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Potential impacts of land use change on streamflow and groundwater resources under changing climate in the Flint River Basin, Georgia, United States

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Abstract

This study ascertains the factors affecting streamflow and irrigation water demand under different land use/cover (LULC) changes and future climate scenarios in the Flint River Basin, Georgia, United States, using the seemingly unrelated regression (SUR) panel model. An advantage of using the SUR model is that it accounts for cross-hydrological correlation, which is important due to the cross-sectional dependence between streamflow and pumpages. A set of streamflow, ground/surface water withdrawal, climatic, and LULC data used in this study was gathered from publicly available data sources and state agencies. Furthermore, the results show that a 10% increase in corn acreage in the watershed could lead to a significant rise in surface water and groundwater pumpings demands, respectively at 124% and 168%. This study identifies potential evapotranspiration (PET) threshold, which may lead to a water deficit in the region. For various LULC scenarios involving corn and urban area expansion, the probability of facing water scarcity at least once from 2025 to 2060 is estimated to range from 0.2% to 3.8% and 0.7% to 2.6% under RCP 4.5 and RCP 8.5 scenarios, respectively. These findings underscore the trade-off between water scarcity and food security in the context of changing climate, highlighting a need to design appropriate incentives to enhance water-use efficiency and adopt climate-smart strategies. The study's significance extends to other similar watersheds worldwide that face similar challenges arising from changing land use and climate, which impact the sustainability of water resources, particularly groundwater resources, over time.

1. Introduction

Groundwater, the world's largest freshwater resource, is vital to global food security as it is a critical source for irrigation (Aeschbach-Hertig and Gleeson 2012). However, population growth and agricultural expansion have led to excessive extraction of groundwater for irrigation, municipal, and public uses, resulting in the depletion of aquifers in many regions (Rodell *et al* 2018, Aribowo *et al* 2019, MardanDoost *et al* 2019, Rufí-Salís *et al* 2019). The changing climate poses additional threats to water resources and, therefore, the sustainability of agriculture in different parts of the world (van Roosmalen *et al* 2009, Karamouz *et al* 2012, Seung-Hwan *et al* 2013, Woznicki *et al* 2015, Herold *et al* 2021, Obahoundje and Diedhiou 2022, Rahmani and Danesh-Yazdi 2022, Ross and Randhir 2022), which is further exacerbated by changes in land use/cover (LULC) (Bellot *et al* 2007, Schilling *et al* 2008, Hurkmans *et al* 2009, Dale *et al* 2015, Kim and Kaluarachchi 2016, Hardie and Bobbi 2018, Garza-Díaz *et al* 2019, Chen *et al* 2020, Deines *et al* 2020, Ueno and Ohta 2020, McGinn *et al* 2021). The decline

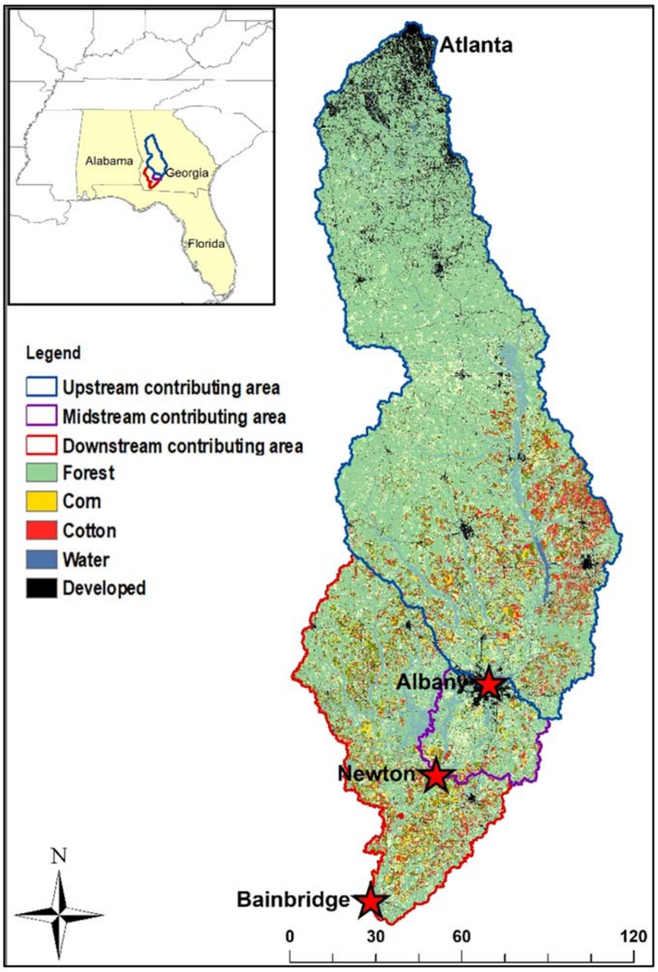

Figure 1. Illustration of the study area and associated land cover. Note: The upstream, midstream, and downstream drainage areas are colored in blue, purple, and red, respectively. The figure shows the study area and associated land cover for year 2008. Source: Cropland Data Layer (CDL) from USDA-NASS (Han *et al* 2012).

in surface- and groundwater resources due to over-exploitation and changing climate is not only a threat to agriculture (Reilly *et al* 2003, Ortiz-Bobea 2020, Doelman *et al* 2022) but is also a critical concern for freshwater biodiversity and ecological sustainability (Ignatius and Stallins 2011, Herrera Estrella *et al* 2021, Phiri and Nyirenda 2022).

