation has both evapotranspiration and infiltration, with infiltration equal to total reclaimed water minus evapotranspiration.

In order to calculate runoff, the pervious and impervious area are required as per Eq. (8). The parcel area, building footprint area, and the parcel area impervious percentage attributes are used to calculate these values. Soil types are categorized by hydrologic soils group which includes characteristics relevant for water runoff volume calculation. The soils groups are defined spatially in shapefiles. Parcels are intersected with soils group boundaries in ArcGIS Pro to determine the hydrologic soils group for the parcel. Each parcel has one soils group.

A Python dictionary is used to associate the hydrologic soils group classification with the curve number for a given area. There are 28 different soils group-curve number pairs given specific conditions of the area, namely, whether the area is pervious or impervious and developed or undeveloped.

Data in the shapefile attribute table includes the actual year built of any structures on the parcel. When the actual year built attribute is zero, there are no built structures on the parcel. Therefore, building area and percent impervious area are also zero.

Runoff volumes per parcel per day are calculated using Eqs. (4) through (7). Runoff from precipitation events are a function of the soil storage, $S$, the depth of the precipitation event, $P$, and the $CN$. The $CN$ is determined by the hydrologic soil group and whether the parcel is developed or in an undeveloped or natural state. Runoff from pervious and impervious areas on the parcel are calculated separately. Pervious and impervious runoff are combined when total runoff results are tabulated and aggregated as monthly and yearly results. As mentioned previously, runoff from irrigation was assumed to not occur so irrigated pervious areas had no runoff calculation.

Daily infiltration per parcel is determined after evapotranspiration and runoff are calculated. When a precipitation event or irrigation occurs, runoff and evapotranspiration occur, leaving the net of the water input and the sum of evapotranspiration and runoff as infiltration.

Daily infiltration from precipitation is calculated by deducting evapotranspiration and runoff from the precipitation event. As discussed earlier, infiltration for irrigation and wetlands is water input net of evapotranspiration and injection well volumes are entirely considered as infiltration. Daily infiltration values are aggregated to monthly and yearly results as needed.

Results are stored in the geodatabase per parcel in daily, monthly, and yearly time steps as appropriate. Variables stored for analysis are shown in Table 1.

**Table 1. Analysis results variables for simulation of the developed condition**

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET_IRR_POT</td>
<td>Evapotranspiration from potable irrigation</td>
</tr>
<tr>
<td>ET_IRR_RECL</td>
<td>Evapotranspiration from reclaimed water irrigation</td>
</tr>
<tr>
<td>ET_WET</td>
<td>Evapotranspiration from wetlands</td>
</tr>
<tr>
<td>ET_PRECIP</td>
<td>Evapotranspiration from precipitation</td>
</tr>
<tr>
<td>ET_TOT</td>
<td>Total evapotranspiration</td>
</tr>
<tr>
<td>RUNOFF_PRECIP</td>
<td>Runoff from precipitation</td>
</tr>
<tr>
<td>INFL_IRR_POT</td>
<td>Infiltration from potable irrigation</td>
</tr>
<tr>
<td>INFL_IRR_RECL</td>
<td>Infiltration from reclaimed water irrigation</td>
</tr>
<tr>
<td>INFL_WET</td>
<td>Infiltration from wetlands</td>
</tr>
<tr>
<td>INFL_INJWELLS</td>
<td>Infiltration from injection wells</td>
</tr>
<tr>
<td>INFL_PRECIP</td>
<td>Infiltration from precipitation</td>
</tr>
<tr>
<td>INFL_TOT</td>
<td>Total infiltration</td>
</tr>
<tr>
<td>POT_TOT</td>
<td>Total potable water use including potable irrigation</td>
</tr>
</tbody>
</table>

Simulation of the hypothetical undeveloped state used to evaluate the impact of changes to water-relevant variables related to development follows similar execution steps with some differences in input data required and analysis results variables. Utility potable water data and waste water treatment processes are not relevant in the undeveloped simulation as are changes in surface imperviousness from buildings and infrastructure. Identical parcel shapefiles, daily weather data, and hydrological soil group coverages are used in both simulations. Daily evapotranspiration, runoff, and infiltration are calculated using Eq. (1) through (8). Results variables are shown in Table 2.

**Table 2. Analysis results variables for simulation of the undeveloped condition**

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET_TOT</td>
<td>Total evapotranspiration</td>
</tr>
<tr>
<td>RUNOFF_PRECIP</td>
<td>Runoff from precipitation</td>
</tr>
<tr>
<td>INF_TOT</td>
<td>Total infiltration</td>
</tr>
</tbody>
</table>

**Results**

The simulation analysis results presented here are for two different spatial scales, namely county and neighborhood scales. Two neighborhoods are from the eastern side of the county and two are from the west. The western side of Alachua County has experienced more intensive growth and development in recent years. This is reflected in the difference in the change in the impervious percentage over time in eastern versus western neighborhoods.
The components of the water cycle, namely evapotranspiration, runoff, and infiltration are analyzed on a yearly time scale at the two spatial scales. A run of the simulation resulted in the creation of an attribute table in ArcGIS Pro containing the data required for further graphical and statistical analysis and visualization. Results are shown in Figures 1 to 5 and Table 3.

