# A GIS-Based Framework to Identify Opportunities to Use Surface Water to Offset Groundwater Withdrawals

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## Abstract

The over-use of groundwater is an increasing issue even in regions of the U.S. traditionally characterized by abundant rainfall and surface water. Part of the groundwater withdrawals in these regions can potentially be replaced by surface water, and quantitative spatial analysis to demonstrate this potential may help to spur policy changes. However, one challenge for this type of spatial analysis is the lack of groundwater withdrawal data at the watershed scale. For example, estimates of groundwater withdraw are only available at the county-level for most of the U.S., which is not granular enough to be useful for local management decisions. The present study developed a GIS-based framework for spatially disaggregating available ground-water withdrawal information based on ancillary information such as the well's minimum casing diameter. This information was used to identify potential opportunities where surface water could be used to offset groundwater withdrawals. The application of this framework to irrigation water demand in the state of Louisiana shows that a significant fraction of ground-water withdrawals can potentially be offset by available surface water. This basic framework can be complemented with additional considerations such as the availability of surface water to more fully evaluate water management scenarios.

**Keywords** Dasymetric mapping · Disaggregation · GIS · Groundwater withdrawal · Proximity analysis

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## 1 Introduction

Groundwater is used for drinking and irrigation purposes worldwide because of its widespread distribution and inherent water quality properties that render it attractive (Shah and Mukherjee 2001; Zektser et al. 2005; Ayotte et al. 2015; Davidsen et al. 2015). Groundwater generally does not require expensive treatment and is relatively protected from contamination. Groundwater is used for drinking for more than half of the U.S. population and its municipal demand has tripled since 1970 (Zektser 2000; Zektser et al. 2005). The excess of groundwater withdrawal relative to the amount of recharge into an aquifer creates the problem of overdrafting. This is not only a problem of arid environments (Scott and Shah 2004; Zektser et al. 2005; Davidsen et al. 2015), but also an increasing issue in regions characterized by abundant annual average rainfall and surface water, like the southeastern U.S. (Liu et al. 2008; Davis and Wilkins 2011; Famiglietti and Rodell 2013; Ritter and de Mooy 2014; Eldardiry et al. 2016). Severe groundwater depletion has recently been observed in the coastal plains aquifer system of the Gulf and Southern Atlantic coasts (Famiglietti and Rodell 2013; Konikow 2013; Ritter and de Mooy 2014). Groundwater depletion can cause subsidence and saltwater intrusion in coastal regions and may also decrease the base flow in streams (Garza and Krause 1996; Heywood and Griffith 2013). Water management practices in the coastal southeast U.S. have focused primarily on flood control for surface water while relying heavily on groundwater for municipal, industrial, and agricultural use. The use of surface water as a replacement for groundwater has been limited by water quality concerns and frequent spatial/temporal mismatches between surface water supply and water demand (Poudel et al. 2013; Hoogesteger and Wester 2015; Eldardiry et al. 2016; Borrok et al. 2018). Hence, a fundamental challenge in developing a sustainable water management strategy for wetter regions of the U.S. (and globally) is to understand the spatial and temporal dynamics of groundwater withdrawal and surface water availability on fine "management-level" scales (e.g., Eldardiry et al. 2016). Within this broader challenge, a particular dilemma in dealing with water withdrawal data is that for many states in the U.S. groundwater wells are not metered and water withdrawal data are estimated on a county-level scale. Demand data at this scale are not always useful for water management planning at a local scale. However, many states maintain well registration databases that include well location, depth, casing size, and type of use. In order to identify, rank, and characterize opportunities for offsetting groundwater withdrawals with surface water, we need to establish a methodology to disaggregate the groundwater demand data at the county scale to smaller watershed scales. Although, some efforts have been made to create smaller-scale water withdrawal datasets, there is no established methodology.

