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Value of irrigation water usage in South Florida agriculture

Yuki Takatsuka [a], Martijn R. Niekus [b], Julie Harrington [b,*], Shuang Feng [b], David Watkins [c], Ali Mirchi [d], Huong Nguyen [e], Michael C. Sukop [f]

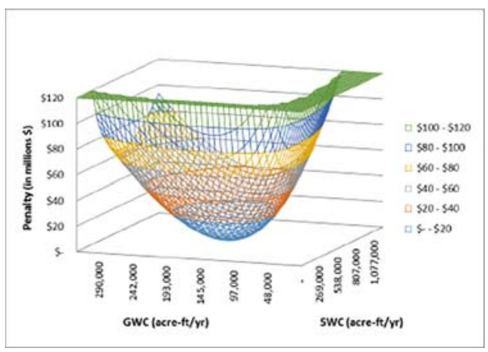
[a] Department of Business Administration and Accounting, Flagler College, Tallahassee, FL, USA
[b] Center for Economic Forecasting and Analysis, Florida State University, Tallahassee, FL, USA
[c] Department of Civil and Environmental Engineering, Michigan Technological University, Houghton, MI, USA
[d] Department of Civil Engineering and Center for Environmental Resource Management, University of Texas at El Paso, El Paso, TX, USA
[e] Department of Economics, University of Miami, Coral Gables, FL, USA
[f] Department of Earth and Environment, Florida International University, Miami, FL, USA

HIGHLIGHTS

- Overall results show economic losses due to irrigation water in S. Fl. agriculture.
- Irrigation water use penalties differ by crop and sub regions in South Florida.
- Given ground water usage changes, the UEC area would experience higher penalties.
- The KB area experiences a significant penalty if surface water irrigation changes.

GRAPHICAL ABSTRACT

Figure: penalty function at various levels of Ground Water Consumption (GWC) and Surface Water Consumption (SWC) inputs per acre-ft/yr in the South Florida Lower East Coast (LEC) region in 2010.



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ABSTRACT

This study estimates economic loss from South Florida croplands when usage of agricultural irrigation water is altered. In South Florida, 78% of the total value of farm products sold is comprised of cropland products. The majority of Florida citrus and sugarcane are produced in the area, and agricultural irrigation was the largest sector of water use in 2010, followed by public water supply. The Florida Department of Environmental Protection announced in December 2012 that traditional sources of fresh groundwater will have difficulty meeting all of the additional demands by 2030. A shortage of water will impose significant damage to the rural and agriculture economy in Florida, which may lead to higher prices and costs for consumers to purchase citrus or other Florida agriculture products. This paper presents a methodology for estimating economic loss when usage of irrigation water is altered, and examines economic values of irrigation water use for South Florida cropland. The efficient allocation of irrigation water across South Florida cropland is also investigated in order to reduce economic cost to the South Florida agricultural sector.

* Corresponding author at: Center for Economic Forecasting and Analysis, Florida State University, FSU Research Complex, 3200 Commonwealth Blvd., Tallahassee, FL 32303, USA.
E-mail address: jharrington@cefa.fsu.edu (J. Harrington).

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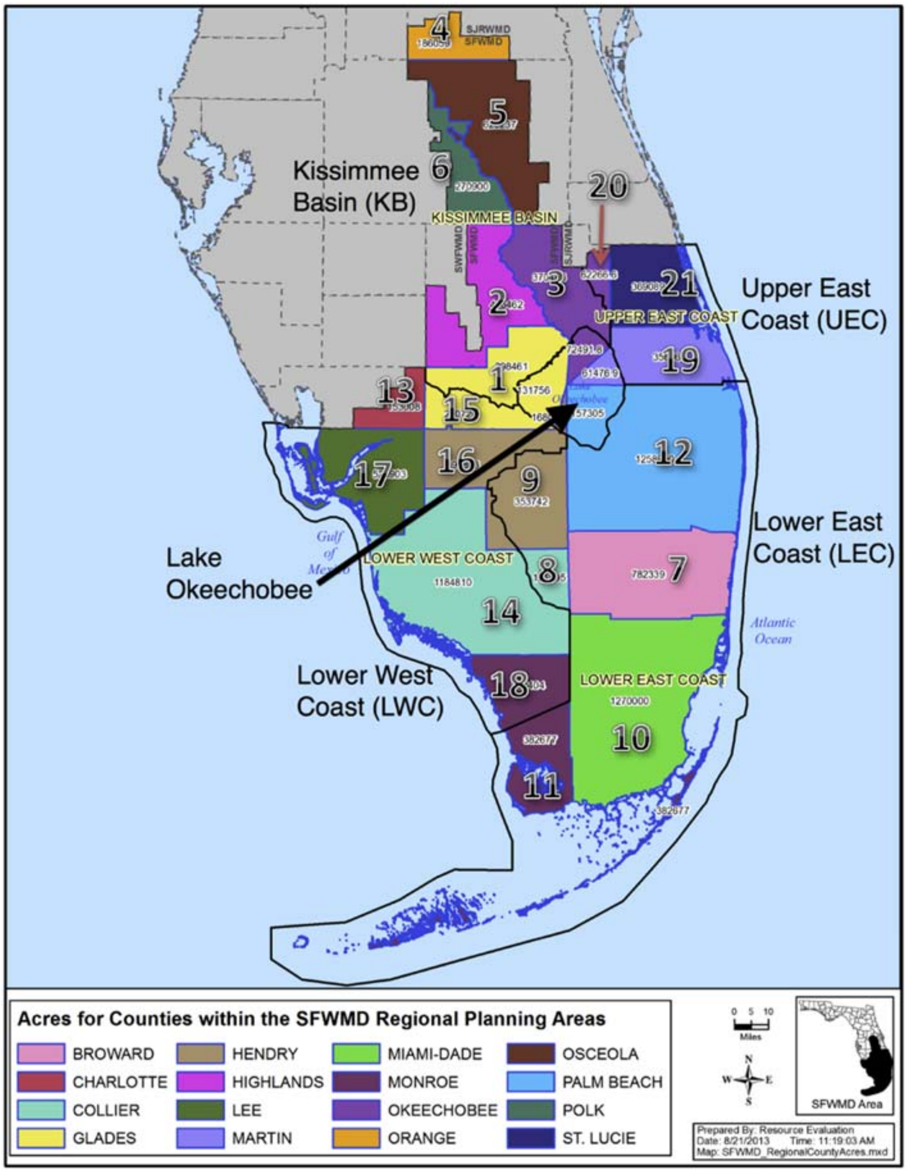


Fig. 1. SFWMD map and area number.

1. Introduction

A recent study indicates that the total annual precipitation has increased over land areas in the U.S. for the last century (EPA, 2015). However, some areas in the country experience severe drought conditions. South Florida is one of the areas that is discussed in the study in the context of pertaining to issues of drought. South Florida experienced severe drought conditions from 2006 to 2009 and in 2011 (SFWMD, 2014). Limited landscape irrigation and reductions in agriculture uses were required during the water shortage in 2011. The Florida Department of Environmental Protection announced that traditional sources of fresh groundwater would have difficulty meeting all of the additional demands by 2030 (FDEP, 2012; SFWMD, 2012). The state of Florida produces approximately 67% of the U.S. oranges and 40% of the world's orange juice (FDACS, 2014). Florida sugarcane production is ranked first in production in the US (USDA, 2012). Limited water resources, as a main production factor, will affect agricultural production and thus the economy in South Florida. Potential water supply issues may impose significant damage on the rural and agricultural economy in Florida, which may lead to higher prices and costs for consumers to purchase citrus or other agriculture products produced in Florida. Water resources in the South Florida system must be managed in order to mitigate costs associated with climate change in the future.

This paper presents a methodology for estimating economic loss for the South Florida cropland when the use of irrigation water is altered. The research focuses on the South Florida Water Management District (SFWMD), which is one of the five water management districts in Florida that are directed by the Florida Water Resources Act to develop a regional water supply plan (FDEP, 2012). This study focuses on cropland in the district, since 78% of the total value of farm products sold in the SFWMD is comprised of cropland products. The majority of Florida citrus and sugarcane are produced in this area, and agricultural irrigation was the largest sector of water use in 2010, followed by public water supply (FDEP, 2012). Changes in irrigation water use for agriculture production will affect the economy in the District. This study examines values of irrigation water usage. Efficient allocations of irrigation water across regions in the SFWMD are also investigated in order to minimize economic losses to the South Florida agricultural sector. The map in Fig. 1

Table 1
Regions and sub-regions (areas) in the SFWMD.

