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Cost-Effectiveness of Sustainable Agricultural Water Policies: Source Switching versus Irrigation Buyout Auctions in Georgia's Lower Flint River Basin

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Abstract: In this paper, a new methodology for comparing the cost-effectiveness of sustainable agricultural water policies during times of drought is developed. The methodology explicitly accounts for regional economic impacts from policy implementation and uncertainty related to drought frequency. The methodology is applied to two policy options being considered by the state of Georgia in the lower Flint River basin: irrigation buyout auctions and source switching. The results demonstrate the following: (1) the importance of modeling uncertainty associated with both the frequency and timing of drought, and the hydrologic effects of source switching; (2) as the frequency of drought increases, the cost-effectiveness of irrigation buyout auctions decreases. Failure to incorporate the regional economic impacts of each policy significantly underestimates the costs of both, but more so for irrigation buyout auctions than source switching. The ability to proactively manage the uncertainty associated with source switching through research and the judicious site selection of new irrigation wells increases its cost-effectiveness.

Keywords: water policy; drought; irrigation; economics; cost-effectiveness

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1. Introduction

Water supplies were long considered abundant in Georgia, but a growing population, increased agricultural water use, and a changing environment and climate have highlighted the need for effective water management strategies, especially during drought. And droughts are occurring more frequently—drought conditions have been recorded in the state during 10 of the last 25 years [1]. Over those same 25 years, statewide, irrigated agriculture has accounted for 30–45% of total withdrawals [2]. Irrigated agriculture, however, accounts for well over 90% of withdrawals in the ecologically sensitive lower Flint River Basin (FRB). Most withdrawals within the lower FRB come either from the Floridan aquifer or surface water [3].

The FRB covers nearly 8500 square miles, with the Flint River stretching 349 miles from the southern edge of the Atlanta metropolitan area in the upper Piedmont region to the wetlands of the Coastal Plain in the southwest corner of Georgia [4]. South of Dooly County, in the lower FRB, the Flint River and many of its tributaries are in hydrologic connection with the Floridan aquifer and either receive water from the aquifer or lose water to it depending on the head difference between the streams and the aquifer [4]. That connectivity has implications for in-stream flows, especially during periods of heavy pumping, and even more acutely during drought. Interestingly, the Floridan is not the only aquifer lying below the lower FRB. This area of the Coastal Plain actually has a stratified groundwater system that also includes the Claiborne, Clayton, and Cretaceous aquifers [5] (see Figure 1).

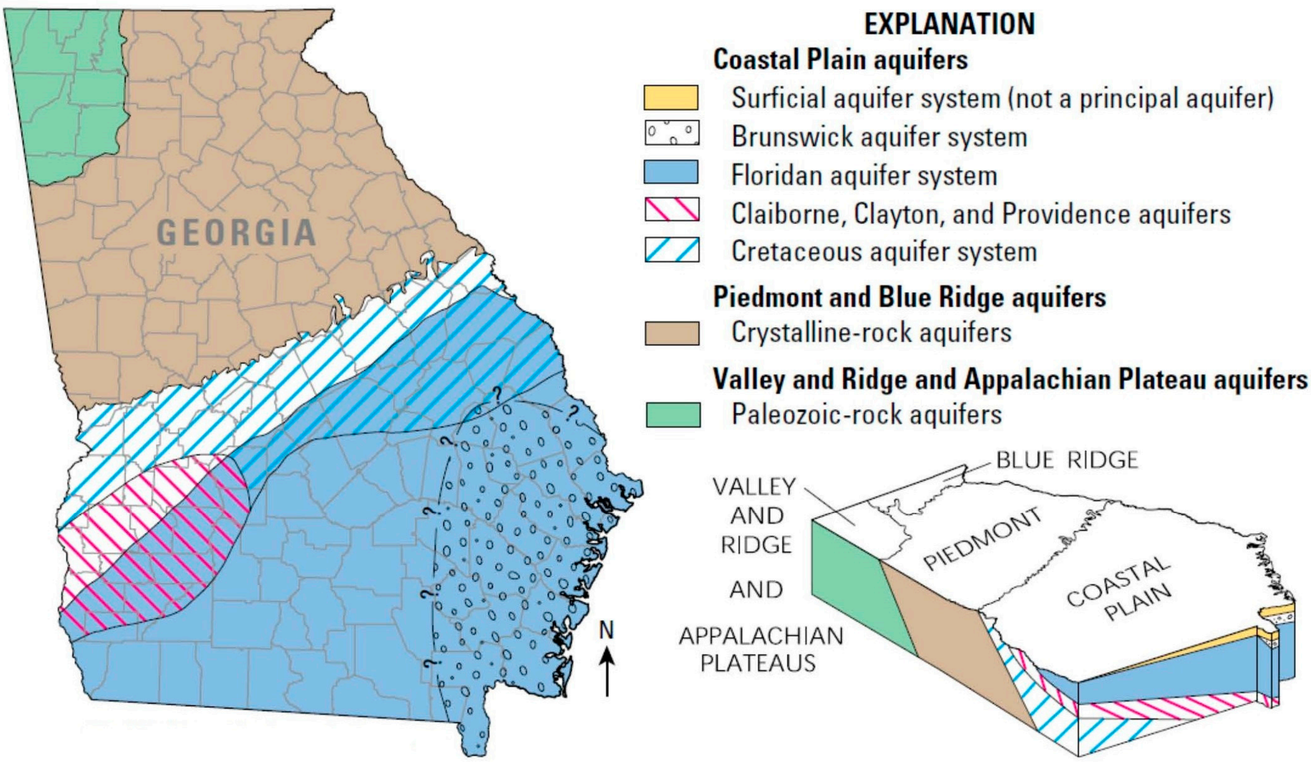


Figure 1. Areas of mMajor aAquifers in Georgia, modified from [5].

In addition to supporting irrigated agriculture, the Flint River and its tributaries in the lower FRB are also home to six freshwater mussel species protected by the U.S. Fish and Wildlife Service [6]. Under the rules of the Endangered Species Act, the state of Georgia is obligated to ensure minimum flows in streams that support these species. During the prolonged drought of 1998–2002, the state executed irrigation buyout auctions in which farmers with surface water withdrawal permits were paid not to irrigate their fields during the 2001 and 2002 growing seasons [4,7]. These auctions were executed under the auspices of the 2001 Flint River Drought Protection Act (FRDPA).

The FRDPA was amended in 2006 to allow groundwater permit holders to participate in future auctions. Mullen [7] examined the cost-effectiveness of different auction rules for protecting instream flows when both surface water and groundwater permit holders were allowed to participate. The results of that study emphasized the need to incorporate the hydrologic connectivity between surface and groundwater at the point of the groundwater withdrawal into the auction rules to maximize the cost-effectiveness of the auction. With the stratified nature of the aquifer system in the lower FRB, there is another policy option available beyond irrigation buyout auctions, namely, source switching.

Source switching is the act of changing the source of an irrigation withdrawal and usually refers to switching from a surface water withdrawal to a groundwater withdrawal. In the lower FRB, there is the possibility of switching surface water withdrawals to any of the four underlying aquifers and of switching from the Floridan—an aquifer with relatively high hydrologic connectivity to the streams—to one of the underlying aquifers that are hydrologically disconnected.

The primary objective of this study is to develop a general methodology to compare the cost-effectiveness of source switching to an irrigation buyout auction as a policy for managing stream flow and/or sustainable yields from an aquifer. Two source switching approaches are considered in this paper: "standard" source switching, in which the new water source is developed and the old source is no longer used, and "emergency" source switching, in which the new source is developed but the old source continues to be used and withdrawals are only switched to the new source during periods when conditions require it. The secondary objective is to apply that methodology to the lower Flint River Basin and determine the conditions under which each policy is more cost-effective. Finally, we discuss the suitability of the methodology for other systems.