In this study, we address this important problem by developing a new methodology for disaggregating county-level spatial data for groundwater withdrawal into much finer resolutions (Hydrograph Unit Code 12 (HUC-12) and 1 km$^2$ management scales). Our study utilizes dasymetric mapping (Mennis 2016) and empirical downscaling to disaggregate spatial data using ancillary spatial data layers such as a well registration database to generate groundwater withdrawal datasets that improve positional accuracy and spatial resolution of subsequent analyses. Using the state of Louisiana as a case study, the authors demonstrate this technique for groundwater withdrawal data in 2010. The study also demonstrates usefulness of such information by performing a simple proximity analysis to examine the feasibility of replacing groundwater withdrawal with surface water. The ultimate goal of this work is to provide a framework for downscaling groundwater withdrawal data so that it can be effectively used to support water management decisions.

## 2 Study Area

The state of Louisiana (Fig. 1) is characterized by a humid subtropical climate and receives about 150 cm of rain per year (Kniffen and Hillard 1988). Louisiana hosts about 40% of the freshwater wetlands in the U.S. (Conner and Day 1976; Mitsch et al. 2013); is a hub for the petroleum industry and the third leading producer of rice in the U.S. (McGuire 2006). Louisiana is also a leading exporter of aquaculture products (Garrett et al. 1997; Romaire et al. 2005). All of these activities demand enormous quantities of high-quality water. The current rate of groundwater usage in some parts of Louisiana is not sustainable (Nyman et al. 1990; LDEQ 1999, 2009; Tollett et al. 2003; Lovelace et al. 2004; Davis and Wilkins 2011). In 2010, the groundwater used for the irrigation and aquaculture in Louisiana (around 2.5 million m$^3$/day) was more than one-half of the total groundwater usage for the state (Sargent 2011). Defining a pathway to groundwater sustainability is critical for the state of Louisiana. Surface water augmentation is recognized as a potentially critical water management tool to reduce demand for groundwater (LDNR 2011).

## 3 Data and Methods

The present study leveraged estimated groundwater withdrawal data available from USGS in 2010 (Sargent 2011) and the state of Louisiana's well registration database (containing location, use types, depth, and casing size information; LDNR at http://sonris-www.dnr.state. la.us/gis/dnld/download.html). Inactive wells were excluded from the database and the water
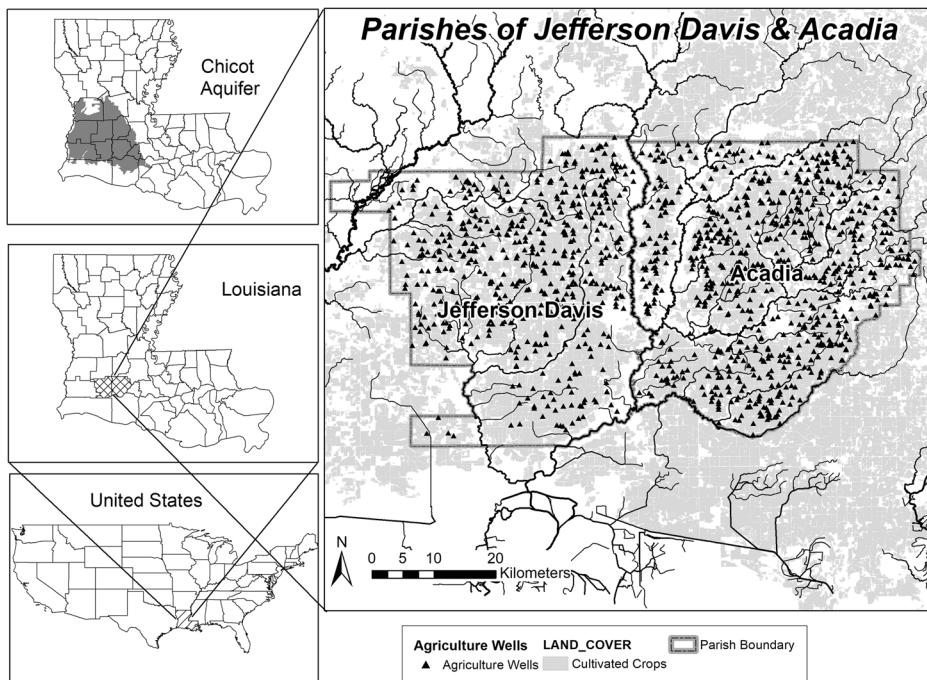