Region no.	Area no.	County	% county area
Kissimmee Basin (KB)			
1	1	Glades	60%
1	2	Highlands	75%
1	3	Okeechobee	75%
1	4	Orange	32%
1	5	Osceola	73%
1	6	Polk	24%
Lower East Coast (LEC)			
2	7	Broward	100%
2	8	Collier	9%
2	9	Hendry	48%
2	10	Miami-Dade	100%
2	11	Monroe	56%
2	12	Palm Beach	100%
Lower West Coast (LWC)			
3	13	Charlotte	35%
3	14	Collier	91%
3	15	Glades	40%
3	16	Hendry	52%
3	17	Lee	100%
3	18	Monroe	44%
Upper East Coast (UEC)			
4	19	Martin	100%
4	20	Okeechobee	13%
4	21	St Lucie	100%

depicts the counties associated with the SFWMD Regional Planning Areas.[1]

2. Study area and data

This study focuses on the SFWMD, which is divided into four regions: 1) Kissimmee Basin (KB); 2) Lower East Coast (LEC); 3) Lower West Coast (LWC), and; 4) Upper East Coast (UEC). Each region contains several sub-regions, with 21 areas encompassing the entire SFWMD. Each area is numbered (see Table 1 and Fig. 1). These four regions are equivalent to the planning areas of the SFWMD Water Supply Plan (SFWMD, 2014).

The data used in this study were collected for years 2000, 2005 and 2010 in the area of the SFWMD, which includes 15 counties (see Fig. 1)[2] and four regions. Since the boundary of the SFWMD does not correspond to the county boundaries, the fraction of the land share in the SFWMD based on each county area was calculated[3] (see Table 1). Based on the percentage or share of the SFWMD in each county, six variables are collected (based on significance): value of farm cropland (CV), employment (EMPC), surface water (SWC), ground water (GWC), share of irrigated land (RICL), and share of fertilized land (FR). CV[4] denotes the value of farm cropland products sold, adjusted by the Producer Price Index for cropland in 2010 (PPI 2010 = 100). EMPC[5] is employment (in number of FTE's) in cropland. SWC is the amount of surface water usage in cropland, in acre-foot per year (acre-ft/yr). GWC[6] is the amount of ground water usage in cropland, in acre-ft/yr. RICL[7] is the rate of land share of irrigated cropland, out of the total cultivated cropland. RF[8] is the rate of the fertilized cropland, out of the total cultivated cropland. The summary of the total samples for the four regions is shown in Table 2.

The LEC is the most intense crop-farming region in the SFWMD, followed by the LWC. The croplands in the LEC shared about 56% of the SFWMD, since the region includes Palm Beach, which is the leading crop farming county, and shares 40% of the total cropland in the SFWMD. The LWC currently uses more ground water than surface water; however, the dependence on ground water is decreasing over time. The LEC and UEC use more surface water than ground water. While the UEC has recently switched from ground water to surface water for irrigation, the LEC is beginning to rely more on ground water. The data in Table 2 also depict that crop farming in the SFWMD is diminishing in economic importance in recent years. Employment and crop value, adjusted by the inflation rate, have decreased across the four regions from years 2000 to 2010. The rates of crop irrigated land and fertilized land, out of the total cultivated cropland, are also decreasing in the SFWMD. Thus, both the area of irrigated lands and crop values decreased in the SFWMD from years 2000 to 2010.

3. Methodology

3.1. Assumptions

This model is based on following economic assumptions:

a) Crop farmers' objective is to maximize their profits by adjusting irrigation quantity or level when they use irrigation water.
b) The actual historic irrigation levels that farmers selected is at maximum profit level, which implies that marginal revenue equals marginal cost of production.
c) Farmers use either surface or ground water for their irrigation and prefer to use surface and/or groundwater depending on which has lower economic loss to their production.

3.2. Production

Numerous studies have examined the economic values of irrigation water. Young (2005) performed water valuation using the theory of product exhaustion, economic rents, and residual analysis. Young's study is based on producer welfare, which examined if a producer is better off from changes in quantity of inputs or outputs (Just et al., 1982). The model uses a production function to explain producer's behavior to choose a combination of inputs, including water, in order to determine the optimal combination of inputs for maximizing the producer's profit and welfare. Medellin-Azuara et al. (2010) investigated the economic value of agricultural water using economic demand curves for irrigation. The study investigated the effect of climate change and spatial aggregation.

The value of agricultural water use can be characterized using a crop production function. Ward et al. (2006) used the quadratic production function (termed the benefit function[9]) in their hydro-economic study to estimate the value of agricultural water in Colorado. In this study, the Cobb-Douglas function is assumed as the production function. The Cobb-Douglas function (1928) is widely used as a production function to represent the relation of inputs to output in economic analysis.

[1] As per Aug. 21, 2013

[2] Monroe County (Area11 and 18 in Table 1) is not included in this study since the data for the county is unavailable. Lake Okeechobee is also not included in this study area since there is no cropland in the lake.

[3] The percentage of land is estimated from the 2010 State & County Facts, U.S. Census Bureau, 2010(http://www.census.gov/en.html) and the Acres of Counties within the SWMD Regional Planning Area, 2013, SFWMDFWMD (http://www.sfwmd.gov).

[4] CV is compiled from the BEBR Florida Statistical Abstract 1997, 2002, 2007, and 2012 issued by the University of Florida, (http://www.bebr.ufl.edu/data). CV is adjusted by PPI cropland product in the year of 2010 (PPI 2010 = 100). PPI cropland product (PPI C) is estimated from PPI agricultural product (http://www.bls.gov/ppi/ppiover.htm).

[5] EMPC is obtained from the BEBR Florida Statistical Abstract 1997, 2002, 2007, and 2012 issued by the University of Florida, (http://www.bebr.ufl.edu/data).

[6] SWC and GWC are from the USGS Florida Water Science Center Years 2000, 2005, and 2010 (http://fl.water.usgs.gov/infodata/wateruse.html).

[7] RICL is compiled from the USDA Census of Agriculture (1997, 2002, 2007, and 2012).

[8] FR is estimated from USDA Agricultural Census Data (http://www.agcensus.usda.gov/).

[9] Wards' benefit function: Economic Benefits $= \beta^0 + \beta^1$ (acre-feet consumed) $+ \beta^1$ (acre-feet consumed)^2 $+ \beta^p$ (acre-feet pumped).

Table 2
Total water penalty function variables, by land share, by SFWMD region.

REGION NO	REGION	YEAR	CV[a] ($ million)	EMPC[b]	SWC[c] (acre-ft/yr)	SWC[d] (acre-ft/yr)	RATIO SWC[e]	RICL[f]	RF[g]
1	KB	2000	$ 617	3,045	57,231	159,615	0.26	0.77	0.92
		2005	$ 649	2,724	66,124	133,319	0.33	0.77	0.83
		2010	$ 446	2,917	93,818	101,124	0.48	0.75	0.70
2	LEC	2000	$ 2,441	15,837	1,209,633	261,927	0.82	0.88	0.97
		2005	$ 2,533	14,321	973,746	195,076	0.83	0.86	0.90
		2010	$ 1,864	12,014	598,084	161,094	0.79	0.77	0.72
3	LWC	2000	$ 929	6,937	237,193	311,545	0.43	0.90	0.96
		2005	$ 886	6,953	186,026	220,900	0.46	0.88	0.88
		2010	$ 650	4,915	273,623	271,108	0.50	0.85	0.71
4	UEC	2000	$ 419	1,357	356,767	72,266	0.83	0.80	0.92
		2005	$ 402	1,182	219,721	47,164	0.82	0.80	0.90
		2010	$ 274	852	107,407	15,454	0.87	0.78	0.81
SFWMD TOTAL		2000	$ 4,406	27,176	1,860,824	805,354	0.70	0.84	0.94
		2005	$ 4,471	25,180	1,445,617	596,459	0.71	0.83	0.88
		2010	$ 3,234	20,698	1,072,932	548,780	0.66	0.79	0.73

[a] CV is the value of crop products sold, adjusted by Producer Price Index for cropland in 2010 (PPI 2010 = 100).
[b] EMPC is the number of employment in cropland.
[c] SWC is the amount of surface water usage in cropland.
[d] GWC is the amount of ground water usage in cropland.
[e] RATIO SWC is the rate of SWC out of the sum of SWC and GWC.
[f] RICL is the rate of land share of irrigated lands out of the total cultivated croplands.
[g] RF is the rate of fertilized lands out of the total cultivated lands.

