Using Water Budgets to Estimate Inflow and Infiltration throughout a Metro Area

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Background

Human activities can have substantial impacts on water budgets.

- Alterations of the landscape and can alter precipitation, actual evapotranspiration (AET), and stream discharge.
- Anthropogenic water inputs to watersheds include inter-basin transfers of water in the form of leaking water-supply pipes, irrigation water, and effluent from wastewater treatment plants (WWTPs).
- Anthropogenic outputs include the withdrawal of surface water and groundwater.

One important anthropogenic outflow that has tended to be overlooked in watershed analyses is the urban phenomenon of inflow and infiltration (I&I) of water into sewage infrastructure.

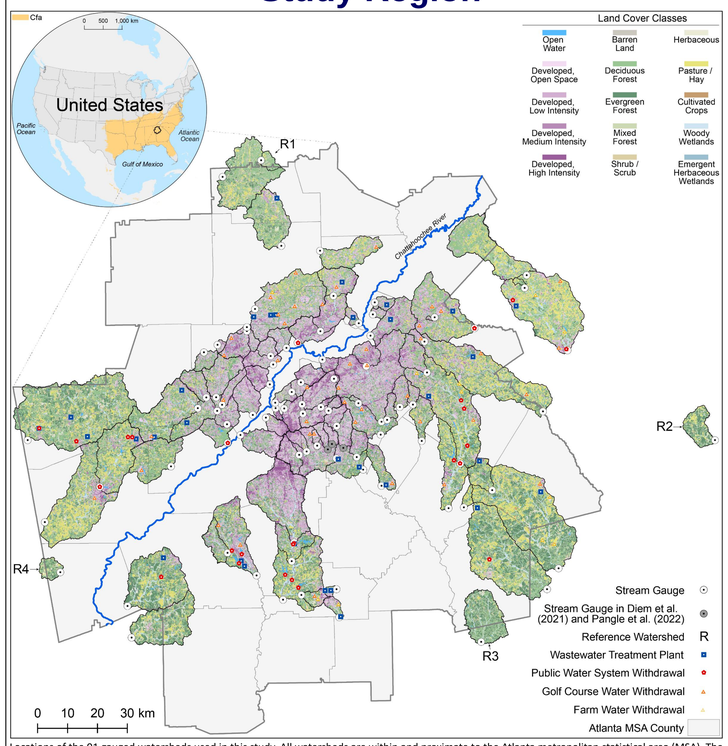
- I&I increases during wet weather and it can overload sewerage systems, thereby causing combined-sewer overflows (CSOs) and sanitary-sewer overflows (SSOs) and subsequent pathogen contamination.
- I&I increases pumping costs at the treatment plant and collection system and likely reduces treatment efficiency Anthropogenic outputs include the withdrawal of surface water and groundwater.
- I&I can be a major outflow in urban watersheds, thereby making it a major contributor to reduced baseflows in urban streams.

Despite the importance of I&I, few studies have provided sufficient I&I information to determine the magnitude of I&I with respect to the water budget.

Purpose

There is a strong need for an examination of I&I in a region across a large number of watersheds with varying sewer-infrastructure and land-cover characteristics. Therefore, **the purpose of this research is to examine the magnitude of watershed-level I&I across a metropolitan area.**

Study Region



Locations of the 91 gauged watersheds used in this study. All watersheds are within and proximate to the Atlanta metropolitan statistical area (MSA). The four reference watersheds are identified as are the three watersheds examined in both Diem et al. (2021) and Pangle et al. (2022). Shown within the watersheds are land cover and locations of wastewater treatment plants and water withdrawals for public water systems, golf courses, and farms. The inset map shows the location of the Atlanta MSA within the Cfa climate type, which covers most of the southeastern United States.

Data and Methods

The equation below was used to estimate I&I that leaves a watershed:

$$I\&I = P + L + Q_E + I_P - W - Q_T - AET_T - Q_G,$$

where P is precipitation, L is water-supply pipe leakage, Q_E is non-I&I effluent from WWTPs, I_P is irrigation water from public water systems, W is water withdrawn by public water systems, Q_S is stream discharge, AET_T is total actual evapotranspiration, and Q_G is net groundwater outflow. In this paper, AET_T is calculated as follows:

$$AET_T = AET_B + E + AET_I,$$

where AET_B is biome AET, AET_I is additional AET from irrigation water, and E is evaporation from impervious surfaces. AET_B is calculated using models in Fang et al. (2015). AET_I is calculated as follows:

$$AET_I = I_P + I_A,$$

where I_P, which was presented earlier as an inflow, is irrigation from public water systems, and I_A is irrigation water withdrawn from the watershed for agriculture, which includes golf courses and farms.

Q_G is assumed to be negligible for the watersheds in this study.

Land cover

- Gridded land-cover, imperviousness, and tree-canopy data were obtained from the National Land Cover Database of the Multi-Resolution Land Characteristics Consortium. The spatial resolution was 30 m.
- Over the 2013-2020 period of this study, land-cover and imperviousness data existed for 2013, 2016, and 2019, while tree-canopy data only existed for 2016.