Importantly, other studies have examined the cost-effectiveness of paying farmers not to irrigate [8–10], but none of them have considered the policy of source switching. Additionally, while those studies have alluded to regional economic impacts from converting irrigated land to dryland production or fallowing a field, they have not explicitly incorporated those impacts into their cost-effectiveness assessments. The methodology developed below does explicitly account for regional economic impacts and includes them in the policy analysis.

2. Materials and Methods

The methodology developed here entails specifying the cost components of the two policies under consideration over a given time horizon. Because some of those cost components are only realized under certain circumstances, the methodology actually calculates the expected present value of costs for each policy over time. Assuming the policies both generate the same benefits—in our empirical example, ensuring ecologically sufficient stream flow is the benefit—then comparing the expected present value of costs would also represent a comparison of their relative cost-effectiveness.

2.1. Expected Present Value of Policy Costs

For each policy (z) considered, the expected present value of costs over a time horizon of length T is shown in Equation (1):

$$E[PV_{z,T}] = \sum_{t=1}^{T} Pr(C_{z,t}) \times \frac{C_{z,t}}{(1+r)^{t-1}} \tag{1}$$

where $E[PV_{z,\,T}]$: expected present value of policy z from years 1 to T;

$C_{p,t}$: cost of policy z in year t;
$Pr(C_{z,t})$: probability of incurring cost of policy z in year t;
r: discount rate.

2.1.1. Costs of Irrigation Buyout Auctions

One of the critical differences between an irrigation buyout auction and source switching is that the auction adversely affects agricultural production either by fallowing the field or by producing under rainfed conditions during drought. As such, the costs of irrigation reduction auctions include both direct payments to farmers and regional economic impacts resulting from reduced agricultural production. In fact, as we will see in our empirical example, the regional economic impacts can dwarf the direct payments, so it is critical to account for them. Because the regional economic impacts can vary based on the location of the field, cost estimates for the irrigation reduction auctions are expressed here at the county level, as shown in Equation (2):

$$C_{Auction,c,t} = Pay_t + EI_{Auction,c,t} \tag{2}$$

where $C_{Auction,c,\,t}$: the cost of an auction in county c, year t;

Pay_t: direct auction payments in year t;
$EI_{Auction,c,t}$: regional economic impact of lost agricultural production in county c, year t.

While the auction payments are a distinct cost, the regional economic impact has several components. First, there is the reduction in the value of agricultural production, also known as the direct economic impact ($EI_{Ag\,Direct}$), resulting from fallowing or not irrigating a field during a drought. Next, the lost economic activity in the agricultural sector affects the purveyors of goods and services needed to (a) prepare the field; (b) sow, grow, protect, and harvest the crop; and (c) process, store, market, and distribute the harvested product. These impacts are referred to as the indirect economic impact ($EI_{Ag\ Indirect}$). However, the firms and employees that support agricultural production also purchase goods and services outside the agricultural sector (e.g., gasoline, electricity, accounting services, restaurants, etc.), so when the agricultural sector expands or contracts, there are also effects on the larger economy. These are referred to as the induced economic impact ($EI_{Ag\ Induced}$). Furthermore, the contraction (expansion) of economic activity in the agricultural sector subsequently leads to a reduction (increase) in tax revenues (ΔTR). Note that from a policy cost perspective, a reduction in tax revenues is a positive cost. The present value of these costs is accounted for in Equation (3):

$$EI_{Auction,c,t} = \frac{\left(EI_{AgDirect,c,t} + EI_{AgIndirect,c,t} + EI_{AgInduced,c,t} + \Delta TR_{Ag,c,t}\right)}{(1+r)^{t-1}} \tag{3}$$

where $EI_{Ag\ Direct,\ c,t}$: direct economic impact due to the change in the value of agricultural production in county c, year t;

$EI_{Ag\ Indirect,\ c,t}$: indirect economic impact due to the change in value of agricultural production in county c, year t;
$EI_{Ag\ Induced,\ c,t}$: induced economic impact due to the change in value of agricultural production in county c, year t;
$\Delta TR_{Ag,c,t}$: change in tax revenue due to the change in value of agricultural production in county c, year t;
r: discount rate.

It is important to remember that the costs of the auction are realized only if the auction is actually held. So, when we consider the cost of the auction as a policy, we need to consider the expected county-level cost of the auction, i.e., the sum of the yearly auction cost multiplied by the likelihood of the auction being held in any given year. An auction would only be held if a drought was severe enough to require the suspension of irrigation. Throughout the remainder of this article, when we refer to "drought", we are referring to a drought of that severity. The likelihood of an auction in year t, then, is equal to the probability of a drought in that year (PrD_t). The expected present value of county-level costs of the auction over T years is represented by Equation (4):

$$E[C_{Auction,c}] = \sum_{t=1}^{T} \frac{PrD_t \times (Pay_t + EI_{Auction,c,t})}{(1+r)^{t-1}} \tag{4}$$

2.1.2. Costs of Source Switching

In this study, source switching refers to switching either from a surface water source to a groundwater source, or from a more hydrologically connected groundwater source to a less hydrologically connected groundwater source. (It is also possible to switch from one surface source to another in order to preserve stream flow. The methodology can handle that situation as well, simply by accounting for the additional conveyance infrastructure costs in place of the well construction costs defined above.) In general, the closer the water table of an aquifer is to the surface, the greater the hydrologic connectivity of the system is likely to be. In other words, source switching often entails digging a well to switch from a surface water source or digging a deeper well to switch from one groundwater source to another.

Digging wells generates both fixed and variable costs. The fixed costs (*FC*) are the costs of drilling, lining, and capping the well. The variable costs (*VC*) of source switching are the extra energy costs required to pump water from a greater depth. Both *FC* and *VC* are functions of well depth, although the *FC* is a function of the actual depth of the well (*Depth*) while the *VC* is a function of the depth to the new water table compared to the old water table ($\Delta Depth$) and the amount of water pumped. For standard source switching (*SSS*), because the original source is no longer used, the extra pumping costs are realized every year. For emergency source switching (*ESS*), however, the extra pumping costs are only realized during drought. Therefore, when evaluating the variable costs of emergency source switching in a given year, we need to multiply them by the probability of a drought occurring that year. Furthermore, the water used for emergency source switching will be the water needed during times of drought. The water used for standard source switching will vary during wet years, typical years, and drought years.

There are additional costs that may or may not be incurred by owners of a deeper well. As a well gets deeper, there are more opportunities for breakages or malfunctions. More importantly, the deeper aquifers may have lower yields, slower recharge rates, and/or their hydrology may be less well understood. As such, wells in those aquifers could have a higher likelihood of running dry as withdrawals increase, especially if the wells are concentrated in a relatively small area. We refer to a well that is inoperable, either through over-drafting or due to breakage or malfunction, as "well failure." When well failure occurs, the value of agricultural production in that field is affected, leading to adverse regional economic impacts.

We can write the expected present value of the costs of standard source switching as in Equation (5), and the emergency source switching as in Equation (6).

$$E[C_{SSS,c,t}] = \sum_{t=1}^{T} \frac{FC_{c,t}(Depth_c) + VC_{SSS,c,t}(\Delta Depth_c, Water_{SSS,c,t}) + PrF \times EI_{F,c,t}}{(1+r)^{t-1}} \tag{5}$$

$$E[C_{ESS,c,t}] = \sum_{t=1}^{T} \frac{FC_{c,t}(Depth_c) + PrD_t \times VC_{ESS,c,t}(\Delta Depth_c, Water_{ESS,c,t}) + PrF \times EI_{F,c,t}}{(1+r)^{t-1}} \tag{6}$$

In Equations (5) and (6), $FC_{c,t}$ is defined as above, $Water_{SSS,c,t}$ and $Water_{ESS,c,t}$ are the amount of water applied in county c in year t, $VC_{SSS,c,t}$ and $VC_{ESS,c,t}$ are the extra pumping costs in county c in year t, PrF is the probability of well failure, and $EI_{F,c,t}$ is the regional economic impact of well failure in county c at time t. In Equation (6), PrD_t is the probability of drought in year t.