Although there are many inputs affecting economic performance of crop production, six input variables are included in the production function in this study, under the economic condition of ceteris paribus (all other things remaining the same), which is presented as:

$$CV_{i,t} = a\ EMPC_{i,t}{}^{b}SWC_{i,t}{}^{c}GWC_{i,t}{}^{d}RICL_{i,t}{}^{e}FR_{i,t}{}^{f}YEAR_{i,t}{}^{g} \quad (1)$$

Eq. (1) can be rewritten as:

$$\ln CV_{i,t} = \ln a + b\ \ln EMPC_{i,t} + c\ \ln SWC_{i,t} + d\ \ln GWC_{i,t} + e\ \ln RICL_{i,t} + f\ \ln FR_{i,t} + g\ \ln YEAR_{i,t} \quad (2)$$

Here, the indices i and t refer to location (region/sub-region) and time (years 2000, 2005 or 2010), respectively. YEAR is the time indicator: $2000 = 2^0$, $2005 = 2^1$, and $2010 = 2^2$, which captures a constant rate of technological development over time for crop production.[10] Coefficient a, is the specific total factor productivity, which explains effects in total output (CV) not caused by inputs. Coefficients b, c, d, e, f, and g are the output elasticities of EMPC, SWC, GWC, RICL, FR, and YEAR, respectively. Since this study is a static analysis and uses historic rather than expected values, the constant a, is adjusted or individualized, to match the data for each location (i) and time (t). Thus, each location's specific constant can be estimated by:

$$a_{i,t} = CV_{i,t}/\left(EMPC_{i,t}{}^{b}SWC_{i,t}{}^{c}GWC_{i,t}{}^{d}RICL_{i,t}{}^{e}FR_{i,t}{}^{f}YEAR_{i,t}{}^{g}\right) \quad (3)$$

Therefore, constant a can be expressed as $a_{i,t}$ in Eq. (1):

$$CV_{i,t} = a_{i,t}EMPC_{i,t}{}^{b}SWC_{i,t}{}^{c}GWC_{i,t}{}^{d}RICL_{i,t}{}^{e}FR_{i,t}{}^{f}YEAR_{i,t}{}^{g} \quad (4)$$

The marginal benefit of water, which is the Producer's Value of Marginal Product (VMP), can be estimated by the derivation of the production function with respect to water. The VMP of water indicates the effect of producer's benefit for a unit change of water, which is equivalent to the willingness to pay for changes in the quantity of water (Johansen, 1993; Freeman III, 2003; Young, 2005). The VMP of surface (VMPS) or ground (VMPG) water in this study is:

$$VMPS_{i,t} = \partial\ CV_{i,t}/\partial\ SWC_{i,t} = c\ a_{i,t}\ EMPC_{i,t}{}^{b}\ SWC_{i,t}{}^{(c-1)}\ GWC_{i,t}{}^{d}\ RICL_{i,t}{}^{e}\ FR_{i,t}{}^{f}\ YEAR_{i,t}{}^{g} \quad (5)$$

$$VMPG_{i,t} = \partial\ CV_{i,t}/\partial\ GWC_{i,t} = d\ a_{i,t}\ EMPC_{i,t}{}^{b}\ SWC_{i,t}{}^{c}\ GWC_{i,t}{}^{(d-1)}\ RICL_{i,t}{}^{e}\ FR_{i,t}{}^{f}\ YEAR_{i,t}{}^{g} \quad (6)$$

Here, it is assumed that the level of surface water use changes from SWC_o (the initial or current level) to SWC_a (alternative level).[11] If all other variables are held constant, then the production (value of crop sold) level would change from CV_o to CV_a.

$$CV_{o,i,t} = a_{i,t}EMPC_{i,t}{}^{b}SWC_{o,i,t}{}^{c}GWC_{i,t}{}^{d}RICL_{i,t}{}^{e}FR_{i,t}{}^{f}YEAR_{i,t}{}^{g} \quad (7)$$

$$CV_{a,i,t} = a_{i,t}EMPC_{i,t}{}^{b}SWC_{a,i,t}{}^{c}GWC_{i,t}{}^{d}RICL_{i,t}{}^{e}FR_{i,t}{}^{f}YEAR_{i,t}{}^{g} \quad (8)$$

When the surface water use level changes from SWC_o to SWC_a, the change of the production level (d CV) is:

$$d\ CV_{i,t} = CV_{a,i,t} - CV_{o,i,t} = a_{i,t}\ EMPC_{i,t}{}^{b}(SWC_{a,i,t}{}^{c} - SWC_{o,i,t}{}^{c})GWC_{i,t}{}^{d}\ RICL_{i,t}{}^{e}\ FR_{i,t}{}^{f}\ YEAR_{i,t}{}^{g} \quad (9)$$

If the ground water use level changes from GWC_o to GWC_a, then the change in the production level would be estimated in the same manner.

[10] This study assumes that technological progress in the agriculture sector is nonlinear (Bodkin and Klein, 1967; Dietrich et al., 2014).

[11] It is assumed that SWC_o is the implicit target level in this study. See the assumptions in Section 3.1.

3.3. Cost

When farmers choose their irrigation practices, it is assumed that their objective is to maximize their profits by adjusting the irrigation quantity or level. Thus, water can be optimally used and efficiently allocated in cropland when farmers utilize irrigation water. Under this condition, producer's profit is maximized,[12] which implies that the marginal benefit of the use of irrigation water is equal to the marginal cost (MC) of supply of irrigation water (Young, 2005; Dudu and Chumi, 2008). The marginal benefit of water is equal to the VMP of water based on Eq. (5). Hence, the marginal cost of surface water becomes:

$$\begin{aligned} MC_{i,t} &= VMPS_{i,t} \\ &= \partial\ CV_{i,t}/\partial\ SWC_{i,t} \\ &= c\ a_{i,t}\ EMPC_{i,t}{}^{b}\ SWC_{i,t}{}^{(c-1)}\ GWC_{i,t}{}^{d}\ RICL_{i,t}{}^{e}\ FR_{i,t}{}^{f}\ YEAR_{i,t}{}^{g} \end{aligned} \tag{10}$$

If the surface water use levels are changed from the current level (SWC_o) to an alternative level (SWC_a), then the cost difference (*d* COST) associated by the change in water use ($SWC_a - SWC_o$) can be calculated from the following:

$$\begin{aligned} d\ COST_{i,t} &= (MC_{i,t})\ (d\ SWC_{i,t}) \\ &= \left(c\ a_{i,t}\ EMPC_{i,t}{}^{b}\ SWC_{o,i,t}{}^{(c-1)}\ GWC_{o,i,t}{}^{d}\ RICL_{i,t}{}^{e}\ FR_{i,t}{}^{f}\ YEAR_{i,t}{}^{g}\right) \\ &\quad (SWC_{a,i,t}-SWC_{o,i,t}) \end{aligned} \tag{11}$$

3.4. Penalty (economic loss)

If surface water use changes from SWC_o to SWC_a, then the agriculture sector may observe some profit loss, which is defined in this study by the term "penalty". In the case where SWC is altered, producer's profit at SWC_o and SWC_a can be calculated by the following equations, respectively:

$$PROFIT_{o,i,t} = CV_{o,i,t} - COST_{o,i,t}, \tag{12}$$

$$PROFIT_{a,i,t} = CV_{a,i,t} - COST_{a,i,t}, \tag{13}$$

Thus, the penalty for changing surface water use from SWC_o to SWC_a is the difference between $PROFIT_o$ and $PROFIT_a$:

$$\begin{aligned} PENALTY_{i,t} &= PROFIT_{a,i,t} - PROFIT_{o,i,t} \\ &= (CV_{a,i,t} - COST_{a,i,t}) - (CV_{o,i,t} - COST_{o,i,t}). \end{aligned} \tag{14}$$

From Eq. (9), the penalty function can be rewritten as[13]:

$$\begin{aligned} PENALTY_{i,t} &= [CV_{a,i,t} - (COST_{o,i,t} + d\ COST_{i,t})] - (CV_{o,i,t} - COST_{o,i,t}) \\ &= (CV_{a,i,t} - CV_{o,i,t}) - d\ COST_{i,t} \\ &= d\ CV_{i,t} - d\ COST_{i,t} \end{aligned} \tag{15}$$