Population and Housing

- Population and housing data at the block-group level were obtained from the U.S. Census Bureau's American Community Survey 5-year estimates for 2010-2014 and 2015-2019.

Watershed Groups

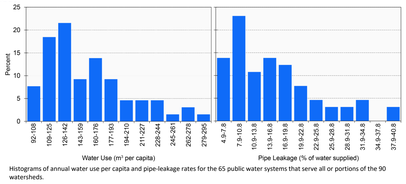
- Watersheds were divided into six groups of 15 watersheds based on percent developed land, percent imperviousness, population density, and housing density.

Precipitation

- Gridded daily precipitation data from 2013 to 2020 were obtained from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) Climate Group. The spatial resolution was 4 km.

Pipe Leakage

- Pipe-leakage estimates relied on annual water-loss audits from 65 public water systems serving populations within the 90 watersheds.



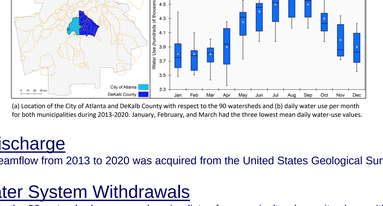
Histograms of annual water use per capita and pipe-leakage rates for the 65 public water systems that serve all or portions of the 90 watersheds.

WWTP Effluent

- Monthly effluent data from 2013-2020 were acquired for 32 WWTPs that discharged effluent into one or more of the 90 watersheds. These data were extracted from the U.S. Environmental Protection Agency's ICIS-NPDES Permit Limit and Discharge Monitoring Report Data Sets.

Landscape Water from Public Water Systems

- Monthly water-use data from the City of Atlanta and DeKalb County drove the estimation of water inflows via irrigation with municipal water. Irrigation water was calculated by applying outdoor water use to grass in developed areas. Outdoor water use was assumed to occur during April-December.



(a) Location of the City of Atlanta and DeKalb County with respect to the 90 watersheds and (b) daily water use per month for both municipalities during 2013-2020. January, February, and March had the three lowest mean daily water-use values.

Stream Discharge

- Daily mean streamflow from 2013 to 2020 was acquired from the United States Geological Survey

Public Water System Withdrawals

- Estimates within the 90 watersheds were made using lists of non-agricultural permits along with water-supplied data from the aforementioned annual water audits.

Agricultural Water Withdrawals

- Estimates were made using lists of permits along with irrigation-prediction information from the Environmental Protection Division of the Georgia Department of Natural Resources

AET

- Mean monthly AET_B totals (i.e., AET that did not include impervious surfaces or account for irrigation) for shrubland, cropland, deciduous forest, evergreen forest, and mixed forest were estimated for the watersheds over the 2013-2020 period using regression models in Fang et al. (2015), which uses precipitation, potential evapotranspiration (PET), and leaf area index (LAI) to predict AET totals.
- AET_B was adjusted based on comparisons of water-budget AET and AET_B at the reference watersheds.
- Annual impervious AET (i.e., evaporation) was estimated using evaporation rates found in the literature. For this study, it was assumed that 20% of precipitation that fell on impervious surfaces was evaporated.
- The final AET total was the sum of biome AET, irrigation AET, and evaporation from impervious surfaces.

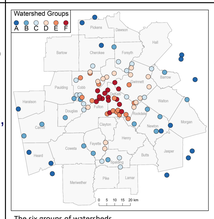
Modeling of I&I

- Multiple linear regression models were developed with annual I&I totals and I&I as a percentage of stream discharge as the predictands and imperviousness, developed land, population density, and multiple housing-density variables as the potential predictor variables.
- All models were evaluated using jackknifing cross-validation.
- Only models with Nash-Sutcliffe E values >= 0.50 were retained.

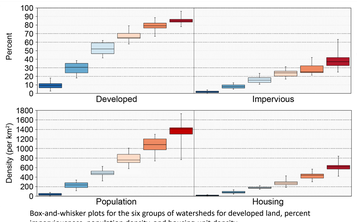
References

Fang, Y., Sun, G., Caldwell, P., McNulty, S. G., Noormets, A., Domec, J.-C., King, J., Zhang, Z., Zhang, X., Lin, G., Zhou, G., Xiao, J., & Chen, J. (2015). Monthly land cover-specific evapotranspiration models derived from global eddy flux measurements and remote sensing data. *Ecohydrology*, 9(2), 248–266. https://doi.org/10.1002/eco.1629

Results



The six groups of watersheds.