As the fixed and variable costs are increasing functions of well depth, the costs of standard and emergency source switching also strictly increase with well depth in a given county. It is important to note, however, that the costs of both types of source switching are also a function of the economic impact of well failure. The economic impact of well failure reflects both the productivity of the land in the county and the strength of the economic linkages between agricultural production and other sectors of the economy. As such, a shallower well in one county could have higher expected costs of source switching than a deeper well in another county.

Another important point is that the expected present value of standard and emergency source switching will only be equal if a drought occurs every year, i.e., $PrD_t = 1$. When the likelihood of drought is less than one, the variable costs of *ESS* will be less than the variable costs of *SSS*. Additionally, because *SSS* will draw water out of the new source each year and *ESS* will not, the probability of well failure from SSS is likely to be greater than that of *ESS*. As a result of these factors, the expected present value of standard source switching will be greater than that of emergency source switching.

2.2. Comparing Policy Costs

Cost-effectiveness is an economic measure used to compare alternative options for achieving a given objective [11,12]. Cost-effectiveness is, essentially, the cost of implementing the option divided by the units of desired outcome generated by the option. For example, a business firm can calculate the cost-effectiveness of a marketing strategy by dividing the cost of the strategy by the number of sales that strategy is likely to generate. The firm could do the same for alternative marketing strategies, and then, determine the most cost-effective among them.

In this study, we compare three water management policies that are assumed to have the same outcome—namely, the avoidance of stream-flow impacts associated with irrigation withdrawals during drought. The irrigation auction accomplishes this goal by prohibiting water withdrawals, whereas both standard and emergency source switching accomplish it by diverting irrigation withdrawals into aquifers that are not hydrologically connected to the streams. Because the policies have the same outcome, the denominator of their respective cost-effectiveness measure is the same and can, therefore, be ignored. The relative cost-effectiveness of the policies is determined entirely by the relative cost of each.

Equations (4)–(6) represent the expected present values of the costs of each policy. The challenge is to find the conditions under which one policy is unambiguously more cost-effective than the others. As noted above, the costs of emergency source switching are less than or equal to the costs of standard source switching, so we focus on *ESS* here. We begin by equating the present value of the expected costs of the policies, as shown in Equation (7).

$$\begin{aligned}\sum_{t=1}^{T} PrD_t \times \left(Pay_t + EI_{Auction,c,t}\right)/(1+r)^{t-1} \\ = \textstyle\sum_{t=1}^{T}\left[FC_{c,t}\left(Depth_c\right) + PrD_t \times VC_{ESSc,t}\left(\Delta Depth_c, Water_{ESSc,t}\right) + PrD_t \times PrF_t \times EI_{F,c,t}\right] \\ /(1+r)^{t-1}\end{aligned} \tag{7}$$

For a given probability of drought, Equation (7) can be rearranged to find the probability of well failure for which the present value of expected costs over a horizon of T years is the same. We refer to this as the threshold probability of well failure (*PrF**). If the actual probability of well failure is greater than *PrF**, then the auction has a lower present value of expected costs than emergency source switching—in other words, the auction is more cost-effective. Emergency source switching is more cost-effective when the actual probability of well failure is less than the threshold probability, *PrF**.

Alternatively, we can use Equation (7) to identify, for a given *PrF*, the probability of drought that equates the present value of expected costs for the two policies (*PrD**). If the likelihood of drought in any given year is greater than *PrD**, then source switching is more cost-effective, and vice versa.

We can also use Equation (7), with a slight modification, to investigate a different question. Imagine that the water manager (e.g., the state) decides to pay for source switching in Year 1. By doing this, the state has avoided the costs of an auction in the future. But the present value of the costs of the auction depends critically on when in the future the auction is held. If the auction is held in Year 1, the present value of the cost is much higher than if the auction is held in Year 20, due to discounting. We can calculate a unique *PrF** that equates the present value of expected costs of emergency source switching implemented in Year 1 to the present value of the costs of a single auction held in any given year of the *T*-year horizon.

Finally, Equation (7) can identify, for any *PrD* and *PrF* pair, the unique auction payment (*Pay**) that equates the two policies. Actual payment levels below *Pay** would make the auction more cost-effective; emergency source switching would be more cost-effective if auction participants required payments greater than *Pay**.

2.3. Comparing Policies in the Lower Flint River Basin

In this section, we demonstrate the application of the methodology in the context of Georgia's lower Flint River Basin. Eleven counties in the lower FRB have more than one aquifer beneath them: Baker, Calhoun, Decatur, Dougherty, Early, Lee, Miller, Mitchel, Randolph, Terrell, and Worth. The components of the expected present value of costs of an irrigation buyout auction and emergency source switching were estimated for each of these counties. The analysis was performed for a 150-acre field over a 25-year time horizon using 2020 as the baseline year. The study area is shown in Figure 2.

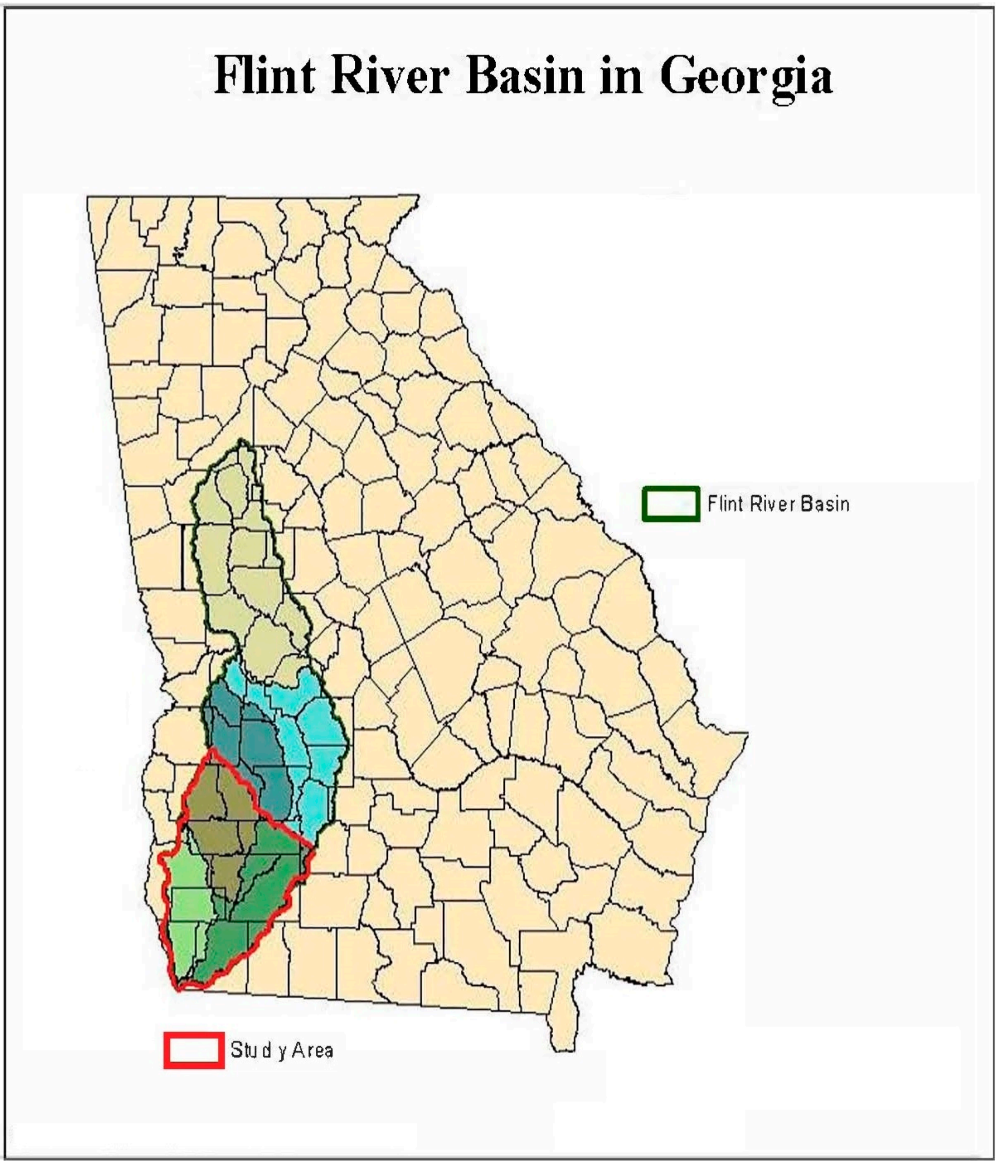


Figure 2. Study area [4].