The Flint River Basin, located in the southeastern United States, is part of the larger Apalachicola-Chattahoochee-Flint (ACF) River Basin that spans parts of Georgia, Alabama, and Florida (figure 1). The river basin is dominated by agriculture in the southern end (Lower Flint), while forest cover predominates the northern part of the river basin (Upper Flint). Critical to agriculture in the Lower Flint River Basin is the underlying Upper Floridan aquifer that serves as the primary source of water for irrigation, supplying about 80% of the total irrigation demand for more than 200,000 ha of agricultural land (Torak and Painter 2006, Painter *et al* 2015). The aquifer is also vital to the paper, manufacturing, and other industries in the region, supplying more than 100 million gallons per day of water each year (Georgia Water Planning 2022). However, excessive water withdrawal for irrigation from the underlying aquifer system has intensified the stress on the water resources in the Lower Flint River Basin, leading to both short- and long-term declines in groundwater levels as well as downstream flow (Torak and Painter 2006, Mitra *et al* 2016). In addition, over the last two decades, the region has encountered more frequent extreme droughts (NIDIS 2021), further exacerbating the stress on the already declining surface- and groundwater resources of the region. During such drought conditions, spring-fed streams have witnessed 50%–100% flow reductions, and groundwater levels have declined by more than 10 m due to excessive withdrawal (Torak and Painter 2006, The Georgia Water Coalition 2017). Consequently, this has not only threatened the sustainability of agriculture but also led to detrimental impacts on the ecology of the region where several endangered endemic mussel species and other amphibians and fish species exist (Golladay *et al* 2004, Shea *et al* 2013). Moreover, declining flow levels in the streams have also impacted the downstream Apalachicola Bay, posing threats to the estuarine oysters, shrimp, and other marine population. The complex interactions between upstream water use and downstream conditions of the Aplachicola Bay have contributed to the water-related conflict between the three states sharing the ACF River Basin, leading to litigation on water use in the United States Supreme Court (Gilbert and Turner-Nesmith 2019, Rugel 2020).

The decline in groundwater levels and streamflow, coupled with the increasing demands for water resources in the Flint River Basin as well as higher climate variability, highlights the need for and importance of understanding the interaction among agricultural water withdrawal for irrigation, groundwater, streamflow, climate, and LULC changes in the region. The insight gained into the interaction between the different components can be valuable in developing watershed management plans that can help achieve long-term agricultural and ecological sustainability in the region. There are multiple studies that have investigated the effect of LULC changes on water resources in the United States (Schilling *et al* 2008, Van Schmidt *et al* 2022) as well as across the world (Hurkmans *et al* 2009, Van Roosmalen *et al* 2009, Rufí-Salís *et al* 2019). There have also been studies in the Flint River basin that investigated the association between groundwater and surface water (Rugel *et al* 2016), the effects of urbanization on freshwater resources (van Schmidt *et al* 2022), and the effect of irrigation withdrawals on streamflow (Rugel *et al* 2012, Qi *et al* 2020). None of the studies, however, have evaluated the implications of changes to irrigation and LULC on streamflow under different climatic conditions, which can be critical for making practical and efficient water and land management decisions for agricultural and ecological sustainability in the region. Hence, this study aims to explore the impacts of LULC changes on streamflow and groundwater withdrawal under different climate scenarios in the Flint River Basin with a focus on the Lower Flint Region by applying the seemingly unrelated regression (SUR). None of the existing studies have applied the SUR approach to investigate the impact of climate and land use changes on streamflow and pumpage. A major advantage of SUR, which sets this study apart from the existing studies, is that SUR is a simultaneous equations model and allows to model multiple correlated dependent variables (streamflow, pumpage, land use, climate, etc) at the same time. Specifically, the study first identifies factors affecting streamflow and irrigation water demand. After identifying the relationship among land use, climate, and water demand using the SUR, we investigate the Potential Evapotranspiration (PET) threshold above which the region could expect water scarcity under given land use change scenarios. Then, we further ascertain the water withdrawal demand and identify the possibility of water scarcity under different land use and climate change scenarios in the Flint River Basin, Georgia, United States.

2. Study area and data

The study area is the Flint River Basin located in the southeastern United States, which was divided into three focus areas, i.e., Albany (upstream), Newton (midstream), and Baingridge (downstream), based on drainage areas associated with three United States Geological Survey (USGS) (2023) streamflow gauging sites as shown in figure 1. According to raster elevation data (i.e., Digital Elevation Models), elevation in the study area ranges from more than 410 m in the north to less than 10 m in the south (USGS 2022). The lower portion of the Flint River Basin, where the three streamflow gauging sites are located, has a well-drained soil and lies on the Coastal Plain with a slope of around 2 m km^{-1} (Rugel *et al* 2012). Precipitation is the primary source of groundwater recharge. The average annual precipitation in the region ranges from 1,365 mm in the south to about 1,161 mm in the north, based on US Climate Normals data between 1981 and 2010 (Arguez *et al* 2012). Groundwater from the Upper Floridan Aquifer serves as the primary water source for irrigation in the lower part of the Flint River Basin due to its productive karstic aquifer system and proximity to the land surface in the region (Torak and Painter 2006). As a result, groundwater resources are indispensable to the region's economy, supporting agricultural and municipal sectors (Torak and Painter 2006). Additionally, the aquifer system plays a vital role in the ecological sustainability of the region as it helps maintain streamflow during low flow conditions, which is critical for preserving the aquatic habitats of numerous endangered endemic mussel species (Golladay *et al* 2004).

The distribution of LULC in the study area for the study period (2008–2019) associated with the three drainage areas is shown in figure 2. Corn and cotton are the major irrigated row crops in the region in terms of respective land shares. Forests, however, make up the majority of the LULC in this region. As shown in figure 2, Albany, which drains the Upper Flint River Basin, has a higher share of forestland and developed (i.e., municipal and industrial, M&I) land than the other two drainage areas. On the other hand, Newton and Bainbridge have higher agricultural land shares for row crop production (cotton and corn) than Albany. One of the objectives of this study was to investigate the impact of LULC change on pumping water demand, which is primarily dictated by agricultural lands. Thus, this study's relevant LULC types include forest, corn, cotton, and developed lands.

The SUR model developed for this study was based on datasets available between 2008 and 2019, which also contained the 2012–13 and 2016 drought periods. Hydrological data used include streamflow from the three USGS stations (United States Geological Survey USGS 2023) along with surface- and groundwater pumpage

