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Journal

San Francisco Estuary and Watershed Science, 12(4)

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Publication Date

2014

DOI

<https://doi.org/10.15447/sfews.2014v12iss4art2>

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Physically Based Modeling of Delta Island Consumptive Use: Fabian Tract and Staten Island, California

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Volume 12, Issue 4, Article 2 | December 2014

doi: <http://dx.doi.org/10.15447/sfews.2014v12iss4art2>

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ABSTRACT

Water use estimation is central to managing most water problems. To better understand water use in California's Sacramento–San Joaquin Delta, a collaborative, integrated approach was used to predict Delta island diversion, consumption, and return of water on a more detailed temporal and spatial resolution. Fabian Tract and Staten Island were selected for this pilot study based on available data and island accessibility. Historical diversion and return location data, water rights claims, LiDAR digital elevation model data, and Google Earth were used to predict island diversion and return locations, which were tested and improved through ground-truthing. Soil and land-use characteristics as well as weather data were incorporated with the Integrated Water Flow Model Demand Calculator to estimate water use and runoff returns from input agricultural lands. For modeling, the islands were divided into grid cells forming subregions, representing fields, levees, ditches, and roads. The subregions were joined hydrographically to form diversion and return watersheds related to return and diversion locations. Diversions and returns were limited by physical capacities. Differences between initial model and measured results point to the importance of seepage into deeply subsided islands. The capa-

bilities of the models presented far exceeded current knowledge of agricultural practices within the Delta, demonstrating the need for more data collection to enable improvements upon current Delta Island Consumptive Use estimates.

KEY WORDS

Sacramento–San Joaquin Delta, consumptive use, modeling, DICU, IDC

INTRODUCTION

The Sacramento–San Joaquin Delta is at the confluence of the Sacramento and San Joaquin rivers in California's Central Valley (Figure 1). Most runoff in California drains towards the Sacramento–San Joaquin Delta, with significant diversions upstream and in the Delta for agricultural and urban uses. In addition, the Delta region is home to over 500,000 water users and over 750 species of flora and fauna (Hutton et al. 1995).

Before being diked, drained, and dredged by European settlers between 1850 and 1920 for agriculture, navigation, and flood control, the Delta was