Thus, the penalty for the change in surface water usage can be measured by the difference in the producer's income subtracted by the difference in the production cost when the surface water use level changes. This penalty function can be rewritten, using Eqs. (9) and (11) as:

$$PENALTY_{i,t} = (CV_{a,i,t} - CV_{o,i,t}) - (MC_{i,t})\ (d\ SWC_{i,t})$$

or:

$$\begin{aligned} PENALTY_{i,t} &= \left[a_{i,t}\ EMPC_{i,t}{}^{b}(SWC_{a,i,t}{}^{c} - SWC_{o,i,t}{}^{c})GWC_{i,t}{}^{d}\ RICL_{i,t}{}^{e}\ FR_{i,t}{}^{f}\ YEAR_{i,t}{}^{g}\right] \\ &\quad -\left(c\ a_{i,t}\ EMPC_{i,t}{}^{b}\ SWC_{o,i,t}{}^{(c-1)}\ GWC_{o,i,t}{}^{d}\ RICL_{i,t}{}^{e}\ FR_{i,t}{}^{f}\ YEAR_{i,t}{}^{g}\right) \\ &\quad (SWC_{a,i,t} - SWC_{o,i,t})] \\ &= \beta^{1}\left[(SWC_{a,i,t}{}^{c} - SWC_{o,i,t}{}^{c}) - \left(c\ SWC_{o,i,t}{}^{(c-1)}\right)(SWC_{a,i,t} - SWC_{o,i,t})\right] \\ &= \beta^{1}\ SWC_{a,i,t}{}^{c} - \beta^{2}\ SWC_{o,i,t}{}^{(c-1)}\ SWC_{a,i,t} - \beta^{3}\ SWC_{o,i,t} \end{aligned} \tag{16}$$

where

$$\beta^{1} = a_{i,t}\left(EMPC_{i,t}{}^{b}GWC_{i,t}{}^{d}RICL_{i,t}{}^{e}FR_{i,t}{}^{f}YEAR_{i,t}{}^{g}\right)$$

$$\beta^{2} = c\ \beta^{1}$$

$$\beta^{3} = (1-c)\beta^{1}$$

The economic loss, or penalty, for ground water use may be calculated in the same manner.[14]

Table 3
The Cobb-Douglas production function.

Production function: LHS = LNCV	Coeff.	Std. err.	T-ratio	*P*-value
LNCONSTANT	−0.497	0.395	−1.261	0.215
LNEMPC	0.550**	0.040	13.648	0.000
LNSWC	0.078**	0.032	2.422	0.020
LNGWC	0.136**	0.044	3.068	0.004
LNRICL	0.692**	0.325	2.127	0.040
LNRF	1.440**	0.593	2.426	0.020
LNYEAR	0.290**	0.133	2.182	0.035
R square	0.928			
Adjusted R square	0.917			
Standard error	0.308			
Log likelihood	−7.038			
Restricted log likelihood	−66.241			
P-value	0.000			

** Significant at the 0.05 level.

4. Results

4.1. Cobb-Douglas production function in the SFWMD

The results obtained from the Cobb-Douglas production function with Eqs. (1) and (2) are presented in Table 3.[15]

Based on the 15 counties for the three-time periods, there are 45 samples in the model.[16] The production function (Eq. (4)) is derived based on the samples. All variables are found to be significant at the 0.05 level. The function is estimated as follows:

$$CV_{i,t} = a\left(EMPC_{i,t}{}^{0.550}SWC_{i,t}{}^{0.078}GWC_{i,t}{}^{0.136}RICL_{i,t}{}^{0.692}FR_{i,t}{}^{1.440}YEAR_{i,t}{}^{0.290}\right) \tag{17}$$

[12] Since information on production cost in South Florida cropland is limited, this condition is assumed in this study. Without the total cost information, the production function (under this condition) can be used to estimate the marginal cost of the production. Agricultural production functions subjected to some conditions were utilized to determine the optimal input combinations without cost information in past economic analyses (Brumbelow and Georgakakos, 2007; Madhoo, 2007).

[13] The new cost level ($COST_a$) at the new surface water use (SWC_a) is:

$$\begin{aligned} COST_{a,i,t} &= COST_{o,i,t} + d\ COST_{i,t} \\ &= COST_{o,i,t} + (MC_{i,t})\ (SWC_{a,i,t} - SW_{o,i,t}) \\ &= COST_{o,i,t} + (c\ a_{i,t}EMPC_{i,t}{}^{b}SWC_{i,t}{}^{(c-1)}GWC_{i,t}{}^{d}RICL_{i,t}{}^{e}FR_{i,t}{}^{f}YEAR_{i,t}{}^{g}) \\ &\quad (SWC_{a,i,t} - SWC_{o,i,t}). \end{aligned}$$

[14] See Appendix A.

[15] Parameters are estimated by means of the multiple regression, using LIMDEP.

[16] The sample data for only the three-time periods were utilized in this study because yearly data or data prior to 2000 were unavailable.

Table 4
The value of marginal product (VMP)[17] of surface or ground water in the SFWMD regions (in $ per acre-ft/yr).

	SURFACE WATER (SWC)			GROUND WATER (GWC)		
	2000	2005	2010	2000	2005	2010
Kissimmee Basin (KB)	845	770	372	527	665	601
Lower East Coast (LEC)	158	204	244	1,272	1,772	1,579
Lower West Coast (LWC)	307	373	186	407	547	327
Upper East Coast (UEC)	92	144	200	791	1,164	2,423
SFWMD	186	243	236	747	1,023	804

Hence, the specific constant $a_{i,t}$ for each location (i) and time (t) is estimated by:

$$a_{i,t} = CV_{i,t} / \left(EMPC_{i,t}^{0.550} SWC_{i,t}^{0.078} GWC_{i,t}^{0.136} RICL_{i,t}^{0.692} FR_{i,t}^{1.440} YEAR_{i,t}^{0.290} \right) \quad (18)$$

which is adjusted to fit the CV data for each location as noted before.

In the following subsections, the expected Value of Marginal Products (VMPs) of different types of irrigation water and the expected Penalty (Economic/Profit Loss), caused by the changing (reduction) of irrigation water, are measured based on the estimated parameters from the historical data.

4.2. The Value of Marginal Product (VMP) of irrigation water in the SFWMD regions

The VMPs by region are calculated with Eqs. (5) and (6), and are shown in Table 4.

The VMPs of surface or ground water are the changes of crop value sold (in dollars) when the water use changes by one acre-foot per year, which implies how much crop values (or farmer's revenue) change when the irrigation level changes by one acre-foot per year.[18] The findings reveal that there is variation in the VMPs of both surface and ground water across the regions. A previous study conducted by Samarawickrema (2009) explains the variation, which implies that VMPs of irrigation water differ depending on crop types. Another finding in this study is that VMPs of ground water are higher than surface water for all regions with the exception of the KB in years 2000 and 2005. In the LEC, the VMP of surface water is much lower than ground water, which can be interpreted as surface water being more easily accessible to the region than ground water. However, the trend of VMP of surface water from 2000 to 2010 shows that the value is increasing in the LEC. In the UEC, the trend of VMP of surface water is the same as the VMP's trend in the LEC. The VMP of ground water in the UEC, however, appears to be rising rapidly. This means that ground water in the UEC is getting more valuable and scarce. It is also notable that the VMP of surface water in KB is much higher than other regions across the SFWMD. This indicates that if there is a shortage of water across the SFWMD cropland, the KB will have higher damage on producers' revenues than other regions.