2.3.1. Calculating Auction Costs

As shown in Equation (2), the auction has two major cost components: direct payments ($P_{auction,t}$) and regional economic impacts ($EI_{auction,c,t}$). The regional economic impacts can be further broken down into direct, indirect, induced, and tax revenue effects associated with lost agricultural production. These regional economic impacts are estimated using IMPLAN (version 6.9), an input–output model of the linkages across economic sectors. IMPLAN is widely used to study how changes in economic activity in one or more sectors ripple through an economy [13,14]. Country-specific IMPLAN models have been developed for use in 66 countries around the world [15]. These analyses can be conducted at varying spatial scales, including at the U.S. county level.

Direct Auction Payments

For our analysis, the direct auction payments (Pay_t) are straightforward to calculate. We simply inflate the average payment per acre from the 2002 auction (USD 135/acre) (2022 auction USD 483/acre) to 2020 dollars (USD 195/acre) using the U.S. Bureau of Labor Statistics' inflation calculator [16] and multiply by 150 acres. This means the auctioning agency, e.g., the state, would incur and a farmer would receive a USD 29,250 direct payment.

Alternatively, if a reference auction value were not available, the prevailing rental rate of irrigated land in the study area could be used. Even without that information, *Pay** could be calculated.

Regional Economic Impacts of Lost Agricultural Production

Our IMPLAN analysis was conducted at the county level using version 6.9. For each of the 11 counties in the lower FRB, the task at hand was to determine the direct economic impacts of taking a standard 150-acre irrigated field out of production ($EI_{Ag\ Direct,c,t}$).

Irrigated land in the lower FRB is dominated by four major row crops: cotton, peanuts, corn, and soybeans. To estimate the lost value of production from a standard 150-acre irrigated field in each county, we calculated the share of harvested irrigated acres for each of these crops in the county using Equation (8). We then multiplied each share by 150 acres, the crop price, and the yield, as in Equation (9), to obtain the direct economic impact associated with the crop. Adding up the crop-specific direct economic impacts (Equation (10)) gives the total direct economic impact of taking the field out of production.

$$S_{c,y} = \frac{HA_{c,y}}{\sum_Y HA_{c,y}} \tag{8}$$

$$EI_{Ag\ Direct,c,y,t} = S_{c,y} \times 150 \times P_{y,t} \times Q_{y,t} \tag{9}$$

$$EI_{Ag\ Direct,c,t} = \sum\nolimits_Y EI_{Ag\ Direct,c,y,t} \tag{10}$$

For the IMPLAN (version 6.9) analyses, the loss of the value of agricultural production must be specified. That specification includes identifying the impacted region (county), the impacted industries, and the change in the value of output for each industry (i.e., the direct impact). Each crop was assigned an industry: corn was assigned "grain farming"; cotton was assigned "cotton farming"; peanut was assigned "all other crop farming"; and soybean was assigned "oil seed farming." The direct, indirect, and induced impacts of taking a 150-acre irrigated field out of production in each county, as well as the state and local tax impacts, are reported in Table 1. Details regarding the county-level data used to calculate $EI_{Ag\ Direct,c,t}$ are available in the Supplemental Materials.

Table 1. Direct, indirect, and induced impacts and state and local tax revenue change (2020 USD) from taking a 150-acre irrigated field out of production.

County	Direct	Indirect	Induced	State and Local Tax	Total
Baker	USD (119,648)	USD (62,127)	USD (24,526)	USD (2629)	USD (208,931)
Calhoun	USD (136,718)	USD (42,699)	USD (23,140)	USD (2180)	USD (204,737)
Decatur	USD (118,184)	USD (49,077)	USD (28,469)	USD (2439)	USD (198,169)
Dougherty	USD (113,111)	USD (54,891)	USD (71,437)	USD (3176)	USD (242,616)
Early	USD (112,829)	USD (30,053)	USD (20,998)	USD (1955)	USD (165,835)
Lee	USD (105,655)	USD (66,128)	USD (39,732)	USD (3108)	USD (214,624)
Miller	USD (131,375)	USD (42,079)	USD (5287)	USD (889)	USD (179,630)
Mitchell	USD (110,705)	USD (44,765)	USD (32,197)	USD (2726)	USD (190,392)
Randolph	USD (121,118)	USD (57,221)	USD (9191)	USD (1384)	USD (188,913)
Terrell	USD (124,101)	USD (61,676)	USD (27,078)	USD (2407)	USD (215,261)
Worth	USD (108,130)	USD (32,299)	USD (11,633)	USD (1158)	USD (153,219)

There are a few critical points to understand about Table 1. First, the direct impacts of taking an irrigated field out of production vary across counties (from USD 105 k to USD 136 k) due to variation in the share of crops in each county and agricultural productivity. Second, due to differences in economic diversity across counties, the indirect and induced effects of lost agricultural production vary significantly. For example, Dougherty county is home to a university and many of the region's retail, restaurant, and entertainment establishments. As a result, the indirect and induced effects of lost agricultural production are more pronounced than in other counties. Third, counties with the largest direct effects do not necessarily have the largest total effects. And finally, the combined economic impacts of lost agricultural production from a 150-acre field are many times larger than the USD 29,250 auction payment to the farmer. All of these points emphasize the need for an economic impact analysis when evaluating the cost-effectiveness of alternative agricultural water management policies.

2.3.2. Calculating Emergency Source Switching Costs

As shown in Equation (6), the costs of emergency source switching are a function of the fixed costs (*FC*), variable costs (*VC*), likelihood of drought, likelihood of well failure, and regional economic impact of well failure. The regional economic impact of well failure is also estimated using IMPLAN (version 6.9).

Fixed Cost

The *FC* of source switching depends on the costs per foot of drilling, lining, and capping the well ($C_{Drilling,c,t}$) in county *c*, at year *t*, and the well depth ($Depth_c$), as shown in Equation (11). $Depth_c$ is the average depth (feet) to the aquifer in county *c*. The Claiborne aquifer that underlies the Upper Floridan in the study area is a viable alternative source of irrigation water. However, there is less information about its depth, thickness, water quality, and water-bearing characteristics [17].

$$FC_{c,t} = C_{Drilling,c,t} \times Depth_c \tag{11}$$

Variable Costs

The *VC* is a function of the depth to the water table and the amount of water pumped. To estimate the marginal cost of pumping water from different depths, we modify the engineering relationships among depth, pressure, and total dynamic head (*TDH*) in [18], to reflect the change in pumping costs due to source switching:

$$\Delta TDH_c = psi \times 2.31 + \Delta Depth_c \tag{12}$$

where *psi* is the pumping pressure and $\Delta Depth_c$ is the difference between the depth to the water table of the new source and the original source. If the original source is surface water, $\Delta Depth_c$ is simply the depth to the water table of the aquifer. The value of *psi* is taken from the literature [18].