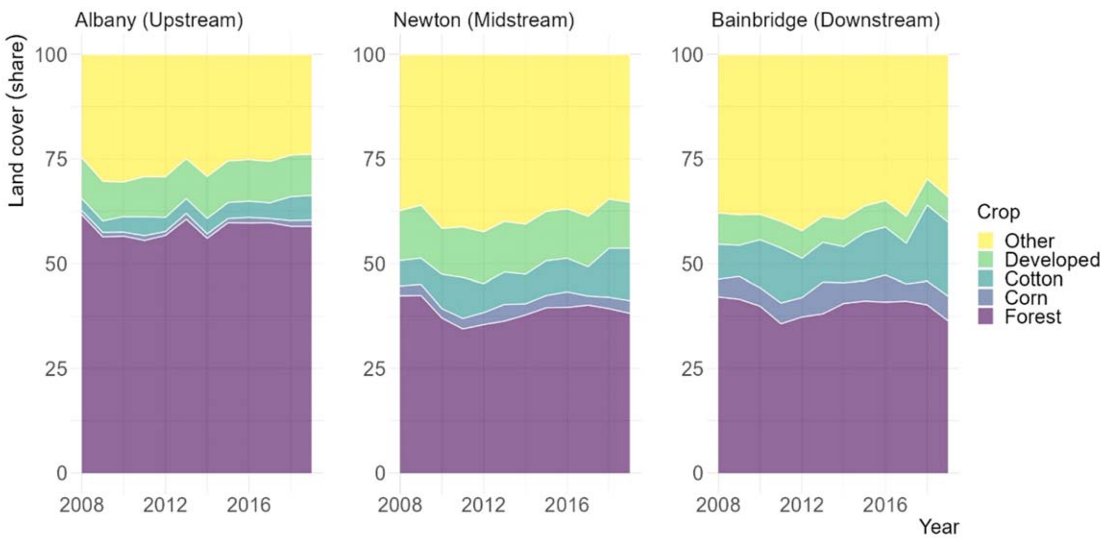

Figure 2. Land use changes in the study area from 2008 to 2019. Note: Forestland includes evergreen forest, deciduous forest, mixed forest, other tree crops, and shrubland. Developed land includes developed/open space, developed/low intensity, developed/medium intensity, developed/high intensity. Other land type includes grassland, open water, woody wetlands, fallow/idle cropland, peanuts, pecans, soybeans, and double-crop (e.g., winter wheat/soybeans). Net drainage areas to the upstream, midstream, and downstream stations are 13,674, 1,256, and 4,366 km^2, respectively. Source: USDA-NASS (Han *et al* 2012).

associated with the three drainage areas (Georgia Environmental Protection Division GAEPD 2020). The estimated surface- and groundwater pumpage data from GAEPD are the total amount of water pumped from surface- and groundwater sources, including the total amount of irrigated acreage and how much water is pumped from irrigation systems. The data also considers the total amount by which groundwater pumping reduces surface water streamflow. Note that the groundwater pumpage includes both agricultural pumping and M&I pumping. A detailed summary of how pumpage has been estimated is documented in Zeng (2016). In addition to the hydrological data, datasets used also include land cover data (USDA-NASS 2021) and precipitation data (from the North American Land Data Assimilation System, NLDAS-2)(Xia *et al* 2012). Potential evapotranspiration (PET) was estimated using the temperature-based Hargreaves method (Hargreaves and Samani 1982), for which daily maximum and minimum temperature data were again derived from NLDAS-2.

Future climate uncertainties will have various impacts on water demands given different LULC changes (Woznicki *et al* 2015, Guswa *et al* 2020). To assess the possibility of water scarcity under future climate in the study area, we also evaluated the potential occurrence of water deficits for the mid-century time horizon between 2025 and 2060. Climate projection data from the Coupled Model Intercomparison Project 5 (CMIP5) under Representative Concentration Pathway (RCP) 4.5 and 8.5 from three Global Climate Models (GCMS), namely the Community Climate System Model version 4 (CCSM4.1) (Gent *et al* 2011) and Geophysical Fluid Dynamics Laboratory's two Earth System Models (GFDL-ESM2M and GFDL-ESM2G) were used for evaluating the probability of water scarcity under future climate change scenarios. Multiple GCMs were used to account for the uncertainty in climate projections data.

3. Methodology

As streamflow and groundwater for irrigation are correlated due to the interconnection between the surface water and groundwater resources in the study area, we applied the SUR to account for the cross-correlating errors in streamflow and pumpage equations. This correlation reflects cross-sectional dependence between streamflow and groundwater usage and can yield less efficient estimates than when error terms in estimated equations are not correlated (Zellner and Theil 1962, Zellner 1962). Since the SUR method jointly estimates a system of equations with correlated error terms, the jointness introduces additional information, providing more available information than when the individual equations are evaluated independently.

Monthly streamflow data acquired for each USGS station (United States Geological Survey USGS 2023) was converted to area normalized net streamflow [LT^{-1}] by taking the difference in observed streamflow [L^3T^{-1}] between the downstream and upstream USGS gages, then dividing it with the drainage area between those sites [L^2] (figure 1). Upstream, midstream, and downstream net drainage area was identified using ArcSWAT (Winchell *et al* 2013), the automated watershed delineation tool for the Soil and Water Assessment Tool (SWAT) model (Neitsch et al 2011). For simplicity, we will term normalized net streamflow as net streamflow, which provides an estimation of the net runoff contribution to each gauging site from the drainage area that contributes downstream of the upstream gaging station and reflects the potential water supply for each corresponding drainage area. The function of the adjusted net streamflow $AF_{i.t}$ (in mm/month), which is net streamflow deducted by surface water pumpage in drainage area i ($i = 1, 2, 3$) during month t, can be expressed as:

$$AF_{i.t} = f(GW_{i.t}, PET_{i,t}, PR_{i,t}, LF_{i,t}, LR_{i,t}, LT_{i,t}, LD_{i,t}, S_t) + \varepsilon_{i,t}^{AF} \quad (1)$$

where $GW_{i.t}$ is groundwater pumped [mm/month]. $PET_{i,t}$ denotes potential evapotranspiration [mm/month], which is an important driver of water demand as it dictates agriculture and forest water use by impacting plant water demand as well as soil evaporation. $PR_{i,t}$ is the total precipitation [mm/month]. $LF_{i,t}$, $LR_{i,t}$, $LT_{i,t}$, and $LD_{i,t}$ are respect shares [in percentages] for the forest, corn, cotton, and developed land. S_t is an indicator variable equaling 1 if the observation during the month t is in the growing season (April to September), 0 otherwise. The indicator variable is meant to control time-varying unobserved factors, such as soil moisture (Kunnath-Poovakka et al 2016), wind speed (Chu et al 2003), farming practice (Schilling et al 2008, Karamouz et al 2012), other relevant such variables. The rationale for including the time-varying term is to control the impact of the unobserved factor of which not much data are available in the study area but can have impacts on the hydrological variables of interest. $\varepsilon_{i,t}^{AF}$ is an idiosyncratic error term.