4.3. Penalty (economic loss) of the SFWMD regions

The penalty in this study is defined as the profit loss in cropland farming when the level of surface or ground water usage is varied. The

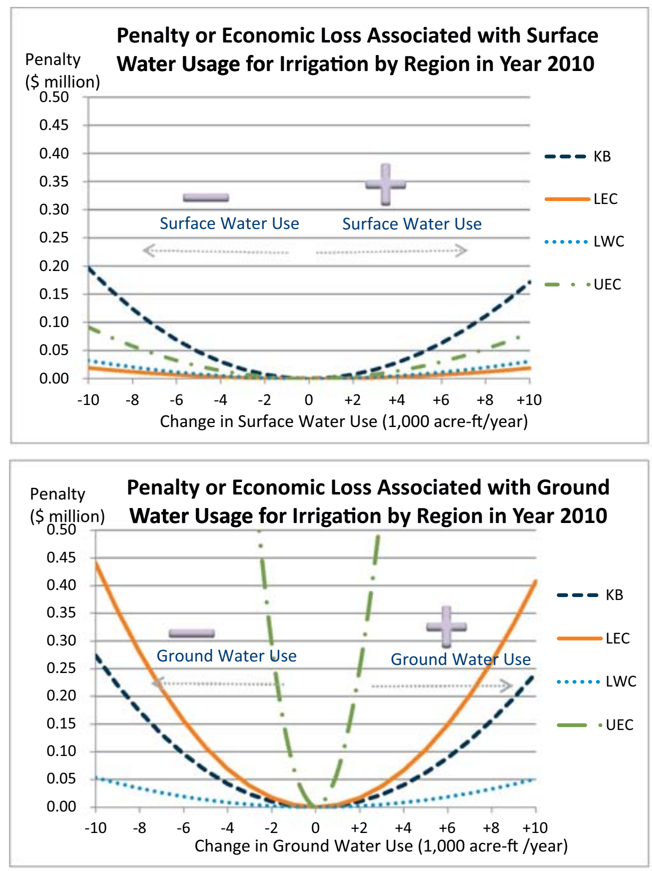


Fig. 2. a Penalty or economic loss associated with surface water usage for irrigation by region in 2010.[19] b Penalty or economic loss associated with ground watersage forregion in 2010.[20]

penalties are estimated from Eq. (14):

$$PENALTY_{i,t} = \beta^1 SWC_{a,i,t}^{0.078} - \beta^2 SWC_{o,i,t}^{(0.078-1)} SWC_{a,i,t} - \beta^3 SWC_{o,i,t} \quad (19)$$

where

$$\beta^1 = a_{i,t} \left(EMPC_{i,t}^{0.550} GWC_{i,t}^{0.136} RICL_{i,t}^{0.692} FR_{i,t}^{1.440} YEAR_{i,t}^{0.290} \right).$$

$$\beta^2 = 0.078\beta^1.$$

[17] VMP is the change in the crop value sold or producer's revenue when SWC or GWC is altered by one-acre foot per year, which is different from the penalty that implies the change in the profit loss in this study.

[18] The VMP of irrigation water is different from the penalty, which measures the profit loss.

[19] Penalty by region: Penalty if surface or ground water is additionally used from − 10,000 to 10,000 acre-ft/yr across the regions in 2010. The horizontal axis shows the change in surface (the upper graphs) or ground water (the lower graphs) in 1,000's acre-ft/yr. The vertical axis shows the penalty in million dollars.

[20] Ibid previous footnote.

$\beta^3 = (1-0.078)\beta^1$.

Each location has a different constant ($a_{i,t}$), which affects the penalty estimation differently in each location.

Fig. 2 presents the changes in penalty or economic loss if surface and ground water are varied over the range from −10,000 to +10,000 acre-ft/yr across the regions in the year of 2010. The water use level is expected to change to either a negative or a positive in case of a shortage or over-abundance of water, and economic loss will be altered in either case. Primarily, this study estimates penalties incurred by changing the amount of surface or ground water use for the four regions in the SFWMD.

Fig. 2 a. reveals that the KB would experience significant damage to crop farming if the amount of surface water irrigation changed, compared to the other regions. On the other hand, if ground water usage changes, the UEC would experience greater profit loss than other regions. These results can be explained from the actual irrigation water use data, which shows that the KB relies relatively more on ground water than surface water for irrigation, while the UEC heavily relies on surface water for its cropland irrigation.

4.4. Penalty function analysis across the SFWMD sub-regions

In this section, it is assumed that the surface and ground water are equally substitutable, and both surface and ground water are available across the SFWMD cropland. If each area needs an additional 1000 acre-ft/yr of the water for cropland, it should choose either surface or ground water associated with lower penalty to the economy. It is assumed that the change in water use is either surface or ground water only. The combined surface and ground water uses in this scenario are not expected to change. Table 5 presents the penalty resulting in using +1000 or −1000 acre-ft/yr of surface or ground water in 2010. The table also shows which irrigation water causes a lower penalty in case of additional water uses and the ranking from the lowest to highest penalty across the SFWMD areas.

The first two columns in Table 5 show the penalties caused by the change in the surface water only. The next two columns show the penalties caused by the change in the ground water only. In the KB, southern Orange County (KB 4) and eastern Polk County (KB 6) have very high penalties. Since these sub-regions use less than 1000 acre-ft of surface water per year, the estimation of the penalties is unavailable. Thus, the loss of groundwater is assumed to correspond to the loss of nearly all income in the area. In the LEC, Broward County (LEC 7) is in the same scenario.

If the water availability changes by +1000 or −1000 acre-ft/yr, then each sub-region chooses the surface or ground water associated with the lower penalty. For example, if northern Glades County (KB 1) needs irrigation water, the area will prefer surface water to ground water, since using ground water brings more economic loss to the area. The fifth and sixth column show lower penalties among surface water (SW) or ground water (GW) use in the case of using +1000 or

Table 5
Penalties (in $ million) associated with the additional +1000 or −1000 acre-ft/yr surface or ground water usage in the SFWMD sub-regions.

		PENALTY ($ million) WHEN SWC CHANGES		PENALTY ($ million) WHEN GWC CHANGES		PENALTY ($ million) WHEN EITHER SWC or GWC CHANGES			
		d SWC = -1,000 acre-ft/yr[a]	*d* SWC = +1,000 acre-ft/yr[a]	*d* GWC = -1,000 acre-ft/yr[b]	*d* GWC = +1,000 acre-ft/yr[b]	*d* IW (SWC or GWC) = -1,000 acre-ft/yr[c]	*d* IW (SWC or GWC) = +1,000 acre-ft/yr[c]	LOWER PENALTY (SWC or GWC)	SFWMD RANK (LOWEST to HIGHEST PENALTY)
Kissimmee Basin (KB)									
KB 1	Glades	0.0002	0.0002	0.0036	0.0034	0.0002	0.0002	SW	2
KB 2	Highland	0.2268	0.1792	0.0104	0.0099	0.0104	0.0099	GW	15
KB 3	Okeechobee	0.0145	0.0126	0.0042	0.0039	0.0042	0.0039	GW	10
KB 4	Orange	n/a	21.2826	2.8970	1.2544	2.8970	1.2544	GW	19
KB 5	Osceola	0.5379	0.2832	0.0076	0.0071	0.0076	0.0071	GW	12
KB 6	Polk	n/a	19.1528	2.1942	1.0680	2.1942	1.0680	GW	18
Lower East Coast (LEC)									
LEC 7	Broward	n/a	9.8376	1.0339	0.5319	1.0339	0.5319	GW	17
LEC 8	Collier	0.5458	0.2260	0.0066	0.0060	0.0066	0.0060	GW	11
LEC 9	Hendry	0.0003	0.0003	0.0047	0.0046	0.0003	0.0003	SW	4
LEC 10	Miami-Dade	0.4507	0.3789	0.0084	0.0082	0.0084	0.0082	GW	13
LEC 12	Palm Beach	0.0002	0.0002	0.1134	0.1072	0.0002	0.0002	SW	1
Lower West Coast (LWC)									
LWC 13	Charlotte	0.0097	0.0086	0.1632	0.1142	0.0097	0.0086	SW	14
LWC 14	Collier	0.0333	0.0307	0.0006	0.0006	0.0006	0.0006	GW	6
LWC 15	Glades	0.0004	0.0004	0.0055	0.0051	0.0004	0.0004	SW	5
LWC 16	Hendry	0.0003	0.0003	0.0043	0.0042	0.0003	0.0003	SW	3
LWC 17	Lee	0.0290	0.0260	0.0028	0.0028	0.0028	0.0028	GW	9
Upper East Coast (UEC)									
UEC 19	Martin	0.0021	0.0020	0.3080	0.2416	0.0021	0.0020	SW	8
UEC 20	Okeechobee	0.1434	0.0578	0.0290	0.0206	0.0290	0.0206	GW	16
UEC 21	St Lucie	0.0015	0.0015	0.2196	0.1817	0.0015	0.0015	SW	7

[a] *d* SWC is the change in surface water usage if amount of surface water use in croplands are altered by −1000 or +1000 acre-feet per year.
[b] *d* GWC is the change in ground water usage if amount of irrigation water use in croplands are altered by −1000 or +1000 acre-feet per year.
[c] *d* IW is the change in irrigation water (surface or ground water), which causes lower penalty from altering the amount of irrigation water in croplands.