**Fig. 1** Map of study area highlighting water well distributions in Jefferson Davis and Acadia Parishes (Counties)

use types provided in the database were picked to match the examined water demand categories (irrigation and aquaculture). Additional data included the boundary lines of counties and HUC-12 watershed units, surface water streamline locations and accumulative flows. A detailed list of data sources and types is shown in Table 1.

## 3.1 Disaggregation of County-Level Groundwater Withdrawal Information into Individual Well Locations

In this research, a dasymetric mapping approach was used to disaggregate the county-level water demand data. Dasymetric mapping is a type of areal interpolation, which transforms data from one spatial unit to another and usually can achieve higher spatial resolution and accuracy (Mennis 2015). The fundamental idea of dasymetric mapping is areal weighting, which assumes that the data are distributed homogeneously across space with one or multiple controlling factors. Areal weighting is extended to account for varying densities in different ancillary data (Mennis 2016). Dasymetric mapping has been widely applied in different domains such as hydrologic analysis (Tarboton et al. 1998; Pellenq et al. 2003; Nguyen et al. 2012), social services (Hay et al. 2005; Mennis and Hultgren 2005; Chakir 2009; Mennis 2009; Gaughan et al. 2013; Goerlich and Cantarino 2013), public health (Maantay et al. 2008; Mennis 2015), public safety (Poulsen and Kennedy 2004; Mennis 2016), and disaster planning and response (Garb et al. 2007; Maantay and Maroko 2009).

The USGS county-level groundwater withdrawal data was disaggregated to individual wells using the demand type and a weighting scheme based on the casing diameter of the wells. In the absence of pumping data for individual wells, the assumption was that the smallest casing diameter for each well controls the potential withdrawal rate for a well. The Casing Diameter Coefficient (CDC) was created as the weighting factor as shown in Eq. 1:

$$CDC_i = \frac{D_i}{\sum_i^n D_{ip}} \tag{1}$$

where, $CDC_i$ is the casing diameter coefficient for individual well $i$, $D_i$ is the casing diameter class for individual well $i$, $D_{ip}$ is the sum of the casing diameter class of all wells in county $p$. A SAS® script was used to classify the CDC based on the casing diameter size information for each well in the well registration dataset. The relationship between casing size and its assigned CDC is provided in Table 2.

**Table 1** The sources, types, and purposes of datasets used in this study

| Dataset | Data type | Data source | Purpose |
|---|---|---|---|
| Groundwater wells | Spatial data | LA Dept. of Natural Resources (LDNR): Well Registration Database | Disaggregation |
| Surface water | Spatial data | US EPA/USGS: National Hydrography Dataset (NHD) Plus | Feasibility of Replacing Groundwater |
| HUC boundaries | Spatial data | US EPA/USGS: Watershed Boundary Dataset - Hydrologic Unit Code (HUC) | Re-aggregation |
| County boundaries | Spatial data | US Census Bureau: Tiger/Line | Re-aggregation |
| Water use | Tabular data | USGS/LDOTD: Water Use in Louisiana Report | Disaggregation |

Using the calculated CDC, the county-level withdrawal rates for each water use type were spatially allocated to each well location as shown in Eq. 2. Quality checks were performed to ensure that the sum of water withdrawal from the individual wells within a county equaled the original USGS withdrawal rate for that county.

$$W_i = W_p \chi CDC_i \tag{2}$$

where, $W_i$ is the groundwater withdrawal rate at well $i$ in units of cubic meters per day (CMD), $W_p$ is the withdrawal rate at county p where well $i$ is located, and $CDC_i$ is the casing diameter coefficient calculated for well $i$ using Eq. 1.