Equation (13) calculates the amount of water pumped, in acre-feet, to irrigate a standard 150-acre field growing our four selected crops.

$$Water_{ESS,c,t} = \sum_{y=1}^{4} WD_{ESS,c,y,t} \times S_{c,y} \times 150 \tag{13}$$

In Equation (13), $WD_{ESS,c,\,y,t}$ is the water application rate (acre-feet/acre) for crop *y* in county *c* in year *t* during a drought year.

Equation (14) is used to derive the extra fuel consumed due to source switching, where Fuel usage is the number of units of fuel needed to lift one acre-foot of water by one foot (units/acre-foot/foot). Fuel usage depends on the type of fuel used.

$$\Delta Total\ fuel\ consumed_{ESS,c,t} = Fuel\ usage \times \Delta TDH_c \times Water_{ESS,c,t} \tag{14}$$

$$VC_{ESS,c,t} = \Delta Total\ fuel\ consumed_{ESSc,t} \times P_{Electricity,t} \tag{15}$$

The *VC* of emergency source switching is the extra pumping cost, which equals the change in total fuel consumed times the fuel price. This estimate of pumping cost is imperfect, as it does not contain possible changes in the cost of distribution once the water has been raised to surface level. Here, we assume those distribution costs to be the same regardless of the water source.

For each county, the fixed costs of a new well tapping into the Claiborne aquifer are reported in Table 2. Also reported in Table 2 are the extra pumping costs during a drought year from a well in the Claiborne aquifer when the original source was either surface water or the Floridian aquifer. The extra pumping costs from an average year are also included in Table 2 as a point of comparison. Details regarding the county-level data used to calculate the fixed and variable costs are available in the Supplemental Materials.

Table 2. Fixed and variable costs of installing a new well into the Claiborne aquifer, by county (2020 USD).

County	Fixed Costs (Drilling)	Annual Variable Costs (Extra Pumping)			
		Switch Surface to Claiborne		Switch Floridan to Claiborne	
		Median Year	Drought Year	Median Year	Drought Year
Baker	USD 100,151	USD 4957	USD 7850	USD 3190	USD 5052
Calhoun	USD 86,660	USD 4063	USD 6707	USD 2425	USD 4003
Decatur	USD 191,184	USD 6492	USD 12,520	USD 4873	USD 9399
Dougherty	USD 149,465	USD 5928	USD 9852	USD 4569	USD 7594
Early	USD 73,002	USD 2641	USD 4731	USD 1303	USD 2334
Lee	USD 69,768	USD 2646	USD 4632	USD 1183	USD 2070
Miller	USD 102,432	USD 4229	USD 7163	USD 2682	USD 4544
Mitchell	USD 160,492	USD 7138	USD 11,935	USD 3495	USD 5843
Randolph	USD 23,717	USD 726	USD 1658	USD 263	USD 600
Terrell	USD 59,985	USD 2595	USD 4489	USD 1003	USD 1734
Worth	USD 124,315	USD 3465	USD 6944	USD 1192	USD 2388

Economic Impacts of Well Failure

When a well failure occurs, farmers are unable to irrigate. Of course, the direct economic impacts of well failure depend on when the well fails. If the well fails prior to planting, then the direct economic impacts are the same as the irrigation buyout auction. If the well fails after planting, however, the impacts would be reduced as the farmer has already spent money to purchase inputs. In this study, we only consider well failure that occurs before planting. As such, the inability to irrigate a field due to well failure leads to the same direct, indirect, and induced impacts as the irrigation reduction auction. The regional economic impacts of well failure used in our analysis, then, are equal to the regional economic effects of lost agricultural production presented in Table 1.

3. Results: Relative Cost-Effectiveness under Different Scenarios

The costs of each policy option depend on the timing of the policy implementation and the likelihood of unknown events occurring. In this section, we investigate the relative cost-effectiveness of emergency source switching versus an irrigation buyout auction under a variety of scenarios. In these scenarios, a drought refers to an event in the study area severe enough that either emergency source switching or a buyout auction must be executed to preserve stream flows for federally protected, endangered aquatic species.

3.1. Imminent Drought in Current Year, No Well Failure

To begin, we consider a situation where a drought is imminent and policy makers need to decide whether to hold an auction or pay the fixed and variable costs of emergency source switching. In the simplest case, we compare, for the current year alone, estimates of the cost of an irrigation buyout auction to the cost of ESS without well failure. This is carried out through Equation (7) with $T = 1$, $P_{Auction}$ = USD 29,250, the economic impact estimates in Table 1, the fixed cost and drought variable cost estimates in Table 2, and setting $Pr(Drought_1) = 1$ and $PrF = 0$. The results for each county are shown in Table 3.

Table 3. Policy costs, by county, for a single year, with *Pr*(*Drought*) = 1 and *PrF* = 0.

County	Auction Payments	Total Auction Cost	Total *ESS* Cost Surface to Claiborne	Total *ESS* Cost Floridan to Claiborne
Baker	USD 29,250	USD 238,181	USD 108,001	USD 105,203
Calhoun	USD 29,250	USD 233,987	USD 93,367	USD 90,663
Decatur	USD 29,250	USD 227,419	USD 203,804	USD 200,683
Dougherty	USD 29,250	USD 271,866	USD 159,317	USD 157,059
Early	USD 29,250	USD 195,085	USD 77,733	USD 75,336
Lee	USD 29,250	USD 243,874	USD 74,400	USD 71,839
Miller	USD 29,250	USD 208,880	USD 109,595	USD 106,976
Mitchell	USD 29,250	USD 219,642	USD 172,427	USD 166,335
Randolph	USD 29,250	USD 218,163	USD 25,374	USD 24,317
Terrell	USD 29,250	USD 244,511	USD 64,474	USD 61,719
Worth	USD 29,250	USD 182,469	USD 131,259	USD 126,703

In this scenario, in every county except Randolph, the auction payments made to farmers are much lower than the costs of emergency source switching, regardless of the original source. When the economic impacts of taking an irrigated field out of production are included, however, the total costs of the auction far exceed those of ESS. In other words, if the probability of well failure is zero and a drought occurs in the year the new well is dug, source switching is more cost-effective in every county when the full economic costs of the auction are considered. If policy makers focus only on the auction payments, they would erroneously conclude that the auction is more cost-effective. This reinforces the imperative of including a regional economic impact analysis when comparing costs across different water management policies.

Another point of interest in Table 3 is the fact that the cost differential between an auction and emergency source switching varies by county. Furthermore, due to the variation in both the total auction costs and emergency source switching costs, the county with the lowest cost differential is not necessarily the one with the lowest auction cost.

The next question is as follows: how high does the probability of well failure need to be for the auction to become the cost-effective policy option?

3.2. One Drought, Known Drought Year, Non-Zero Likelihood of Well Failure

When the probability of well failure is non-zero, the expected value of the costs of emergency source switching in a given year increases by the product of the regional economic impacts of lost agricultural production and the probability of well failure in that year. We can calculate county c's threshold probability of well failure (PrF_c*), the likelihood of well failure above which the auction is more cost-effective, by rearranging Equation (7), as shown in Equations (16) and (17), below.

$$PrF_c^* = \frac{\frac{(Pay + EI_{Auction,c}) - VC_{ESS,c})}{(1+r)^{t^*-1}} - FC_c}{EI_{Failure,c} \Big/ (1+r)^{t^*-1}} \quad (16)$$

$$PrF_c^* = 1 + \frac{(Pay - VC_{ESS,c})}{EI_{Fail,c}} - \frac{FC_c}{EI_{Fail,c} \Big/ (1+r)^{t^*-1}} \quad (17)$$

In this section, we examine the threshold probability of well failure for a specific scenario, namely, when a well is dug for a source in Year 1 and there is only one drought over a 25-year time horizon, and it occurs in year t*. Looking at Equation (16), we are solving for PrF_c* by setting PrD_t equal to 1 in the drought year and equal to zero in all other years. The numerator of Equation (16) comprises the expected present value of the auction costs minus the expected present value of the fixed and variable costs of emergency source switching. The fixed costs of ESS occur only in year 1 when the well is dug. The denominator of Equation (16) is the present value of the regional economic impacts of well failure in year t^*. Figure 3 plots each county's PrF_c* against the year of the drought. Looking at Year 1, we see some variation in PrF_c* across counties, with a high of 1 for Randolph and a low of 0.12 for Decatur. This means that source switching in Year 1 would be more cost-effective than an auction in Year 1 in Randolph county no matter the chance of the new well failing in the drought year. In Decatur county, on the other hand, the Year 1 auction is more cost-effective when the chance of well failure in the auction year is 12% or higher.