The groundwater pumping demand function is expressed as:

$$GW_{i.t} = g(SW_{i.t}, PET_{i,t}, PR_{i,t}, LR_{i,t}, LT_{i,t}, LD_{i,t}, S_t) + \varepsilon_{i,t}^{GW} \quad (2)$$

where $SW_{i.t}$ is surface water (mm/month) pumped. $\varepsilon_{i,t}^{GW}$ is an idiosyncratic error term, and the rest of the terms are the same as in equation (1). Since there is no irrigation in forestlands in the study area, the groundwater demand function doesn't include $LF_{i,t}$. On the other hand, the study region does pump groundwater to meet municipal water needs. Hence, $LD_{i,t}$ is included in equation (2).

The surface water pumping demand function is expressed as:

$$SW_{i.t} = h(GW_{i.t}, PET_{i,t}, PR_{i,t}, LR_{i,t}, LT_{i,t}, S_t) + \varepsilon_{i,t}^{SW} \quad (3)$$

here $\varepsilon_{i,t}^{SW}$ is an idiosyncratic error term, and the rest of the terms are the same as in equation (1). Note that $PET_{i,t}$ and $PR_{i,t}$ are included in equations (2) and (3) because together, they provide information about actual ET. PET provides information about the demand for evaporation and plant water uptake, and precipitation provides information about supply. Moreover, due to the karstic nature of the region, groundwater level and streamflow respond quickly to precipitation and pumping (Torak and Painter 2006). Other studies have also pointed out the critical role of PET and precipitation in pumping water demand (Torak and Painter 2006, Kaplan et al 2014, Painter et al 2015), so $PET_{i,t}$ and $PR_{i,t}$ are included in equations (2) and (3). In addition, there is no surface water pumping demand from the municipal sector since it is easier and cheaper to treat groundwater than surface water (City of Albany 2022). Thus, $LD_{i,t}$ is not included in equation (3). Equations (1)–(3) are in a linear functional form. Since water supply (equation (1)) and water demand (equations (2) and (3)) are influenced by each other, the error terms in equations (1)–(3) are correlated (Zellner and Theil 1962, Zellner 1962). The SUR estimation procedure is as follows:

(i). Pre-modeling analyses and tests:

 (a). Seasonality test: this analysis allows us to have a correct model specification. Refer to Supplementary Information (SI) 2 for details.

 (b). Correlation analysis (refer to SI 3): this analysis allows us to confirm that the SUR model is an appropriate model to use due to the interdependent of our primary variables, i.e., streamflow and water pumping.

 (c). Stationarity test (refer to SI 4): Levin-Lin-Chu (Levin et al 2002) and Im-Pesaran-Shin (Im et al 2003) unit root tests are used to examine the stationarity of the hydrological, climate, and LULC data. If data are non-stationary, the data will require to be calibrated to be stationary. Otherwise, non-stationary data can lead to a spurious regression and produce mistaken inference (Phillips 1986, 1998, Phillips and Moon 2007).

(ii). Construct the SUR model based on the analyses and tests in Step i. The total number of estimated equations is three (i.e., three endogenous hydrological variables), along with a total of estimated twenty-two coefficients.

(iii). Estimate the SUR parameters by Two-Stage Least Squares (2SLS) and Three-Stage Least Squares (3SLS) methods (Zellner and Theil 1962, Zellner 1962), respectively. This can be done in R using *systemfit()* from package *systemfit*.

Table 1. Selected land use change scenarios.

Land use scenarios	Changes in land use shares
Scenario 0: Baseline Scenario	Average LULC shares from 2008 to 2019
Scenario 1: Urban Expansion Scenario	Developed land (+5%), Grassland and fallow/idle cropland (−5%)
Scenario 2: Ag Expansion Scenario	Corn (+10%), Grassland and fallow/idle cropland (−10%)
Scenario 3: Ag&Urban Expansion Scenario	Developed land (+5%), Corn (+10%), Grassland and fallow/idle cropland (−15%)

(iv). Conduct Hausman test (Hausman 1978) to determine whether the 2SLS or 3SLS estimator is statistically more efficient (i.e., having the smallest possible variance).

(v). Validate the model results by comparing the observational data and predicted values estimated by the SUR model (refer to SI 5).

As one of the objectives of this study is to assess the impacts of potential LULC changes on streamflow and pumpages, three LULC change scenarios are developed and compared to the baseline scenario (i.e., average LULC shares from 2008 to 2019). Because cropland and developed land are the primary water users in the region (Torak and Painter 2006), the proposed LULC change scenarios aim to explore the impact of changes in these two types of land on the hydrological variables of interest. Table 1 summarizes the proposed LULC change scenarios. For details about land use scenario descriptions and the rationale of the selected scenarios, please refer to SI 1.

4. Results

4.1. Streamflow and pumping water use

Figures 3(a)–(c) present the time series of monthly net streamflow as well as surface- and groundwater pumpage in the study domain. Overall, net streamflow (figure 3(a)) in the study domain is highly variable with no distinct trend compared to the surface- and groundwater pumpage, which shows a distinct seasonality with increasing water use during the growing season (figures 3(b) and (c)). The amount of surface- and groundwater pumped is higher during the growing season (in red).

Negative net streamflow in figure 3(a) indicates that the flow downstream of the drainage region is less than the flow it received from upstream in a given month, meaning a net negative contribution to streamflow from the specific drainage/contributing area (figure 1). For instance, there was a significant net negative streamflow at the Newton site in December 2015, implying a reduction in flow from midstream (Newton) to downstream (Bainbridge) station. As the midstream contributing area is fairly small but has a major city in Albany (figure 1), the contribution to streamflow could be negative under high water use conditions (i.e., more water is being used by the region to municipal or agricultural than is being replenished). This can especially happen during low precipitation/drought conditions.

It is also important to note that the area contributing flow to the Albany station (northern part of Flint River Basin) is mostly urban and forested, with only a small fraction used for row crop agriculture (figure 1). Therefore, groundwater pumping demand for the Albany site is mostly associated with M&I use, as groundwater is more cost-effective (City of Albany 2022) when compared to surface water due to treatment costs. It is also evident that groundwater used by M&I in Albany is considerably lower than used in other drainage areas for agricultural irrigation (figure 3(b)).