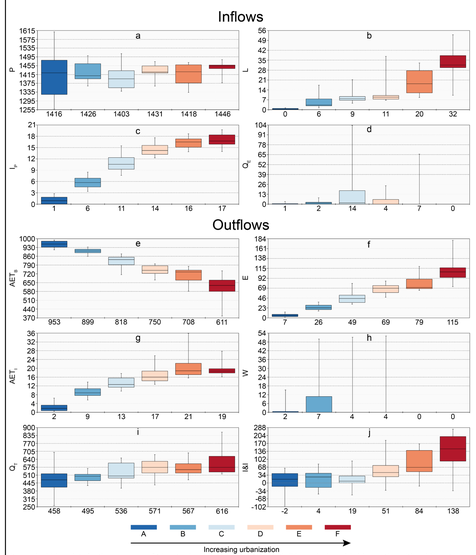


Box-and-whisker plots for the six groups of watersheds for developed land, percent imperviousness, population density, and housing-unit density.

Group A and Group F are the least urbanized and most urbanized watersheds, respectively.

Group A watersheds have 9% developed land, 39% impervious surfaces, 42 persons km^{-2}, and 16 housing units km^{-2}.

Group F watersheds have 85% developed land, 2% impervious surfaces, 1376 persons km^{-2}, and 610 housing units km^{-2}.



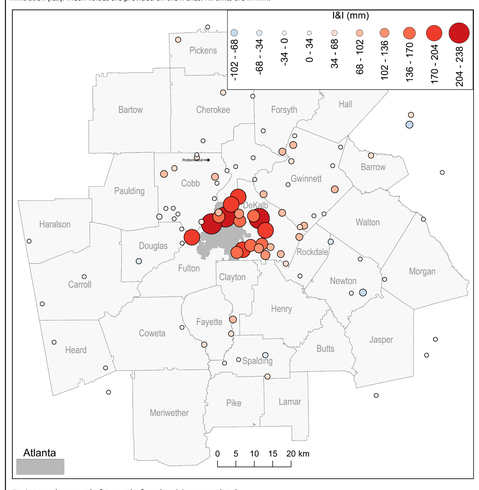
Box-and-whisker plots for the six groups of 15 watersheds for (a) precipitation (P), (b) pipe leakage (L), (c) irrigation with public water (I_A), (d) effluent rom wastewater treatment plants (Q_E), (e) biome AET (AET_B), (f) evaporation from impervious surfaces (E), (g) additional AET from irrigation (AET_I), (h) water withdrawal by public systems (W), (i) stream discharge (Q_S), and (j) inflow and infiltration (I&I). Mean values are provided on the x-axes. All units are in mm.

Panels to the left are box-and-whisker plots for all the terms found in the Data and Methods section, and table to the right shows mean values for terms in the water-budget equation.

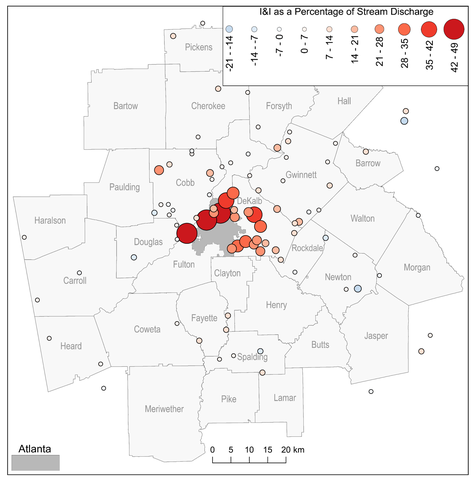
- I&I increases with degree of urbanization
- The most urban watersheds (Group F) have a mean annual I&I total of 138 mm, which is similar to what has been found for similar urban catchments in Europe.
- I&I is the Largest anthropogenic flow into or out of the urban landscape

Mean annual totals for the groups of watersheds for the water-budget terms.

	I&I	P	L	Q_E	I_P	W	Q_T	AET_T
A	-2	1416	0	1	1	2	458	961
B	4	1426	6	2	6	7	495	934
C	19	1403	9	14	11	4	536	878
D	51	1431	11	4	14	4	571	834
E	84	1418	20	7	16	0	567	810
F	138	1446	32	0	17	0	616	741



Estimated annual I&I totals for the 90 watersheds.



Estimated annual I&I as a percentage of stream discharge for the 90 watersheds.

The largest estimated I&I totals occur in the City of Atlanta and DeKalb County. These two municipalities have been under consent decrees to improve their sewage infrastructure.

The mean value of the five largest I&I totals is 216 mm. This is 40% of stream discharge.

One urban watershed has negligible I&I, most likely because it recently had its trunk sewer replaced.

Modeling Results

Most accurate model for I&I (Nash-Sutcliffe E = 0.60)
-10.140 + 0.365 * HD_{70} + 1.052 * PD

Most accurate model for I&I (Nash-Sutcliffe E = 0.58)
-1.548 + 0.072 * HD_{70} + 0.009 * PD

HD_{70} = density of housing units (units km^{-2}) built prior to 1970; PD = population density (persons km^{-2})

Conclusions

For most urban watersheds in the Atlanta region, I&I water leaving the watershed is larger in magnitude than all other anthropogenic flows.

However, there is a lot of uncertainty when using the water-budget approach to estimate I&I. There can be large errors associated with the estimation of every term in the water budget.