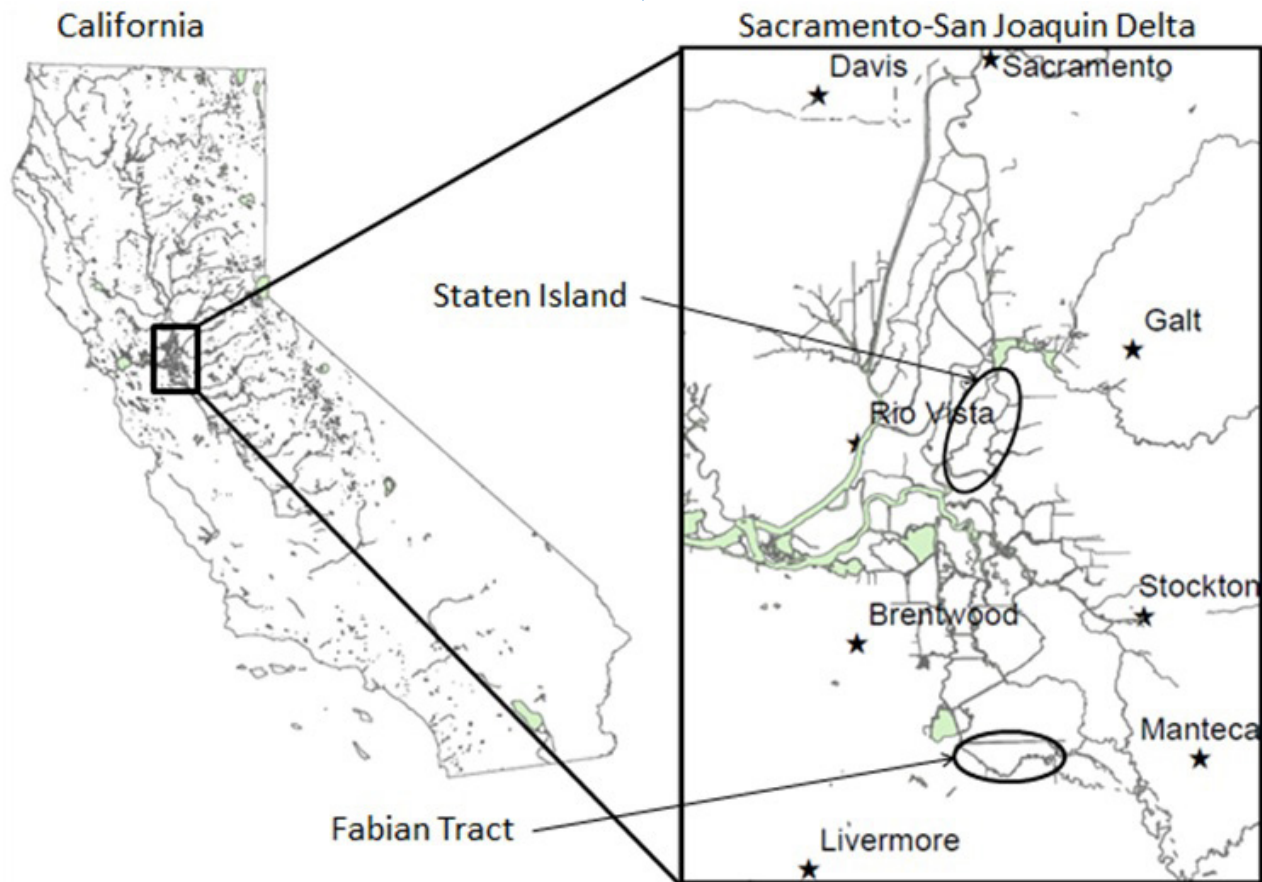


Figure 1 The Sacramento–San Joaquin Delta, depicting the channels and tracts which define the Delta as well as the Delta islands

a freshwater tidal marshland (Hutton et al. 1995; Lund et al. 2010). By the end of the 1930s, channelization of the Delta created about 57 land masses—300,000 ha of reclaimed land for agricultural use known as the Delta islands—surrounded by water (Thompson 1957; Whipple et al. 2012).

Knowledge and understanding of flows in Delta channels and streams is crucial for sustainable solutions for the Delta (DeGeorge 2005). The water diversions, water operations, and land-use changes upstream and within the Delta starting in the 1850s impaired Delta water flows, quality, and suitability for many native fish species as well as some long-term human uses of the Delta (Lund et al. 2007, 2010; Moyle et al. 2012).

In-Delta diversions and return flows are currently aggregated at 142 subarea locations in the Delta as monthly averages, and are designated as Delta Island Consumptive Use (DICU) by the California Department of Water Resources (CDWR). The 142 sub-areas were chosen as a simple way to regionalize the Delta but currently are applied at up to 258 sub-areas as internal boundary conditions in one-, two-, and three-dimensional hydrodynamic and water quality models of the Delta. Over 1800 diversion locations and over 210 return locations in the Delta have been identified (California Department of Water Resources 1995), many of which are no longer used. In addition, significant differences in reported and modeled peak withdrawals and diversions have been identified (Siegfried 2012).

The objective of the work presented here is to improve upon current DICU estimates in a non-invasive manner, using data which may be accessed remotely. This work represents a proof-of-concept pilot study to produce more realistic DICU estimates and create a model that can be extended to other Delta islands. This effort incorporates improved consumptive use knowledge developed in the integrated water flow model (IWFM) demand calculator (IDC) with drainage patterns extracted from recent LiDAR work on the islands. Many models and acronyms are referenced throughout this document. For clarification, a list of these models and acronyms, providing definitions and descriptions where appropriate, is provided at the end of this document.