## 3.2 Allocation of Well-Level Groundwater Withdrawal Information to New Enumeration Units

Groundwater withdrawal information was allocated to both HUC-12 (vector) and 1 km$^2$ (raster) scales. The HUC-12 scale is the smallest unit of the WBD HUC watershed system (US EPA/USGS 2014). All input spatial data was geospatially registered for overlay analysis using the NAD83 horizontal datum, NAVD88 vertical datum, and UTM 15 North projection. For the vector data, methods of Spatial Join and Summary Statistics were used to aggregate point data of wells to HUC-12 polygons. The groundwater withdrawal rate for a HUC-12 polygon was calculated as shown in Eq. 3.

$$W_j = \sum_i^m W_i \tag{3}$$

where, $W_j$ is the groundwater withdrawal rate for the HUC-12 polygon $j$, $m$ is the total number of wells located in polygon $j$, $i$ is one of the wells located in the polygon $j$, and $W_i$ is the groundwater withdrawal rate at well $i$. In addition, the well-level groundwater withdrawal data (point vector file) was converted to a raster with a cell size of 1 km and map algebra was used to allocate groundwater withdrawal to each 1 km$^2$ grid.

## 3.3 Identification of Opportunities for Replacement of Groundwater Withdrawal with Surface Water

To demonstrate the usefulness of disaggregated groundwater withdrawal information for addressing problems of groundwater overdrafting, a surface water replacement feasibility test was conducted using two Parishes (Counties) in Southwest Louisiana - Jefferson Davis and Acadia. The water in both of these counties is mainly used for the irrigation of rice (Fig. 1).

**Table 2** Classification schema for casing diameter of well registration data

| Casing diameter size range | Casing diameter class | Agricultural wells in each class (%) |
| --- | --- | --- |
| 0–1 | 1 | 0.01 |
| 1–2 | 2 | 51.09 |
| 2–3 | 3 | 3.61 |
| 3–4 | 4 | 33.33 |
| 4–8 | 8 | 3.62 |
| 8–12 | 12 | 4.63 |
| 12–16 | 16 | 2.92 |
| > 16 | 17 | 0.77 |

For this demonstration the amount of available surface water was estimated based on several assumptions. Firstly, the authors assumed that the regions immediately adjacent to large streams represented the best opportunities to harvest surface water because the streams receive significant runoff during rainfall and have continuous flow that can be more easily and consistently relied upon. The distance to available surface water resources was also considered as a critical factor since the cost of infrastructure needed to use the water is less in closer proximity to streams. Finally, the authors assumed that in addition to direct use of surface water, water management strategies such as short-term storage and managed aquifer recharge (MAR) could be effective to offset disparities in seasonal distributions and demand. Hence, timing of water availability, as well as factors such as water quality, were ignored for this first-order test.

A simple buffer analysis was performed to determine as how much groundwater withdrawal for irrigation was taking place near streamlines of a certain size, including NHD stream levels 1, 2, and 3 in the research area from the streams mouth to the ocean to upstream identifying the main flow paths (USGS 2009). It was also verified that there was enough surface water available in these streams on an annual basis to effectively offset the groundwater withdrawal from the nearby wells. A 500 m buffer zone from streamlines was selected; based on an assumption that the water withdrawal represented by any well within this zone has the potential to be replaced by surface water use if the right management strategies were in place. Calculation of the availability of surface water in the buffer zone was accomplished by using the monthly average stream discharge values provided by the NHDPlus version 2 dataset (McKay et al. 2012) with an assumption that 50% of the base flow is unavailable for use because of necessary environmental flows (Eldardiry et al. 2016). The amount of available surface water in a given watershed served as a cap on how much groundwater withdrawal could be offset. However, in almost all cases there was more than enough surface water available to offset all the groundwater withdrawal for irrigation within a 500 m distance from the major streamlines.