Graphical
County scale results for developed and undeveloped conditions are compared in Figure 1. The figure shows total evapotranspiration, runoff, and infiltration for developed and undeveloped conditions and annual precipitation, potable water use, and percent impervious area at a yearly time step for years 2010 through 2018. The graph indicates that there are clear differences in total evapotranspiration, runoff, and infiltration when development occurs. Developed conditions have lower infiltration and greater runoff. Evapotranspiration appears to have the least change when comparing developed and undeveloped states.

Figure 2 is a graph of a neighbourhood scale analysis of the Tioga neighbourhood. Tioga is an established neighborhood in western Alachua County that has experienced steady growth over the past 25 years. The increase in impervious percentage in Tioga between 2010 and 2018 can be seen in the graph. Evapotranspiration, runoff, and infiltration in Tioga follow the same trends as the county as a whole. Tioga has more average potable water input than Alachua County as a whole. Potable water is approximately equal to precipitation in the analysis. Tioga has a higher impervious percentage compared to Oakmont, the other western Alachua neighborhood included here.

The Oakmont neighbourhood is a recent development that has comparatively low potable water use because of its relatively low density over the time period of the analysis and the use of reclaimed water for irrigation. Evapotranspiration and infiltration appear to have less difference in the undeveloped and developed states. Runoff appears to increase in the later years as development occurs and the impervious percentage of Oakmont increases.

Duval is a neighborhood in eastern Alachua County that has not experienced significant change in developed land area in the analysis time span. The impervious percentage of the neighbourhood remains steady. In general, the comparisons between developed and undeveloped evapotranspiration, runoff, and infiltration follow the same trends as Alachua County. Although the impervious area percentage in Duval is similar to Tioga, the use of potable water is significantly lower. Duval’s potable water is about one-quarter of precipitation rather than approximately equal to precipitation as in Tioga.

Lastly, the Lincoln neighbourhood in eastern Alachua County shows similar trends and some unique aspects. Lincoln has the highest impervious area percentage of the four neighborhoods in the analysis. The impact can be seen in the differences in developed and undeveloped runoff and infiltration, which are the most pronounced in this neighbourhood. The high density also contributes to the high ratio of potable water and precipitation. Lincoln’s water use is greater than precipitation.

**Paired Sample T-Test**
Paired sample t-tests were conducted at the parcel level to compare evapotranspiration, runoff, and infiltration at the developed and undeveloped states for the county and neighbourhoods in the previous section. The mean difference and the significance are shown in Table 3.

Runoff and infiltration are significantly different in all cases. Runoff is lower in the undeveloped condition compared to the developed condition. Infiltration is the reverse. Infiltration is higher in the undeveloped condition compared to the developed condition.

Evapotranspiration is mixed. In some cases the differences are significant and in some cases it is not. Alachua County has a significant difference between the undeveloped and developed condition. The western Alachua County neighborhoods follow the county as a whole and show a significant difference as well. However, the difference in evapotranspiration in the eastern Alachua neighborhoods is not significant.

**Conclusion**
In conclusion, the use of Python in ArcGIS used in this simulation analysis helped address the impact development has on the water cycle and ultimately future water availability. The analysis also revealed different behaviour in different locations. Further broad-based investigation of these differences will reveal physical as well as social differences which result in different development and water use patterns.

**References**


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**Figure 1:** Alachua County-scale total evapotranspiration, runoff, and infiltration for developed and undeveloped conditions showing annual precipitation, potable water use, and percent impervious area at a yearly time step.

**Figure 2:** Neighborhood-scale (Tioga) total evapotranspiration, runoff, and infiltration for developed and undeveloped conditions showing annual precipitation, potable water use, and percent impervious area at a yearly time step.
Figure 3: Neighborhood-scale (Oakmont) total evapotranspiration, runoff, and infiltration for developed and undeveloped conditions showing annual precipitation, potable water use, and percent impervious area at a yearly time step.

Figure 4: Neighborhood-scale (Duval) total evapotranspiration, runoff, and infiltration for developed and undeveloped conditions showing annual precipitation, potable water use, and percent impervious area at a yearly time step.

Figure 5: Neighborhood-scale (Lincoln) total evapotranspiration, runoff, and infiltration for developed and undeveloped conditions showing annual precipitation, potable water use, and percent impervious area at a yearly time step.
Table 3: Paired sample t-Test mean difference and significance of total evapotranspiration, runoff, and infiltration for developed and undeveloped conditions for county and neighborhood scales at a yearly time step.

<table>
<thead>
<tr>
<th></th>
<th>Alachua</th>
<th>Tioga</th>
<th>Oakmont</th>
<th>Duval</th>
<th>Lincoln</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Sig</td>
<td>Mean</td>
<td>Sig</td>
<td>Mean</td>
</tr>
<tr>
<td>Total evapotranspiration</td>
<td>0.0150</td>
<td>0.004</td>
<td>0.0219</td>
<td>0.026</td>
<td>0.0075</td>
</tr>
<tr>
<td>Total runoff</td>
<td>-0.1285</td>
<td>0.000</td>
<td>-0.2375</td>
<td>0.000</td>
<td>-0.1325</td>
</tr>
<tr>
<td>Total infiltration</td>
<td>0.1334</td>
<td>0.000</td>
<td>0.1963</td>
<td>0.000</td>
<td>0.1228</td>
</tr>
</tbody>
</table>

= not significant at the 95% confidence level