4.2. Climate variations

Figures 3(d)–(e) illustrate the two climate variables (i.e., precipitation and PET) from January 2008 to December 2019. Precipitation data cover both non-drought and drought years (e.g., 2008, 2011, 2012, and 2016 are drought years) (figure 3(d)). It is important to note that the dry years impart the highest influence on irrigation water demand for the surface- and groundwater resources, which is further exacerbated during prolonged drought periods like the 2011–2012 drought as it limits aquifer recharge during the non-growing season. It is also evident from figure 3(d) that the region generally experiences precipitation throughout the year. Thus, there are no distinct wet/dry periods.

Figure 3(e) shows that PET variation aligns well with variation in pumping surface and groundwater use (figures 3(b) and (c)). Notably, there is higher plant water demand during the growing season, which is dictated by the high PET requirement (figure 3(e)). Moreover, PET is negatively correlated with net streamflow ($r = -0.28$) and positively correlated with surface- ($r = 0.48$) and groundwater ($r = 0.29$) pumping in the

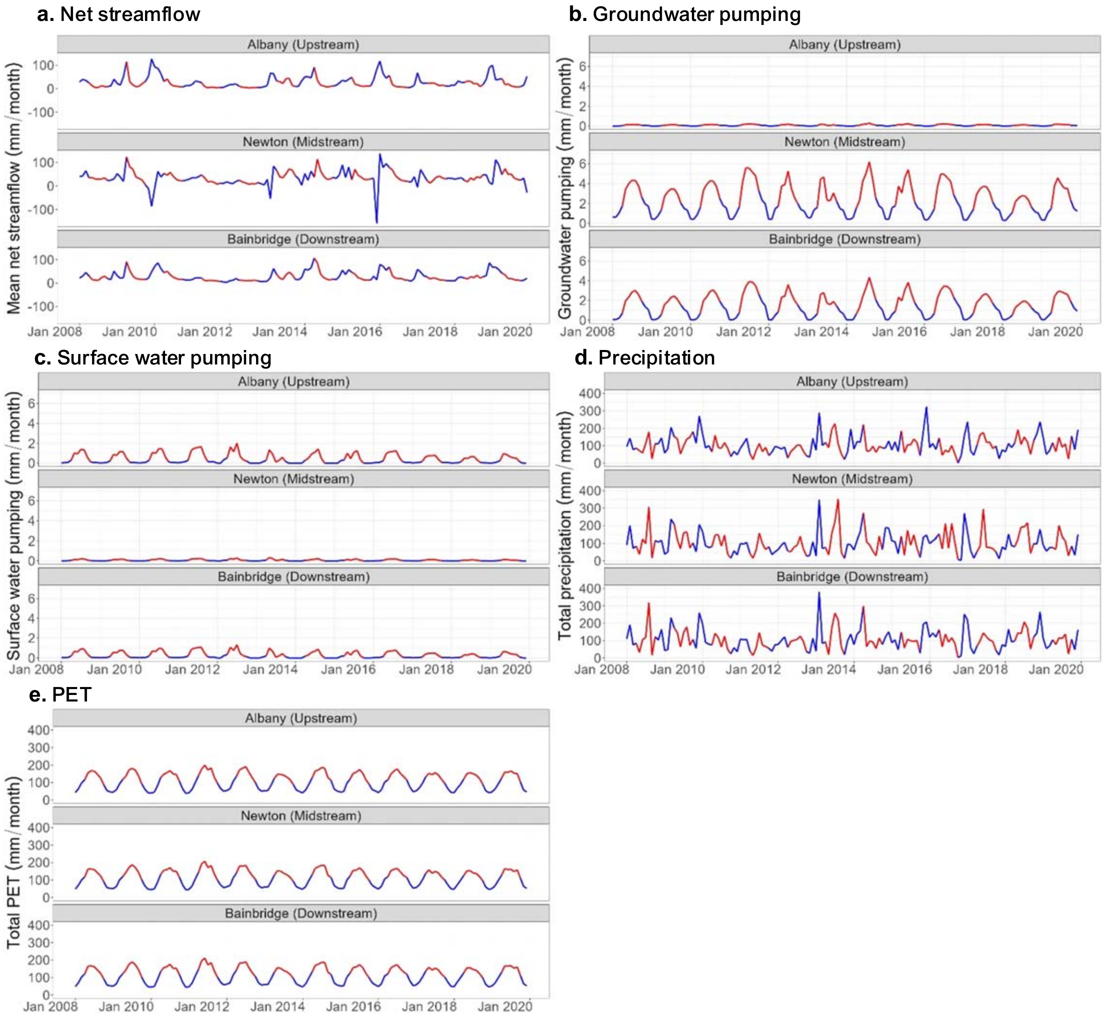

Figure 3. Hydrological and climate variables from 2008 to 2019. Note: Red lines indicate the growing season (April to September); blue lines indicate the non-growing season. PET: potential evapotranspiration. Source: United States Geological Survey USGS (2023) and Georgia Environmental Protection Division GAEPD (2020).

growing season (for details, please refer to SI 3). These correlations indicate that when PET is high, net streamflow is expected to be low, and pumpage is expected to increase.

4.3. SUR model results

The SUR parameters are estimated using both 2SLS and 3SLS. Stationary tests and model validation are documented in SI 4 and SI 5, respectively. Table 2 summarizes the SUR model results using the 3SLS method. The result shows that, on average, a 10 mm increase in monthly PET would lead to a 0.1 mm and 0.3 mm increase in surface- and groundwater pumping, respectively, to satisfy an increase in the water demand. Streamflow, as a result, would be reduced by 3.3 mm. On the other hand, an increase of 10 mm month in precipitation increases adjusted net streamflow by 1.0 mm month^{-1}. Furthermore, the functions for surface- and groundwater pumpage have negative precipitation coefficients but are not statistically significant. Despite the statistically insignificant coefficients, the proposed model specification still includes the precipitation variable because existing studies support the relevance of precipitation in the context of irrigation demand in the region (Torak and Painter 2006, Painter *et al* 2015).

The water sources for pumping (surface- and groundwater) appear to have a substitute relationship. Specifically, increasing surface water pumping by 10 mm month is expected to decrease groundwater pumping by 37.4 mm month^{-1}. In contrast, increasing groundwater pumping by 10 mm month is expected to reduce surface water use by 2.1 mm month^{-1}. The difference in the estimated magnitude between surface- and groundwater pumping is aligned with the historical water volumes pumped in the region (figure 3(b) and (c)). For instance, groundwater pumping is significantly higher than surface water pumping in the midstream and downstream locations. This outcome likely reveals that, for most agricultural lands, it is cheaper to pump water

Table 2. Effects of land use and climate on water resources from SUR model.