## 4 Results and Discussion

The original county-level total groundwater withdrawal (considering in aggregate for all demand usages) and its disaggregation to individual wells can be seen in Fig. 2. The spatial disaggregation was weighted by the minimum casing diameter of each well as described in Section 3.1. The total groundwater withdrawal volume for each well is color-coded by standard deviation in units of CMD. High consumption wells can be observed clustering in the cropland areas as shown in Figs. 1 and S1. Well-level groundwater withdrawal information was spatially allocated to new enumeration units, including the HUC-12 (Fig. 3) and 1 km$^2$ cell raster scales (Fig. 4) using the methods described in Section 3.2.

The well-level disaggregated groundwater withdraw data for the irrigation category were used to perform an example analysis to see as how much groundwater withdrawal could hypothetically be replaced by surface water for this purpose. The method described in Section 3.3 was used to identify potential replacement of irrigation well withdrawals within a 500 m distance from major streamlines. This method assumed nothing about the water management strategies or costs associated with using surface water to replace groundwater but provided an idea of whether such strategies are feasible. The results of this feasibility analysis are shown in Fig. 5. There are 4151 irrigation wells in these two counties examined for this test and those wells represent total groundwater withdrawal of

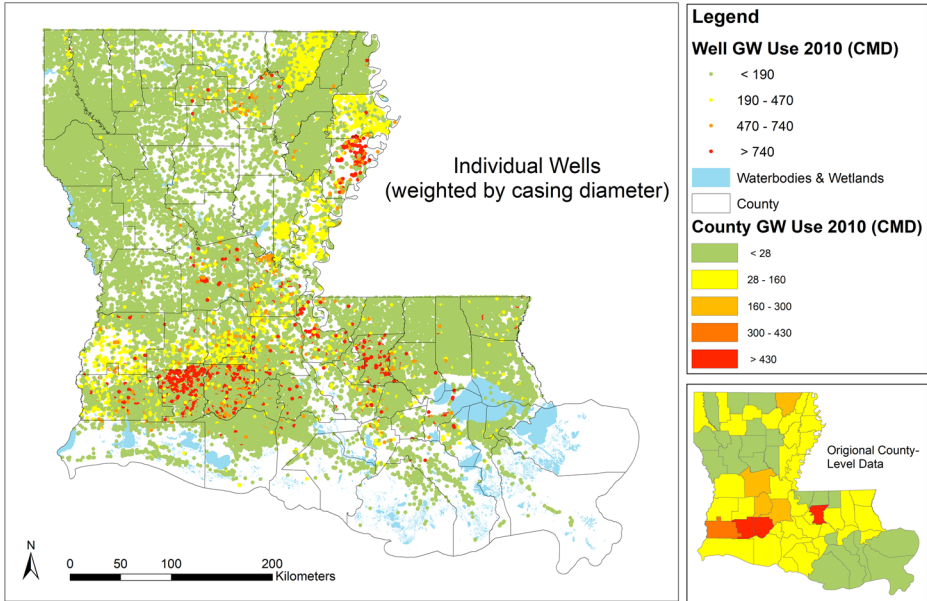## Groundwater usage disaggregation by wells



**Fig. 2** Groundwater total usage disaggregation to individual wells for the State of Louisiana in 2010

1,270,000 m³/day for irrigation. Of these irrigation wells, 997 were present within the 500 m buffer zone of major streamlines in the 2-county test site area. This represents 214,000 m³/day of groundwater withdrawal for irrigation which is 16.8% of the overall irrigation groundwater