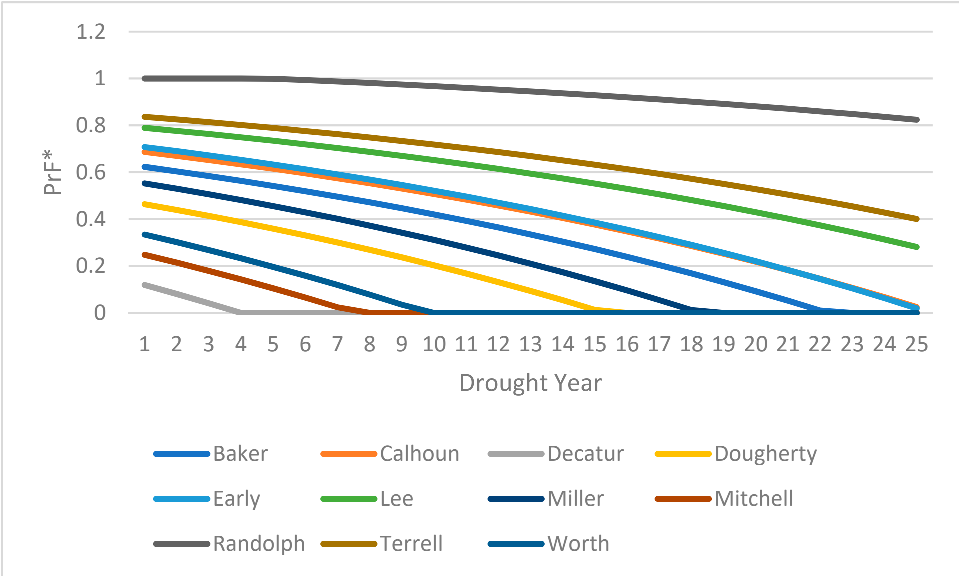


Figure 3. Probability of well failure above which an auction is cost-effective, by drought-year and county, when only 1 drought occurs in 25 years.

For all counties, as the year of the auction moves further into the future, the first two components of Equation (17) are unaffected while the denominator of the fixed cost component falls. As a result, PrF_c* also decreases when the auction occurs further in the future. Once the threshold probability of well failure goes to zero, the auction is always more cost-effective than source switching. This occurs in Year 4 for Decatur county, Year 8 for Mitchell county, Year 10 for Worth county, etc. It never occurs in Randolph, Terrell, and Lee counties over a 25-year time horizon.

If there is more than one drought during the 25-year time horizon, the expected present value of auction costs would increase. The timing of the additional drought(s) would dictate the change in the expected present value of auction costs as well as the threshold probability of well failure. When looking over a 25-year time horizon, however, we do not know when drought(s) will occur. We examine this in the next section.

3.3. Uncertain Drought Timing and Likelihood, Non-Zero Probability of Well Failure

In this scenario, the timing of drought(s) over a 25-year time horizon is unknown, and the probability of well failure is assumed to be non-zero. Here, policy makers are faced with the decision of whether to invest in source switching now (Year 1) to avoid an auction(s) in an unknown year(s) in the future (in our analysis, we assume the probability of a drought is the same every year). This is the situation policy makers in the lower Flint River Basin currently face each year.

To gain insight into this issue, we vary the probability of drought and use Equation (7) to find the associated threshold probability of well failure for each county. Figure 4 plots PrF* over a range of drought probability from 0.01 to 0.40. The first thing to notice in Figure 4 is that when the probability of drought is one in one hundred, the threshold probability of well failure is zero in every county except Randolph. This means that, in the other ten counties, if we only expect one drought per century, it is more cost-effective to hold an auction to address low stream flows; in Randolph county, emergency source switching would still be more cost-effective than an auction up to the point where the likelihood of well failure is over 37%. The second thing to notice in Figure 4 is how steeply *PrF** rises in every county as the likelihood of drought increases.

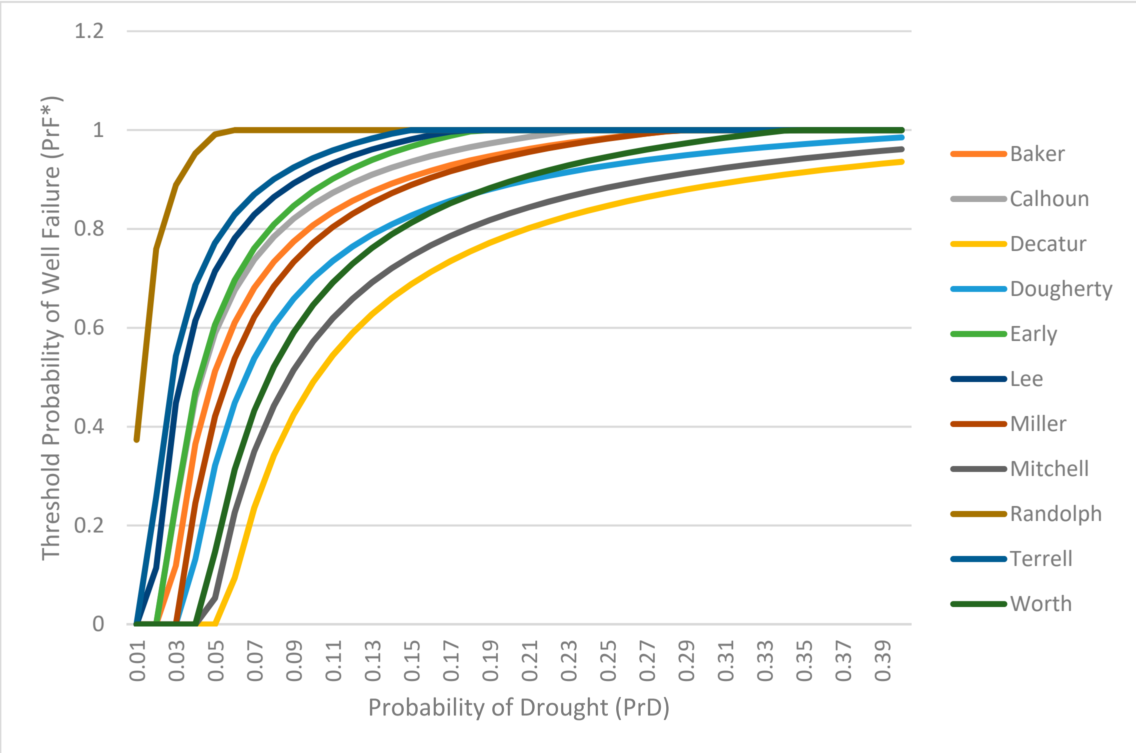


Figure 4. Threshold probability of well failure as a function of probability of drought. Note: If the actual likelihood of well failure is greater than *PrF**, then an irrigation buyout auction is more cost-effective than emergency source switching, and vice versa.