	Coefficients	Standard errors
a. Adjusted Net Streamflow (equation (1))		
Constant	54.06***	(15.42)
Potential evapotranspiration (PET) (mm/month)	−0.33***	(0.12)
Precipitation (mm/month)	0.10**	(0.05)
Groundwater pumping demand (mm/month)	−1.05	(1.82)
Growing season (1 if the growing season, 0 otherwise)	28.71***	(11.04)
Forestland share (Percentage, 0–100)	−0.43*	(0.23)
Developed land share (Percentage, 0–100)	1.00	(0.64)
b. Groundwater Pumping (equation (2))		
Constant	−3.02***	(0.44)
Potential evapotranspiration (PET) (mm/month)	0.03***	(0.00)
Precipitation (mm/month)	−0.00	(0.00)
Surface water pumping demand (mm/month)	−3.74***	(0.20)
Growing season (1 if the growing season, 0 otherwise)	0.20	(0.37)
Corn land share (Percentage, 0–100)	0.21***	(0.05)
Cotton land share (Percentage, 0–100)	−0.00	(0.02)
Developed land share (Percentage, 0–100)	0.09***	(0.02)
c. Surface Water Pumping (equation (3))		
Constant	−0.46***	(0.10)
Potential evapotranspiration (PET) (mm/month)	0.01***	(0.00)
Precipitation (mm/month)	−0.00	(0.00)
Groundwater pumping demand (mm/month)	−0.21***	(0.01)
Growing season (1 if the growing season, 0 otherwise)	0.05	(0.09)
Corn land share (Percentage, 0–100)	0.03***	(0.01)
Cotton land share (Percentage, 0–100)	−0.01	(0.01)

Note: *** $p < 0.01$; ** $0.01 < p < 0.05$; * $0.05 < p < 0.1$.
Numbers in parentheses indicate standard errors. +/−0.00 indicates small values (<0.01). The SUR panel model result was estimated by the 2SLS and 3SLS methods (Zellner 1962; Zellner and Theil 1962) using lagged six months streamflow (aligned with the growing season), groundwater pumping, surface water pumping, PET, precipitation, and fixed effects (area and year) as instrumental variables. The estimation procedure was conducted in R using *systemfit*() from package *systemfit*. Hausman test (Hausman 1978) suggests the 3SLS estimator is more asymptotically efficient than the 2SLS estimator, implying the contemporaneous residual correlation exists across three hydrological equations. Thus, the reporting result is estimated by the 3SLS model.

from the underlying groundwater source as it is close to that land surface than pumping surface water from river sources that, for most agricultural lands, are much farther away and require pumping water over long distances.

The Impact of LULC on the hydrological variables varies by land use type. Increasing forestland by 1% is expected to reduce the adjusted net streamflow by 0.4 mm month^{-1}. Reduction in water yield due to an increase in forest acreage can be expected due to increased water use for forests by evapotranspiration and leaf interception and has been noted in existing studies (Bosch and Hewlett 1982, Wu and Haith 1993). In addition, an increase of 1% in corn land is estimated to increase groundwater and surface water pumping demand by 0.2 mm month and 0.03 mm month, respectively. Note that the impact of cotton land on the net streamflow, surface water pumping, and groundwater pumping is not statistically significant. This can be expected as the crop water demand for corn is higher than for cotton (Porter 2020). As mentioned in section 4.1, there is groundwater demand for M&I use as groundwater is more cost-effective compared to surface water in the study region due to treatment costs (City of Albany 2022). This is reflected by the positive coefficient of 0.1 in the groundwater pumping demand function, implying an increase of 1% of the developed land increases groundwater pumping demand by 0.1 mm/month.

5. Discussions

5.1. The impact of LULC changes on water withdrawal

Figure 4 shows the impact of the LULC change scenarios on the hydrological variables given the 25th percentile, mean, and 75th percentile of historical monthly PET to account for primary seasonal climate variations from 2008 to 2019. Under mean PET, the results show that groundwater pumping demand is expected to increase by 35.2%, 168.0%, and 203.2% under Urban Expansion, Ag Expansion, and Ag&Urban Expansion Scenarios, respectively, compared to the baseline scenario (the middle panel of figure 4). Groundwater pumping demand is significantly higher under Ag Expansion and Ag&Urban Expansion Scenarios than Urban Expansion Scenario, implying that the effect of agricultural expansion on increasing groundwater pumping demand outweighs the