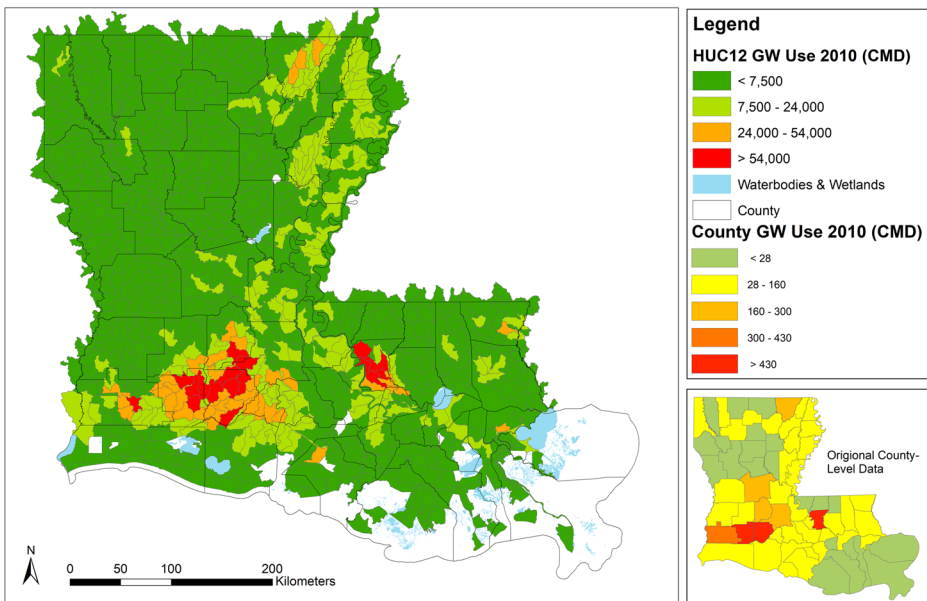## Groundwater usage disaggregation by HUC12 Unit