To put the probability of drought into perspective, there were two auctions in the lower FRB from 2001 to 2020, i.e., a 10% probability of an auction. However, as mentioned in the introduction, over the last 25 years, drought conditions occurred in 10 years (40% of the time) in the lower FRB, although no funds were budgeted for an irrigation buyout auction in eight of those years. If the drought probability were 10%, emergency source switching would always be more cost-effective in Randolph county, regardless of the likelihood of well failure; even in Decatur county, the county with the highest source switching costs, the likelihood of well failure would have to exceed 49% for the auction to be more cost-effective.

As mentioned in the introduction, over the last 25 years, drought conditions occurred in 10 years (40% of the time) in the lower FRB, although no funds were budgeted for an irrigation buyout auction in eight of those years. At that frequency of drought, for the auction to be more cost-effective, the likelihood of well failure would need be to over 93% in every county. A well failing 93% of the time would only happen if the well construction was exceptionally poor, or if the water table of the aquifer was extremely sensitive to irrigation pumping. However remote it is, the latter is more likely to occur as more withdrawals are switched from the original source to the new source.

Identifying the Threshold Value of Economic Impacts

In this section, rather than relying on the IMPLAN (version 6.9) results, we allow the regional economic impacts of taking a field out of production to vary. By doing so, we can identify, for a given *PrF* and *PrD* pair, how high the regional economic impacts would have to be for source switching to become more cost-effective than an auction. We use Equation (7) to solve for the threshold regional economic impacts (*EI**). Table 4 presents the results for two scenarios: (1) when the probability of drought is 0.1 and the probability of well failure is 0.01, and (2) when the probability of drought is 0.1 and the probability of well failure is 0.25. Also included for reference are the regional economic damages estimated by IMPLAN (version 6.9). The results in Table 4 show that emergency source switching would be more cost-effective than an irrigation buyout auction even if the regional economic impacts were significantly lower than the IMPLAN (version 6.9) estimates. This is the case even when there is a one-in-four chance the new well will fail each year.

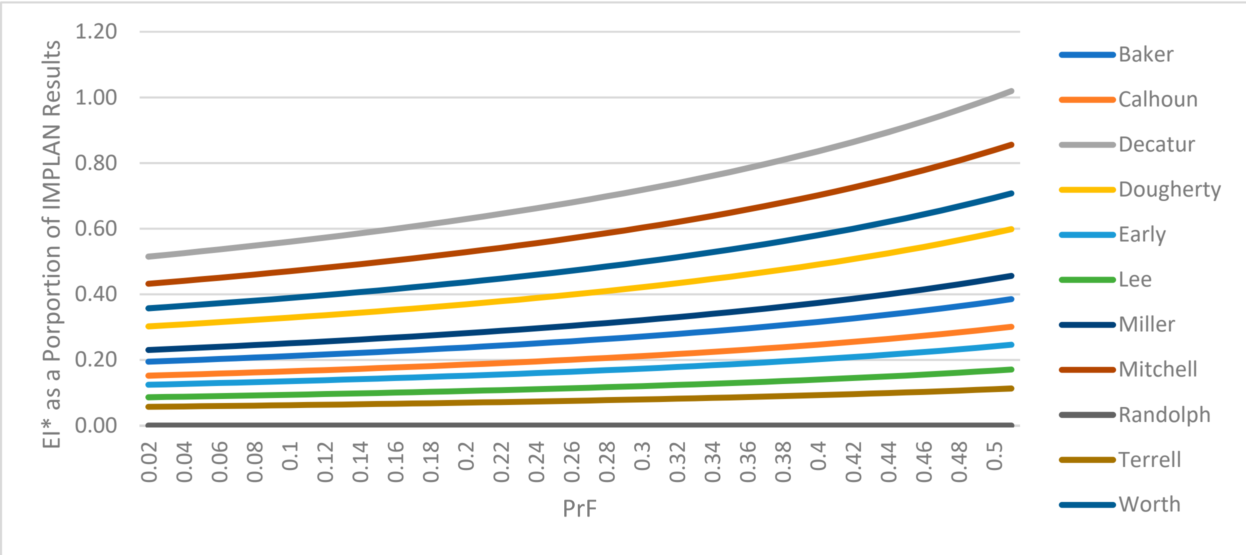
Table 4. Threshold level of regional economic impacts (*EI**) from taking a 150-acre irrigated field out of production, given drought and well failure probabilities.

County	*EI* from IMPLAN [a]	*EI** [b]	
		***PrD* = 0.1, *PrF* = 0.01**	***PrD* = 0.1, *PrF* = 0.25**
Baker	USD 208,931	USD 40,649	USD 53,657
Calhoun	USD 204,737	USD 31,107	USD 41,062
Decatur	USD 198,169	USD 102,026	USD 134,674
Dougherty	USD 242,616	USD 73,331	USD 96,797
Early	USD 165,835	USD 20,620	USD 27,218
Lee	USD 214,624	USD 18,509	USD 24,432
Miller	USD 179,630	USD 41,374	USD 54,613
Mitchell	USD 190,392	USD 82,291	USD 108,624
Randolph	USD 188,913	USD 0	USD 0
Terrell	USD 215,261	USD 12,282.24	USD 16,212.56
Worth	USD 153,219	USD 54,757.60	USD 72,280.03

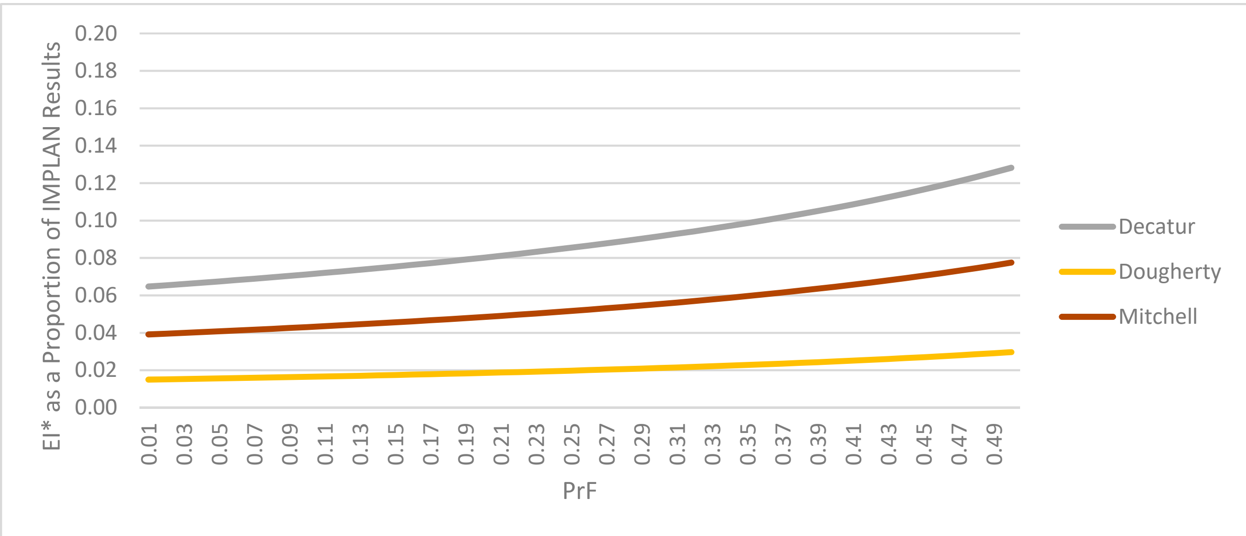
Notes: [a]: Values in this column are the total of the direct, indirect, and induced economic impacts and the change in tax revenue reported in Table 1, i.e., the total regional economic impact. [b]: *EI** is the amount of total regional economic impact above which emergency source switching is more cost-effective than an irrigation buyout auction, given the probability of drought and the probability of well failure.