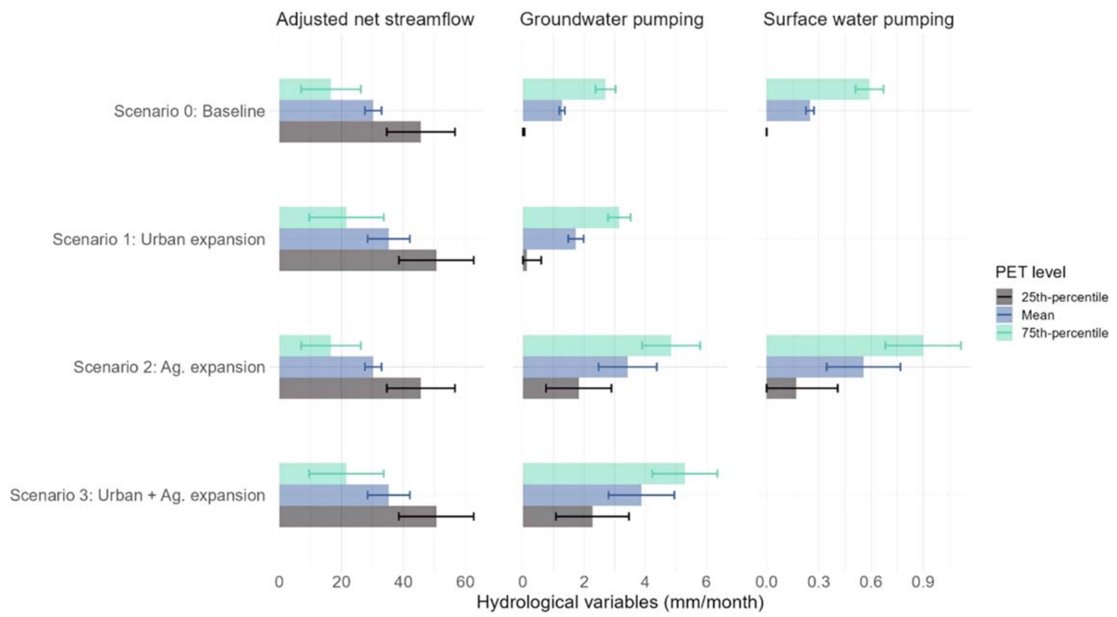

Figure 4. Impact of LULC change on hydrological variables given distinct PET levels. Note: The results are presented under different historical PET levels based on data from 2008 to 2019: the 25th percentile (65 mm month), average (111 mm month^{-1}), and 75th percentile (152 mm month^{-1}). The error bars denote 95% confidence intervals. The right panels (pumping surface water) only show two scenarios that don't involve urban expansion because the function of pumping surface water does not consider municipal water use since it is not cost-effective to pump surface water for M&I use in the study region (City of Albany 2022). A similar analysis regarding the impact of precipitation on the hydrological variables conditional on different precipitation levels and LULC scenarios is documented in SI 6.

effect under urban expansion alone. In addition, the right panel of figure 4 shows that surface water pumping demand is expected to increase by 124.2% under Ag Expansion Scenario relative to the baseline scenario, but the increases are insignificant when PET is low (e.g., 25th percentile).

Note that since the estimated coefficient parameters from regres'sion models are a point estimate (i.e., a single estimated value for each coefficient parameter), which doesn't consider statistical errors, regression result usually also reports confidence intervals to show statistical errors, as we show in figure 4. The error bars of each bar denote 95% confidence intervals. If the error bars overlap with zero, it indicates that the estimated pumpage values are statistically indifferent from zero. The implication of this result shows that no water pumping is needed, given the corresponding climate condition. Due to the physical nature of the pumping in the region, we impose a physical constraint on the model, which ensures that all the negative pumpage values should be treated as zero. In addition, the adjusted net streamflow is lower under the Ag Expansion Scenario than other scenarios (left panel of figure 4) due to higher agricultural water use in the Ag Expansion scenario, which can lead to a reduction in streamflow. This outcome echoes the findings of previous studies in the region. Rugel *et al* (2012) found that intensive groundwater irrigation is correlated with streamflow declines and exhibits spatial heterogeneity in the Flint River Basin. Similarly, Qi *et al* (2020) showed that groundwater withdrawal due to irrigation results in streamflow declines in the Flint River Basin, especially during the region's growing season and drought period.

Overall, findings from the LULC scenario evaluations indicate that water demand (i.e., surface water and groundwater pumping) is expected to increase when LULC changes to agriculture and/or developed land. Although the combination of urban and agricultural expansion is expected to further increase groundwater pumping demand, the increased pumpage may not lead to a significant reduction in streamflow. This could be attributed to the fact that urban land use can contribute to streamflow through an increase in surface runoff which can dampen the streamflow reduction due to increased agricultural land (Viger *et al* 2011). This also helps explain the higher reduction in streamflow under Ag Expansion Scenario than Ag&Urban Expansion Scenario (left panel of figure 4).

In comparing the findings from existing studies relating to LULC and water resources in agriculture-intensive regions, there are both differences and similarities with the present study, and the results are region-dependent. For instance, urbanization or cropland expansion has little impact on water overdrafts overall in California's Central Coast (Van Schmidt *et al* 2022). Increasing corn production relative to perennial grasses in west-central Iowa is expected to decrease actual annual ET and increase water yield (Schilling *et al* 2008). These findings don't appear to be true in the Flint River Basin. Additionally, previous studies show that increasing

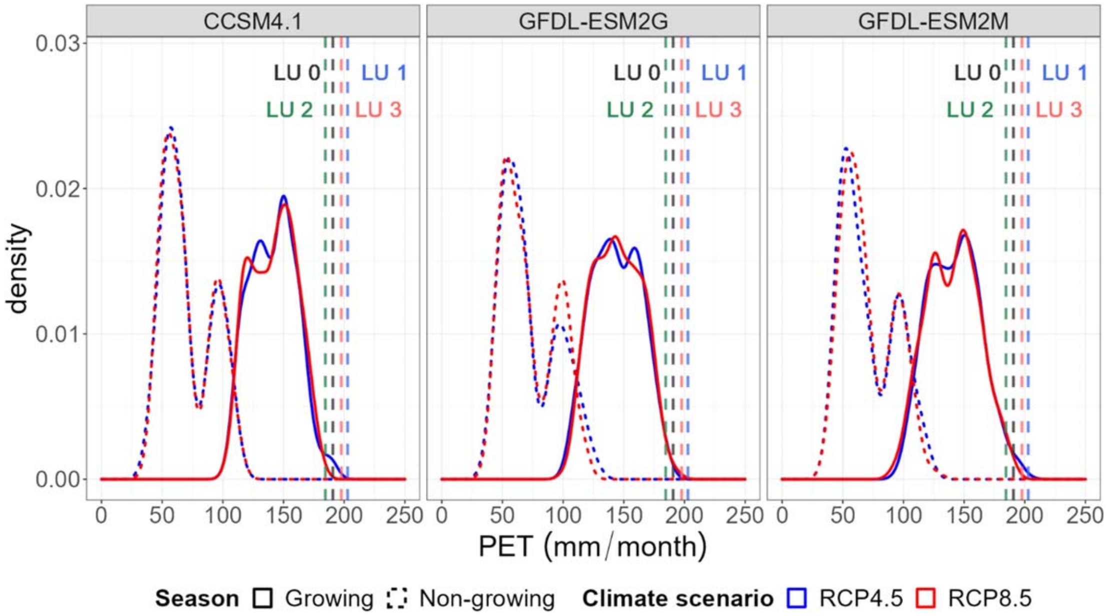

Figure 5. Probability distribution of PET from 2025 to 2060 under different LULC and climate scenarios. Note: LU 0, 1, 2, and 3 denote LULC under baseline Scenario, Urban Expansion Scenario, Ag Expansion Scenario, and Ag&Urban Expansion Scenario, respectively. The total area under the right-tail of the probability density curve intersected with the PET threshold vertical lines signifies the probability of water deficit occurrence under corresponding LULC scenarios (vertical dashed lines).

forestland is expected to cause a reduction in recharge in Denmark (Van Roosmalen *et al* 2009), Catalonia (Rufí-Salís *et al* 2019), and the Rhine River in western Europe (Hurkmans *et al* 2009). This result accords with table 2 of the present study, which shows that increasing forestland is expected to decrease streamflow recharge.