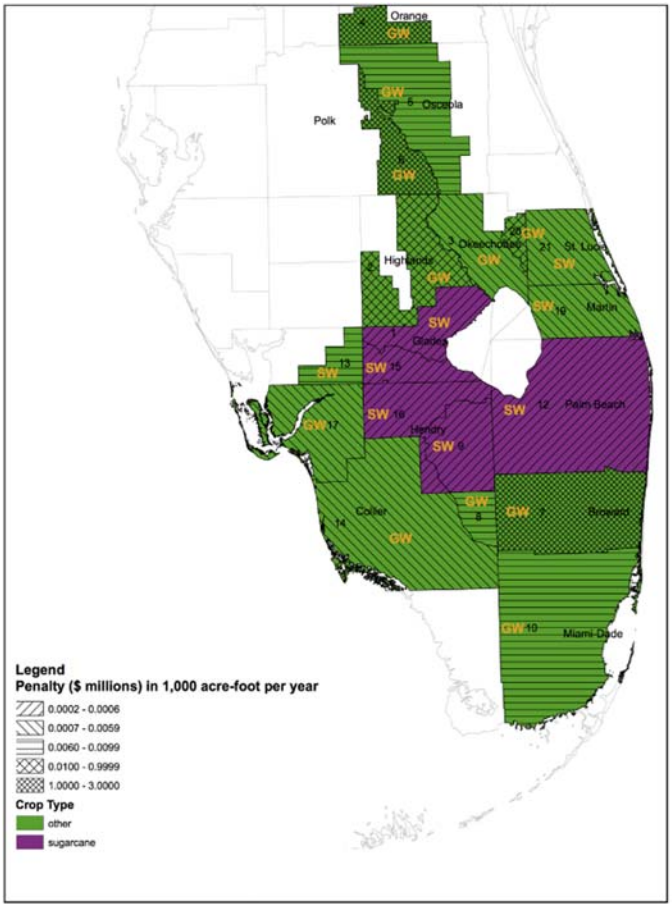


Fig. 3. Penalty, crop type[21], and weighted irrigation water in the SFWMD sub-regions 1 through 19.

−1000 acre-ft of irrigation water. The next column (LOWER PENALTY) indicates the preferred irrigation water with lower penalty: SW or GW. The last column shows the ranking from the lowest to the highest penalty in the SFWMD.

In Table 5, the variation of penalties can be seen across the sub-regions. Because different types of crops are produced in South Florida, the VMPs of irrigation water are varied in the area (Samarawickrema, 2009). Thus, the penalties are more likely to have a wide range of variation in the result. The highest two penalties are in southern Orange County (KB 4) and Polk County (KB 6), where surface water is used more than ground water. The lowest penalty is seen in Palm Beach County (LEC 1) which mainly uses surface water. Like Palm Beach County, Glades County (KB 1 and LWC 15) and Hendry County (LEC 9 and LWC 16) use more surface water than ground water and have lower penalties compared to other sub-regions. Those sub-regions are located on the south side of Lake Okeechobee and produce sugarcane as one of the major crops. Fig. 3 exhibits the results in a map, which shows penalties, dominant weighted irrigation water source (surface or ground water), and crop type (sugarcane as a major crop or not) across the SFWMD.

4.5. Analysis for per-acre based penalty across the SFWMD sub-regions

This study estimated penalties per acre of cropland in each sub-region, as exhibited in Table 6. Because this analysis is based on a per-acre-basis, the range of the irrigation level is much smaller than in the previous analysis. Water penalties were measured when the irrigation (surface or ground water) level are altered by +0.1 or −0.1 acre-ft/year per-acre-basis. This estimation clarifies the comparison of profit loss per acre-basis of cropland across the SFWMD sub-regions.

It is found that the estimation of the penalties is not possible in Highland County (KB 2), southern Orange County (KB 4), eastern Polk County (KB 6), and Broward County (LEC 7), because these areas use less than 0.1 acre-ft of surface water per year in an acre of cropland in 2010, there would be no surface water available if the amount of surface water decreases by 0.1 acre-ft, which will lead to significant damages to cropland and high economic penalties to the areas.

The results in this analysis are similar to the previous of analysis of penalties for changing surface or ground water by +1000 or −1000 acre-ft/yr (Table 6). The lowest penalties are shown in Glades County (KB 1 and LWC 15), followed by Collier County (LEC 8 and LWC 14) and Hendry County (LEC 9 and LWC 16). These results are slightly different from the previous analyses (Table 6), in which Palm Beach County (LEC 12) was shown as the lowest penalty area. In this analyses, Glades and Hendry Counties show lower penalties compared to other areas.

4.6. Extended remarks

This study assumes that farmers use either surface or ground water for their irrigation and prefer to use surface and/or groundwater, depending on which has lower economic loss to their production. The penalties for the use of surface or ground water are estimated by considering alternate use of surface or ground water. To conduct further penalty analyses, a case that considers the substitution between surface and ground is desired. Appendix B presents an example case of tradeoff between surface and ground water. For example, the penalty associated with the combined water in the LEC in 2010 can be estimated from the result of the penalty function in Appendix B. Fig. 4.a. shows the Agricultural Crop Value (bottom production possibility shape) and Costs (top plane) at various levels of GWC and SWC Inputs per acre-ft/yr in the LEC in 2010. Fig. 4.b shows the difference or penalty at various levels of GWC and SWC inputs per acre-ft/yr in the LEC in 2010,[22] and Fig. 4.c shows the penalty (from Fig. 4.b) in tabular format at various levels of GWC and SWC inputs per acre-ft/yr in the LEC in 2010. Color-shading in Fig. 4.c is provided to show the off-circular shape of the penalty function, where bottom (blue) and top (red) shading indicates lower and higher penalties, respectively. This approach, in combination with inter-temporal analyses, is needed to further develop the model into a decision-making tool and should be analyzed across the SFWMD regions to determine the efficient irrigation water allocation in South Florida.

4.7. Limitations of the study

There are a number of limitations in this paper pertaining to available data related to crop irrigation use in South Florida. There were no crop enterprise budgets (e.g., no variable, fixed nor breakeven costs associated with various crops), and no data on irrigation use for individual crops (and associated crop yields). The data on surface and groundwater water use for the crop regions is only collected every five years by the USGS. That said, this paper estimated the shares of irrigation water as well as of other production factors by employing the natural-logged Cobb-Douglas production function, and predicted the unit (1000 acre-ft) economic loss caused by a reduction of water for regions and sub-

[21] If sugarcane is included in the top three of crop production in a sub-region, the region is categorized as sugarcane. Otherwise, it is categorized as other.

[22] Fig. 4b was arbitrarily truncated at the $120 million level, leaving an unintended flat impression.

Table 6
Per-acre based penalties (in $) associated with the additional +0.1 or −0.1 acre-ft/yr surface or ground water usage in the SFWMD sub-regions.