**Fig. 3** Groundwater total usage disaggregation to HUC-12 polygons for the State of Louisiana in 2010

# Groundwater usage disaggregation by 1 KM grid
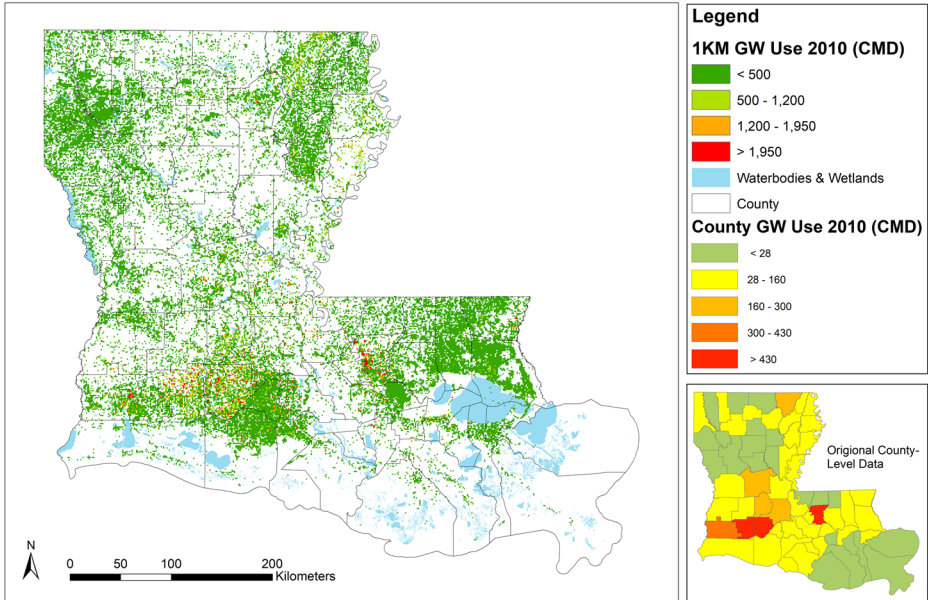


**Fig. 4** Groundwater total usage disaggregation to 1 km² cells for the State of Louisiana in 2010

withdrawal for the two counties. The amount of available surface water represented by the streams within a 500 m proximity to these wells was more than enough to offset the calculated groundwater withdrawal even considering the need for 50% (of annual average) environmental flow. Hence, water management strategies that utilize stream water could replace around 17% of the current annual groundwater withdrawal for irrigation demand using relatively simple and low-cost management strategies. Possible water quality issues might limit the applicability of surface water use or require larger economic investments in water treatment that were not considered in this example analysis. This analysis demonstrates the possibility that conjunctive management of water resources in wetter regions like the Southeast United States and can be a valuable tool for building sustainable groundwater resources. Reducing groundwater withdrawal by such practices may have significant impacts in coastal regions like Louisiana, where land subsidence and coastal salt-water intrusion are rising environmental concerns. In addition to direct use of surface water, strategies such as short-term storage and managed aquifer recharge (MAR) can be used effectively to manage disparities in seasonal distribution and demand.

## 5 Conclusion

Groundwater withdrawal data are often estimated and reported at county-level scales, but water managers and stakeholders need more granular level data for decision making. This problem necessitates the development of new strategies for downscaling county-level groundwater withdrawal information by leveraging other information such as commonly available well registration databases. In this study, a dasymetric mapping approach was developed to disaggregate groundwater withdrawal estimates at the county scale to the level of individual wells by weighting simple well characteristics (i.e., casing size) available through a state-wide well registration database. The
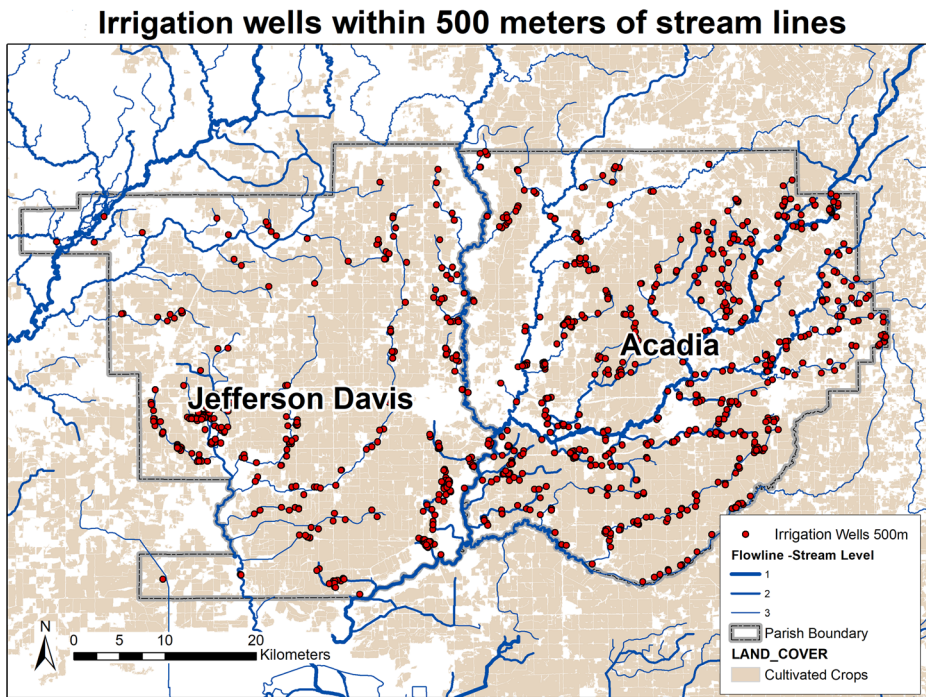
**Fig. 5** Irrigation wells within a 500 m distance from any streamlines in Parishes (Counties) of Jefferson Davis and Acadia in Louisiana

resulting framework was used to assess the first-order feasibility of water management strategies that use surface water to counter the over-use of groundwater in two counties in Louisiana. The results indicate that a substantial amount (450,000 m³/day, i.e. 17% of the total groundwater use) can be offset by surrounding surface water with modest (and likely low-cost) change in water management. This method for disaggregating groundwater demand data can be used as a starting point to perform similar analysis in other areas where surface water may be more effectively used to offset groundwater use. Future work in this area should additionally consider surface water quality and the economic feasibility of increased surface water use.

## Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no conflict of interest.

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