BACKGROUND

Much of the water entering the Delta is diverted for agriculture. Owen and Nance (1962) found about $7,410 \text{ m}^3 \text{ ha}^{-1}$ of water to be consumed by agriculture on Twitchell Island in 1960. During this time, the Delta had roughly 300,000 ha of agricultural land and conveyed 14.8 billion m^3 of water exports and outflow (Owen and Nance 1962). If the consumptive use estimate from Owen and Nance is applicable to the entire Delta for 1960, 2.12 billion m^3 of water would have been consumed by Delta agriculture dur-

ing 1960, roughly 15% of water conveyed through the Delta. Agricultural land use in the Delta has increased since 1960, potentially leading to a larger percentage of consumed water within the Delta (Templin and Cherry 1997).

Reclamation and agriculture on developed islands in the central and western Delta between 1850 and 1930 led to the subsidence of the land surface at long-term average rates of 2.5 to 7.6 cm yr^{-1} (Rojstaczer et al. 1991; Rojstaczer and Deverel 1993). As a result, many Delta islands are 3 to 8 m below sea level (Figure 2) (Ingebritsen 2000). Reductions in organic soil thicknesses are suspected to increase seepage under levees, increasing water-logged areas on Delta islands.

To prevent the islands from flooding internally, and maintain adequate ground water levels for agriculture, an extensive network of drainage ditches and return pumps exist on these lands (Ingebritsen 2000). Many Delta island land elevations are below sea level and require accumulated agricultural drainage to be returned by pumping the water over the levees into surrounding channels (Figure 3A). Additionally, because of the often higher channel elevations, much water used on Delta islands is siphoned rather than pumped from Delta channels (Figure 3B). The divert-