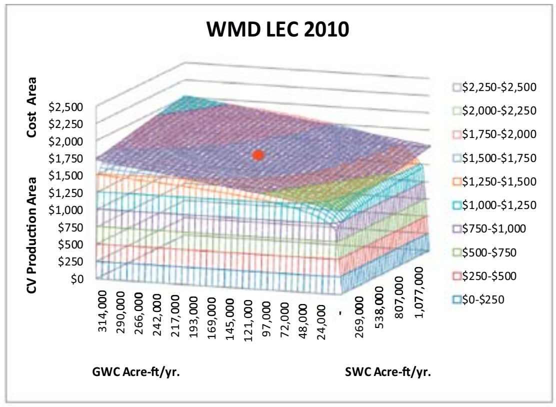
		PENALTY ($) PER ACRE WHEN SWC CHANGES		PENALTY ($) PER ACRE WHEN GWC CHANGES		PENALTY ($) PER ACRE WHEN EITHER SWC or GWC CHANGES			
		d SWC= -0.1 acre-ft/yr[a]	*d* SWC= +0.1 acre-ft/yr[a]	*d* GWC= -0.1 acre-ft/yr[b]	*d* GWC= +0.1 acre-ft/yr[b]	*d* IW (SWC or GWC) = -0.1 acre-ft/yr[c]	*d* IW (SWC or GWC) = +0.1 acre-ft/yr[c]	LOWER PENALTY (SWC or GWC)	SFWMD RANK (LOWEST to HIGHEST PENALTY)
Kissimmee Basin (KB)									
KB 1	Glades	0.07	0.07	1.07	0.93	0.07	0.07	SW	1
KB 2	Highland	n/a	69.74	6.48	5.16	6.48	5.16	GW	16
KB 3	Okeechobee	3.87	2.78	1.04	0.91	1.04	0.91	GW	13
KB 4	Orange	n/a	1536.82	86.18	62.34	86.18	62.34	GW	18
KB 5	Osceola	195.86	44.17	1.44	1.28	1.44	1.28	GW	14
KB 6	Polk	n/a	2430.90	n/a	206.17	n/a	206.17	GW	19
Lower East Coast (LEC)									
LEC 7	Broward	n/a	558.38	21.91	18.30	21.91	18.30	GW	17
LEC 8	Collier	10.60	8.35	0.19	0.19	0.19	0.19	GW	4
LEC 9	Hendry	0.30	0.28	4.75	3.87	0.30	0.28	SW	5
LEC 10	Miami-Dade	518.56	158.88	4.95	4.45	4.95	4.45	GW	15
LEC 12	Palm Beach	0.78	0.69	n/a	216.20	0.78	0.69	SW	8
Lower West Coast (LWC)									
LWC 13	Charlotte	0.59	0.55	9.00	8.00	0.59	0.55	SW	7
LWC 14	Collier	10.60	8.35	0.19	0.19	0.19	0.19	GW	3
LWC 15	Glades	0.07	0.07	1.00	1.00	0.07	0.07	SW	1
LWC 16	Hendry	0.30	0.28	5.00	4.00	0.30	0.28	SW	5
LWC 17	Lee	5.94	4.80	1.00	1.00	1.00	1.00	GW	11
Upper East Coast (UEC)									
UEC 19	Martin	0.79	0.71	192.57	69.52	0.79	0.71	SW	9
UEC 20	Okeechobee	3.87	2.78	1.04	0.91	1.04	0.91	GW	12
UEC 21	St Lucie	0.91	0.80	301.86	301.86	0.91	0.80	SW	10

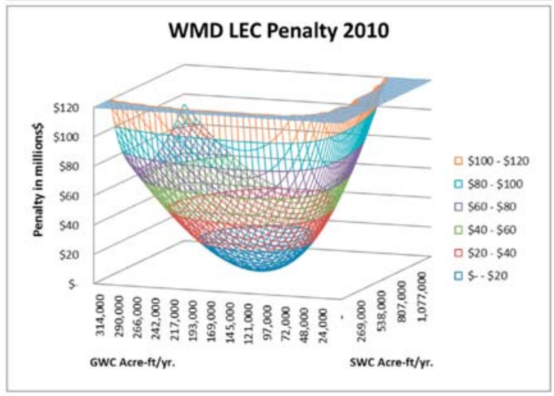
[a] *d* SWC is the change in surface water usage if the amount of surface water uses is altered by −0.1 or +0.1 acre-feet/year per acre cropland.
[b] *d* GWC is the change in ground water usage if amount of irrigation water use in croplands are altered by −0.1 or +0.1 acre-feet/year per acre cropland.
[c] *d* IW is the change in irrigation water (surface or ground water), which causes lower penalty from altering the amount of irrigation water in croplands.

regions. As the estimation of the production function parameters was conducted as a first step, the historic irrigation levels are assumed to be at the profit maximization levels. As the parameters (or shares) were assumed to be at the recommended (not the absolute) levels, it's thus possible in the future to provide a set of various irrigation water use quantities in the future (that represent potential deviations from the profit-maximized levels). The expected Value of Marginal Products (VMPs) of different types of irrigation water and the expected Penalty (Economic Loss) caused by the changing (reduction) of irrigation water were calculated based on the estimated parameters from the historical data. At this time, the agricultural water market in South Florida is characterized by the following: 1) water has no price 2) availability is based on the allocation allowance according to the water permit issued, and; 3) there is no monitoring or enforcement related to irrigation water use in South Florida. Since the irrigation water has no price in South Florida, the price is internalized in the model based on the assumption that farmers are maximizing their expected profits. Although the irrigation water is a “free” production factor by definition, the crop products require other scare resources, e.g., skilled labor, materials and land. For certain crops, those production factors are not substitutable for each other. As mentioned earlier, the VMP's of irrigation water differ depending on crop types. If we assume the VMP = MC, this implies the water use is managed or limited and differ per crop type. Farmers are aware of the optimal water quantity per crop type per fixed land area. Unless the quantity of water use for the fixed number of water permits is expanded to include additional croplands (i.e., the irrigation area is expanded), in this paper, we assume the current level of irrigation water usage per permit will not extend beyond permitted levels. We assume, through use of the irrigated land share variable, that other production factors are controlled in the regression equation since the area share of crop type shares do no change much of the time period from years 2000 to 2010. The model presented has its limitations, in both variable use (abstraction), and its inherent static basis. However, it does present some novel features regarding the allocation and use of water. The model might be further extended as more five-year data series become available, and the results might also be subjected to a more dynamic evaluation.

5. Summary

This study analyzed the water penalties (or economic losses) associated with varying irrigation water usage in South Florida cropland. The results indicate that water penalties caused by changing surface and ground water usage are significantly high in the LEC and KB. The LEC is the most important crop farming region in the SFWMD in terms of revenues. The high rate of penalties relative to the change in irrigation water use levels would negatively impact the economy in South Florida. Recent data show that the amount of irrigation water usage is declining in the SFWMD, which correlates to the crop value sold in the region. Although economic losses to the agriculture sector are already being experienced in the region, this study provides some strategies to minimize the economic loss associated with the reduction in irrigation water use in the region. Through the analyses of the penalties associated