5.2. Implications of climate change to LULC changes and water scarcity

Climate change is a threat to the region's agricultural and ecological sustainability due to the expected increase in more frequent and prolonged summer drought conditions (Wang *et al* 2010), which can lead to water scarcity, particularly under agriculture-intensive LULC scenarios. We use the projected PET data during 2025–2060 from the three GCMs (CCSM4.1, GFDL-ESM2M, and GFDL-ESM2G) to assess the possibility of water scarcity in the future. The detailed procedure for identifying the probability of water scarcity is described in SI 7.

Figure 5 shows the probability density function of PET between 2025 and 2060 under different GCMs and warming scenarios. Under the baseline scenario, the summary of three GCM results shows 0.7%–2.4% and 0.7%–1.0% chances of having water scarcity under RCP 4.5 and RCP 8.5 scenarios, respectively. In addition, the result of the Urban Expansion Scenario indicates a 0.2% chance of having water scarcity under RCP 8.5 scenarios. Moreover, the result under Ag Expansion Scenario shows that there are 1.7%–3.8% and 2.1%–2.6% chances of having water scarcity under RCP 4.5 and RCP 8.5 scenarios, respectively. Lastly, Ag&Urban Expansion Scenario is expected to have a 0.2% chance of having water scarcity under the RCP 4.5 scenario. Only the baseline and Ag Expansion Scenarios during the growing season have evident chances of leading to water scarcity, as scenarios involving urban expansion will increase groundwater pumping and streamflow as return flows, leading to higher PET thresholds and becomes less likely to have water scarcity (SI 7). The implication of the above findings is that, under either an optimistic (RCP4.5) or pessimistic (RCP 8.5) climate scenario from 2025 to 2060, there will be a nontrivial chance to have water scarcity which will lead to detrimental impacts on the local ecology as well as agricultural sustainability. Hence, information from this study can be important to the watershed planners for the region to develop management plans that help mitigate the adverse impacts of climate in the future.

6. Conclusions

This study aims to identify factors affecting streamflow and pumping water demand and to predict the water withdrawal demand under different LULC and climate change scenarios in the Lower Flint River Basin, Georgia, United States. The SUR method is applied to account for cross-sectional dependence between streamflow and pumpages. The SUR estimation results show that the sources of pumped water appear to have a substitute relationship. This outcome reflects that the region depends more on groundwater than surface water due to the relative ease of access and a lower pumping cost. In addition, the primary groundwater pumping demand is from corn and developed land, emphasizing the crucial consideration of the land use effect on groundwater pumping demand. The LULC scenarios evaluation shows that increasing corn land by 10% is expected to raise the surface water and groundwater pumping demand by 124% and 168%, respectively, compared to the baseline scenario. Thus, the increases in water demand due to the increase in corn land are potentially significant, especially when the potential expansion of biofuel mandates could result in further expansion of corn acreage (Chen *et al* 2021, Ferin *et al* 2021) as it can potentially lead to a reduction in streamflow. This study further incorporates climate projection data with the identified PET threshold. Given different LULC scenarios, the result shows that the probability of water scarcity by 2060 is 0.2%–3.8% and 0.7%–2.6% under RCP 4.5 and RCP 8.5 scenarios, respectively. These findings indicate the potential struggle among water scarcity, food security, and ecology under future climate and highlight an urgent need to design incentive programs to improve water-use efficiency and adopt climate adaptation strategies.

This study has a limitation related to the model parameters, which are estimated as the mean estimation (i.e., central tendency). As a result, the developed model has its limitations in predicting extreme events, such as extreme streamflow (e.g., extreme values in the net streamflow at the Newton station) and extremely low pumping water volumes (e.g., very low pumping groundwater at the Albany station and pumping surface water at the Newton station). Due to these limitations, there are discrepancies in our validation results for these extreme events. For instance, observed data shows no pumping at Albany (upstream). However, the model estimation still shows some pumpage, albeit with a relatively small magnitude (figure S4), indicating the model's limitation in capturing the extremely low pumpage. Nevertheless, it is essential to note that the relatively low pumping of groundwater at the Albany station and the pumping of surface water at the Newton station also suggests that the actual pumping demand for these drainage areas is very low in reality. This helps mitigate the potential adverse effect of the model limitation on accurately understanding the primary water supply and demand in the study region. Furthermore, we alleviated the impact of this limitation by incorporating our modeling results with the probability distribution of future climate data. This approach allows us to identify potential drought events and derive the probability of water scarcity under various LULC and climate scenarios. By integrating this probabilistic approach, our results provide valuable insights into the likelihood of water scarcity occurrences, helping to overcome the limitations posed by the model's inability to predict extreme events accurately.

More research is needed to investigate the potential adverse impact of extreme weather (e.g., droughts). For instance, agriculture-related water pumping entities could utilize El Niño Southern Oscillation (ENSO) and/or decadal climate variability (DCV) information to adopt climate change adaptation strategies, e.g., climate-tolerant crop, crop insurance, and provisions of adaptation financing (Fan *et al* 2017, Wang *et al* 2021). The relationship among hydrological variables, climate variables, and ENSO/DCV have been identified in existing studies by applying a percentile method (Cayan *et al* 1999, Sankarasubramanian and Lall 2003), simulation (Mehta *et al* 2012), or regression-based methods (Jithitikulchai 2018, Huang *et al* 2020, Ding and McCarl 2021). In the future, these approaches can be tested relative to the methods adopted in this study. In addition, the current model doesn't consider the impact of pumping water costs on water use (Brill and Burness 1994, Katsifarakis and Tselepidou 2009), although the costs have been considered stable in past years. A greater focus on the water pumping costs could potentially provide insightful findings that reveal the impact of economic incentives on pumping water. Last but not least, similar analyses focusing on habitat restoration in stressed agricultural landscapes (Bryant *et al* 2020) would also be warranted and crucial to improving global water management and biodiversity loss.

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Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

Conflicts of interest

The authors declare that there is no conflict of interest.

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