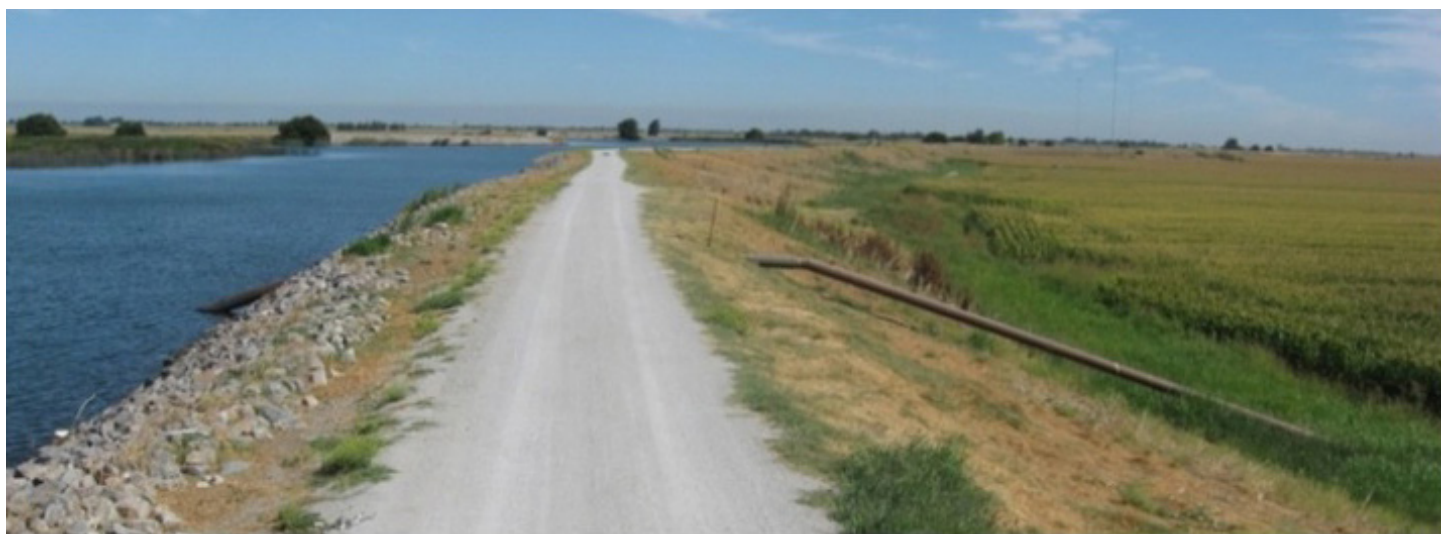


Figure 2 Subsidence on Staten Island, depicting a diversion siphon for scale

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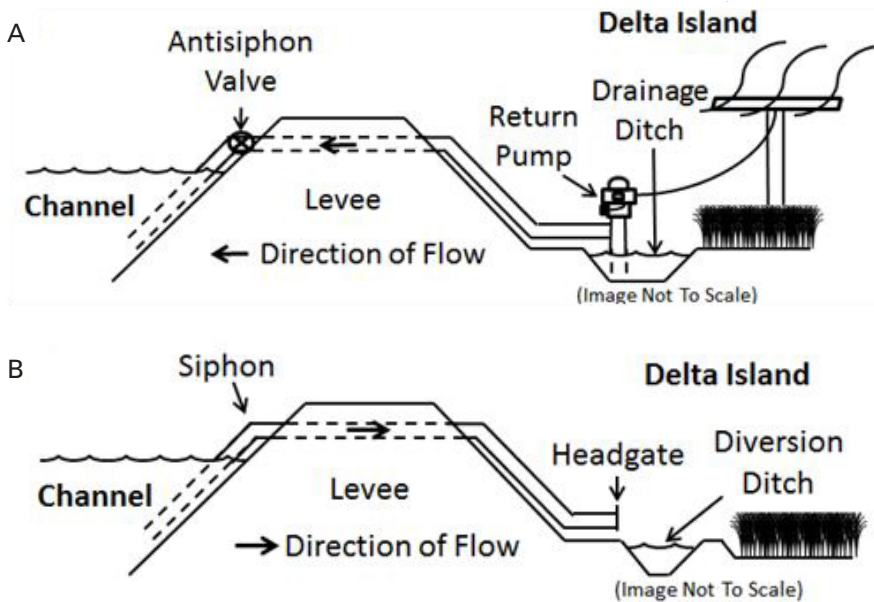


Figure 3 Delta island (A) return pump and (B) diversion siphon drawings

ed water is then usually run down-grade through a series of diversion ditches and piping for irrigation.

Agricultural water can come from surface and sub-surface sources; however the regulation of groundwater and surface diversions is historically separate. Additionally, many surface water returns from agricultural runoff are unregulated. This gap in regulation of water diversions and returns has made predicting agricultural discharges of water and nutrients to streams difficult (Jung 2000; Madani and Lund 2011).

Studies of DICU were conducted during 1954 and 1955 when the State of California Water Project Authority monitored water quality and consumptive use and found the following:

1. Delta islands return the most water during the winter rather than during the agricultural season;
2. Most DICU occurs in March through October;
3. Subsurface seepage inflows are a significant source of Delta island return flow; and
4. Agricultural practices on subsided Delta islands enhance rather than degrade the water quality

of the Sacramento River through the Delta (Ingerson et al. 1956).

Between October 1959 and March 1961, Owen and Nance (1962) monitored surface inflow, drain discharge, precipitation, changes in soil moisture content, weather data, and cropping patterns to estimate DICU water supply and utilization characteristics on Twitchell Island. They concluded that short-term consumptive use rates are not necessarily the rate of channel depletion in the Delta; soil moisture changes need to be considered in computing net channel depletion over short periods; and including soil moisture in computations is expected to increase the computed net channel depletion from the Delta during critical water supply months but decrease computed net channel depletion in

wetter months. Templin and Cherry (1997) employed electrical power-consumption data to estimate Twitchell Island drainage returns and physically measured selected surface-water withdrawals, concluding that drainage return estimates from power-consumption data nearly matched those measured.