GWCn

SWCn

	-	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###
-	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###	###
30,000	###	464	386	342	311	289	273	260	250	243	237	232	229	227	226	225	225	226	227	229	231	234	237	240	244	248	252	257	261	266	271	276	282	288	293	299	305	311	318	324	331
60,000	###	420	338	290	257	234	215	201	190	181	174	169	165	162	160	159	158	159	159	161	162	164	167	170	173	177	180	184	189	193	198	203	208	213	219	224	230	236	242	248	254
90,000	###	396	311	261	227	202	183	168	156	147	139	133	129	125	123	121	120	120	120	121	123	125	127	129	132	136	139	143	147	151	156	160	165	170	176	181	187	192	198	204	210
120,000	###	381	293	242	207	181	161	145	133	123	115	109	104	100	97	95	94	94	94	95	96	97	99	102	104	108	111	114	118	122	127	131	136	141	146	151	157	162	168	174	180
150,000	###	370	280	228	192	165	145	129	116	106	98	91	86	82	79	77	75	74	74	75	76	77	79	81	84	87	90	93	97	101	105	110	114	119	124	129	135	140	146	151	157
179,000	###	362	271	217	181	154	133	117	103	93	84	77	72	68	64	62	60	59	59	60	60	62	63	65	68	71	74	77	81	85	89	93	97	102	107	112	117	123	128	134	140
209,000	###	356	263	209	172	145	124	107	93	82	74	67	61	56	53	50	49	48	47	47	48	49	51	53	55	58	61	64	68	71	75	79	84	89	93	98	103	109	114	120	125
239,000	###	351	258	203	166	138	116	99	85	74	65	58	52	47	44	41	39	38	38	38	38	39	41	43	45	47	50	53	57	61	64	69	73	77	82	87	92	97	103	108	114
269,000	###	348	254	199	161	132	110	93	79	68	59	51	45	40	36	34	32	30	30	30	30	31	32	34	36	39	42	45	48	52	56	60	64	68	73	78	83	88	93	99	104
299,000	###	346	251	195	157	128	106	88	74	62	53	45	39	34	30	28	25	24	23	23	23	24	26	27	29	32	34	38	41	44	48	52	56	61	65	70	75	80	85	91	96
329,000	###	345	249	192	153	125	102	84	70	58	49	41	35	30	26	23	20	19	18	18	18	19	20	22	24	26	29	32	35	38	42	46	50	54	59	64	69	74	79	84	90
359,000	###	344	247	190	151	122	99	81	67	55	45	37	31	26	22	18	16	15	14	13	14	14	15	17	19	21	24	27	30	33	37	41	45	49	54	58	63	68	73	79	84
389,000	###	344	246	189	150	120	97	79	64	52	43	34	28	23	18	15	13	11	10	10	10	11	12	13	15	17	20	22	26	29	33	36	40	45	49	54	59	64	69	74	79
419,000	###	344	246	188	149	119	96	77	63	50	40	32	26	20	16	13	10	8	7	7	7	8	9	10	12	14	16	19	22	26	29	33	37	41	46	50	55	60	65	70	76
449,000	###	345	246	188	148	118	95	76	61	49	39	31	24	18	14	11	8	6	5	5	5	5	6	7	9	11	14	16	19	23	26	30	34	38	43	47	52	57	62	67	72
478,000	###	346	247	188	148	118	94	76	61	48	38	30	23	17	13	9	7	5	4	3	3	3	4	6	7	9	12	14	17	21	24	28	32	36	40	45	49	54	59	64	70
508,000	###	347	247	189	148	118	94	75	60	48	37	29	22	16	12	8	6	4	2	2	2	2	3	4	6	8	10	13	16	19	22	26	30	34	38	43	47	52	57	62	68
538,000	###	349	249	190	149	118	95	76	60	48	37	29	22	16	11	8	5	3	2	1	1	1	2	3	5	7	9	11	14	18	21	25	28	32	37	41	46	51	56	61	66
568,000	###	351	250	191	150	119	95	76	61	48	37	29	22	16	11	7	5	3	1	0	0	0	1	2	4	6	8	11	14	17	20	24	27	31	36	40	45	50	54	60	65
598,000	###	353	252	192	151	120	96	77	61	48	38	29	22	16	11	8	5	3	1	0	-	0	1	2	4	5	8	10	13	16	19	23	27	31	35	39	44	49	54	59	64
628,000	###	356	254	194	152	121	97	78	62	49	39	30	22	17	12	8	5	3	1	0	0	0	1	2	4	5	8	10	13	16	19	23	27	31	35	39	44	48	53	58	63
658,000	###	358	256	196	154	123	99	79	63	50	40	31	23	17	12	9	6	3	2	1	1	1	1	2	4	6	8	10	13	16	19	23	27	30	35	39	44	48	53	58	63
688,000	###	361	258	198	156	125	100	81	65	52	41	32	24	18	13	10	6	4	3	2	1	1	2	3	4	6	8	11	13	16	20	23	27	31	35	39	44	48	53	58	63
718,000	###	364	261	200	158	127	102	82	66	53	42	33	26	20	15	11	8	5	4	3	2	2	3	4	5	7	9	11	14	17	20	24	27	31	35	40	44	49	54	59	64
748,000	###	367	263	203	160	129	104	84	68	55	44	35	27	21	16	12	9	7	5	4	3	3	4	5	6	8	10	12	15	18	21	25	28	32	36	40	45	49	54	59	64
778,000	###	370	266	205	163	131	106	86	70	57	46	37	29	23	18	14	10	8	6	5	5	5	5	6	7	9	11	13	16	19	22	26	29	33	37	41	46	50	55	60	65
807,000	###	373	269	208	165	133	108	88	72	59	48	38	31	25	19	15	12	10	8	7	6	6	7	8	9	10	12	15	17	20	23	27	30	34	38	42	47	51	56	61	66
837,000	###	376	272	211	168	136	111	91	74	61	50	41	33	27	21	17	14	11	10	9	8	8	8	9	10	12	14	16	19	22	25	28	32	36	40	44	48	53	57	62	67
867,000	###	380	275	214	171	139	114	93	77	63	52	43	35	29	23	19	16	13	12	10	10	10	10	11	12	14	16	18	20	23	26	30	33	37	41	45	50	54	59	64	69
897,000	###	384	279	217	174	141	116	96	80	66	55	45	37	31	26	21	18	16	14	12	12	12	12	13	14	16	18	20	22	25	28	31	35	39	43	47	51	56	60	65	70
927,000	###	387	282	220	177	144	119	99	82	69	57	48	40	33	28	24	20	18	16	15	14	14	14	15	16	18	20	22	24	27	30	33	37	41	45	49	53	57	62	67	72
957,000	###	391	285	223	180	147	122	102	85	71	60	50	43	36	31	26	23	20	18	17	16	16	16	17	18	20	22	24	26	29	32	35	39	43	47	51	55	59	64	69	74
987,000	###	395	289	227	183	151	125	105	88	74	63	53	45	39	33	29	25	23	21	19	19	19	19	19	21	22	24	26	29	31	34	38	41	45	49	53	57	61	66	71	76
1,017,000	###	399	293	230	187	154	128	108	91	77	66	56	48	41	36	32	28	25	23	22	21	21	21	22	23	25	26	28	31	34	37	40	43	47	51	55	59	64	68	73	78
1,047,000	###	403	296	234	190	157	132	111	94	80	69	59	51	44	39	34	31	28	26	25	24	24	24	25	26	27	29	31	33	36	39	42	46	49	53	57	62	66	71	75	80
1,077,000	###	407	300	237	194	161	135	114	97	83	72	62	54	47	42	37	34	31	29	28	27	26	27	27	28	30	31	34	36	39	42	45	48	52	56	60	64	68	73	78	83
1,106,000	###	411	304	241	197	164	138	118	101	87	75	65	57	50	45	40	37	34	32	30	30	29	29	30	31	32	34	36	39	41	44	47	51	54	58	62	66	71	75	80	85
1,136,000	###	415	308	245	201	168	142	121	104	90	78	68	60	54	48	43	40	37	35	33	33	32	32	33	34	35	37	39	41	44	47	50	53	57	61	65	69	73	78	83	88
1,166,000	###	420	312	249	205	172	146	125	108	93	82	72	64	57	51	47	43	40	38	36	36	35	35	36	37	38	40	42	44	47	50	53	56	60	64	68	72	76	81	85	90
1,196,000	###	424	316	253	209	175	149	128	111	97	85	75	67	60	55	50	46	43	41	40	39	38	38	39	40	41	43	45	47	50	53	56	59	63	67	71	75	79	84	88	93

Fig. 4. a Agricultural crop value and costs at various levels of GWC and SWC inputs per acre-ft/yr in the LEC in 2010. b Penalty at various levels of GWC and SWC inputs per acre-ft/yr in the LEC in 2010. c Penalty in table format with shading LEC 2010 at various levels of GWC and SWC inputs per acre-ft/yr in the LEC in 2010. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

with water use across the SFWMD, the highest penalty due to a reduction in irrigation water use is evident in Orange and Polk Counties in the KB and in Broward County in the LEC. On the other hand, lower penalties are seen in Glades, Palm Beach, and Hendry Counties, which are located near Lake Okeechobee. In summary, this study observes that water can be traded to the counties associated with high water penalties from other regions associated with low water penalties in the SFWMD, which can be an efficient water allocation and can lead to minimized economic loss in the SFWMD overall. The results might be useful for farmers, engineers, and policy makers to determine efficient water management in the South Florida agriculture lands. Since data for irrigation usage and production costs are limited, this study assumes that producers are maximizing profits at the current condition. Without cost information, this study estimates economic loss due to alternative irrigation levels, and highlights areas that require urgent management strategies for irrigation in order to mitigate economic loss. Water usage data in croplands is currently only collected once every two or three years by the USGS. It would be beneficial to collect water usage data at least annually, if not quarterly (or more frequently). Additional data including production costs will help determine the optimal allocation of irrigation water and future economic impacts for the South Florida region.

For further discussion on water management practices to sustain production and the economy in the South Florida, water penalty analysis, for not only agriculture, but also for other sectors, should be performed. Currently, water penalties for urban water use, ecosystem services, the Everglades, and fisheries are examined by researchers engaged in the South Florida Water, Sustainability, and Climate (SFWSC) Project,[23] which includes this study as a part of the project. The results of those penalty analyses will be integrated into a hydro-economic optimization model, which can help further determine the strategies for sustainable economy and water management in South Florida.

6. Conclusions

This study finds the penalties, or economic losses, associated with changing surface and ground water use in the SFWMD. Recent data shows that the amount of irrigation water is declining in the SFWMD, which correlates to the value of crop product sold in the region. This study may provide some additional perceptions and options to minimize the economic loss by comparing water penalties across regions. The results might be useful for farmers, engineers, and policy makers to determine efficient water management in the South Florida agriculture lands.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.12.240.

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[23] The website of the SFWSC project is located at http://sfwsc.fiu.edu.