Figure 5 plots *EI** as a proportion of the IMPLAN (version 6.9) estimates across a range of well failure probabilities. In panel (a), the probability of drought is set to 0.1 (the proportion of times an auction was held between 2001 and 2020); in panel (b), $PrD = 0.4$ (the proportion of times a drought occurred in the study area between 2001 and 2020). When the likelihood of drought is 0.4, emergency source switching is strictly more cost-effective than an irrigation buyout auction in eight of the eleven counties in the study area. In the three other counties (Decatur, Mitchell, and Dougherty) emergency source switching would be the cost-effective policy when the actual regional economic impacts are a fraction of the IMPLAN (version 6.9) estimates.

In 2006, when the Georgia Environmental Protection Division evaluated the costs of the 2001 and 2002 irrigation buyout auctions, the costs of the auction focused exclusively on the payments to farmers [4]. This is analogous to setting the regional economic impacts to zero. Our final scenario examines this situation. Here, we set the regional economic impacts to zero and calculate the threshold probability of drought ($PrD^{*}_{EI=0}$) above which emergency source switching is more cost-effective. The results of doing so are presented in Table 5. The value of $PrD^{*}_{EI=0}$ ranges from a low of 0.05 in Randolph county to a high of 0.7 in Decatur county. In other words, if the regional economic impacts are ignored, in Decatur county, emergency source switching would only appear to be an attractive alternative to an irrigation buyout if a drought was expected to occur in 7 out every 10 years, or more frequently. From Figure 5b, we can see that the regional economic impacts do not have to be very high to make emergency source switching more cost-effective when the likelihood of drought is 0.4. This is true even in Decatur county.



(**a**)



(**b**)

Figure 5. Threshold level of regional economic impacts (*EI**) as a function of probability of well failure (*PrF*). (**a**) Probability of drought = 0.1. (**b**) Probability of drought = 0.4.

Table 5. Threshold probability of drought when regional economic impacts are zero (*EI* = USD 0).

County	$PrD^{*}_{EI=0}$
Baker	0.29
Calhoun	0.24
Decatur	0.70
Dougherty	0.47
Early	0.18
Lee	0.17
Miller	0.29
Mitchell	0.57
Randolph	0.05
Terrell	0.15
Worth	0.34

4. Discussion

From an ecological perspective, the lower Flint River Basin in southwest Georgia supports a diverse array of freshwater aquatic species, including several mussel populations protected by the Endangered Species Act. From an economic perspective, agricultural irrigation withdrawals from the region's surface water and groundwater resources are critical to its economic vitality. To ensure the long-term ecological and economic sustainability of the region, water policy options need to be evaluated and deployed with respect to their cost-effectiveness.

The hydrologic connectivity between surface water and the Floridan aquifer in the lower FRB is well documented [19]. Over the past 20 years, the state of Georgia has considered paying to switch surface water and Floridan aquifer withdrawals to deeper aquifers with less hydrologic connectivity to the streams. The state has also funded irrigation buyout auctions to actively protect instream flows during times of drought. When funds are limited for water management, it is critical to select a policy that can achieve sustainability goals—both economic and ecological—in a cost-effective manner. The methodology developed in this study identifies the essential components and key parameters for evaluating the cost-effectiveness of these two policies. These include accounting for the full range of regional economic impacts, including the indirect and induced effects of lost agricultural production, and understanding the capacity and reliability of the new source to accommodate withdrawals.

A state agency with a limited budget can use the information in Figure 4 to prioritize source switching investments by county. That same information can also prioritize investments in research related to the hydrologic features of the new source. For example, because Randolph county has the highest threshold probability of well failure, it should be the first county to focus funds on source switching. Source switching should be considered in the other counties in descending order of their PrF_c*. On the other hand, because Decatur county has the lowest PrF_c*, it is especially important to understand the hydrology of the Claiborne aquifer in that area, so research funds should be directed there first.

There are two sources of uncertainty related to the cost-effectiveness of these water management policies: the likelihood of drought, and likelihood of well failure. Given recent climate trends and the anticipated acceleration of those trends in the future, the probability of drought is likely to increase, thereby increasing the expected present value of irrigation buyout auctions. Importantly, the probability of drought is something that cannot be managed at the state level. There is, however, some ability to manage the probability of well failure through a better understanding of the spatial variability of maximum sustainable yields from the Claiborne aquifer. That information is essential to the judicious selection of where and how much to invest in source switching to protect the economic and ecological health of the lower Flint River Basin.

The cost-effectiveness of irrigation management policies to address water shortages has been investigated in multiple settings. Ding and Peterson [8] compared the relative cost-effectiveness of subsidizing improved irrigation technology to paying farmers for not irrigating. They found that crop prices and aquifer water levels were important parameters in determining the relative cost-effectiveness of those policies. The regional economic impacts of converting irrigated fields to dryland production, however, were not evaluated.

Similarly, Luitel et al. [9] modeled irrigation water restrictions coupled with irrigation water trading in the Ogallala aquifer in Texas. In that paper, the authors state that both the restrictions and water trading would have definite regional economic impacts, but those impacts are not assessed in their analysis.

The impacts of irrigation efficiency gains have been examined in multiple countries. Scott et al. found that gains at the intensive margin (water use per hectare) would likely be negated through an expansion of the extensive margin (irrigated hectare) in Chile, the US, and Spain [20]. The implications for water scarcity are discussed but the regional economic impacts are not estimated.

Mulligan et al. parameterize an optimal control model to compare a water quota to a water tax in the Republican River basin in the US [21]. That model was optimized with respect to the agents' profits, not regional economic performance. The linkages across economic sectors were not incorporated into the impacts of groundwater policy in the optimization model.

In China, Pang et al. evaluated the costs of achieving stream-flow targets through irrigation restrictions by compensating farmers for their lost revenues [22], although the regional economic impacts of those lost revenues were not taken into consideration. Our results suggest that this is a mistake that would likely significantly underestimate the true costs of the policy. Also in China, Zou et al. compare the cost-effectiveness of alternative irrigation technologies for mitigating climate change's impacts on agriculture [23].

In Spain, Ballesteros-Olza et al. [24] investigated the effects of using reclaimed water as a substitute for groundwater; Perni and Martinez-Paz used stakeholder surveys to estimate the cost-effectiveness of policies to restore waterways [25]; and Blanco-Gutierrez et al. [10] examined the cost-effectiveness of irrigation water price structures and irrigation water markets. None of those studies included the regional economic impacts of these policies in their analyses. Blanco-Gutierrez et al. do, however, conclude that "Additional studies on net social costs are highly recommended" [10].

Aulong, Bouzit, and Dorfliger also stress the importance of including social costs in their case studies of river basin management in Lebanon and Jordan [26]. In particular, they acknowledge the need to account for environmental costs and resource scarcity costs, but do not attempt to trace the sectoral linkages and resulting economic impacts of water management policy through their study regions.

The key features of the methodology developed in this paper are that it explicitly accounts for (1) the regional economic impacts of irrigation water management policies and (2) the uncertainty of drought frequency. Furthermore, the methodology is applicable to other locations weighing multiple policy options to address water scarcity. The state of California, for example, is considering expanding their forced groundwater recharge program in which surface water is injected into the ground as a storage mechanism. This is analogous to source switching, with the injection costs taking the place of drilling costs. It is an expensive proposition at face value. There are, however, likely to be significant regional economic impacts of fallowing irrigated land when surface water is unavailable. The lesson from our analysis is that considering the regional economic impacts is critical to conducting an accurate assessment of the cost-effectiveness of such policies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15193381/s1, Table S1: 2020 Harvested irrigated acres by crop and county; Table S2: 2020 Share of irrigated acreage, by crop and county; Table S3: 2020 Crop price and yield, by county; Table S4: Well depth data; Table S5: Water application rates (acre-feet/acre) by county and crop; Equations (S1)–(S3): Calculating $EI_{\text{Ag Direct, c, t}}$; Equation (S4): Calculating county-level fixed costs of source switching; Equations (S5)–(S8): Calculating county-level extra pumping costs of source switching.

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