Models considered for this study to compute water demands, such as the Delta Evapotranspiration of Applied Water model (DETAW) and IWFM, have been developed to simulate agricultural water use by computing soil water budgets. These models rely on estimates of evapotranspiration (ET), which can be determined using conservation of energy, conservation of mass, meteorological data, and regressions (Siegfried 2012). DETAW was released by the CDWR and UC Davis to improve spatial and temporal estimation of consumptive water use in the Delta for CDWR models CalSim-II and DSM2 (Integrated Hydrological Models Development Unit 2011). Originally known as the Integrated Groundwater–Surface water Model version 2 (IGSM2), IWFM was released to the public by the CDWR in 2002 as a FORTRAN-based mathematical surface–subsurface hydrologic model using an irrigation-scheduling-type approach to simulate ground water interactions including groundwater

flow, stream flow, and surface flow (Dogrul et al. 2010; Integrated Hydrological Models Development Unit 2011). In 2009, the IWFM demand calculator (IDC) version 4.0 was released as a stand-alone root zone modeling tool to estimate irrigation water requirements and route the soil moisture through the root zone for integrated hydrologic modeling (Integrated Hydrological Models Development Unit 2011).

METHODS AND PROCEDURES

This project progressed through the following major tasks:

1. Selection of Delta DICU areas to be examined.
2. Development and confirmation of required topography from existing GIS data, LiDAR, and ground-truthing.
3. Selection of a model incorporating the latest GIS along with cropping and irrigation schemes to predict return flows.

Each task is discussed below, summarizing and extending work by Siegfried (2012).

1. Selection of Study Location

Coordinating with the State Water Resources Control Board and The Nature Conservancy, and considering data availability and island accessibility, we selected Fabian Tract and Staten Island for this proof-of-concept modeling effort (Figure 1). Fabian Tract is in the southern Delta, between Brentwood, Manteca, and Livermore, has an area of 2,700 ha used primarily for agriculture, with subsided field elevations of -3 to 1 m and maximum levee elevations of 10 m. Staten Island, in the central-east Delta, covers 3,700 ha and is primarily agricultural, with subsided field elevations of -5.5 to 0.6 m and maximum levee elevations of 7 m.

2. Development of Delta Island Topography

LiDAR digital elevation model (DEM) data and existing diversion and return data were collected and analyzed to identify likely diversion and return locations,

as well as field drainage patterns in a non-invasive manner. The validity of these predictions was then analyzed by ground-truthing.

Diversion and return data were collected from the California Department of Fish and Wildlife (CDFW) and CDWR. CDFW place of use data, collected from 1993 to 2005, consisted of 5,461 locations with descriptions of the location, owner, type of diversion or return, and use at each location. Water rights claims for 2011 were collected from the California Water Board Division of Water Rights and consisted of a description of location, right type, owner, activity, and use at each claim location. Comparing the CDFW and CDWR data sets through GIS analysis identified differences between the data sets (Figure 4). Most locations provided by CDFW and CDWR data are classified as diversions.

To determine agricultural return locations on Fabian Tract, we attempted to analyze DEM LiDAR data using hydrological analysis tools in ArcGIS, including the hill slope model, basin analysis, and sink analysis. However, the built-in ArcGIS hydrological tools failed to produce valid drainage results where slopes were very mild ($\text{slope} \ll 1\%$), so we made visual observation of island drainage patterns in ArcGIS and we used Google Earth to examine suspected diversion and return locations (Siegfried 2012).

To verify collected data and validate predicted return locations, we surveyed each island for existing diversion and return locations through ground-truthing. Surveying included

1. validating or discrediting diversion and return locations;
2. visually examining the island for unmarked diversions and returns; and
3. determining the activity of located diversions and returns.

Two unexpected challenges were encountered during ground-truthing: (1) determining the status of a diversion or return location as active or inactive; and (2) determining if a location is permanent or temporary. If the location appeared to be well maintained, the site was assumed to be active. However,

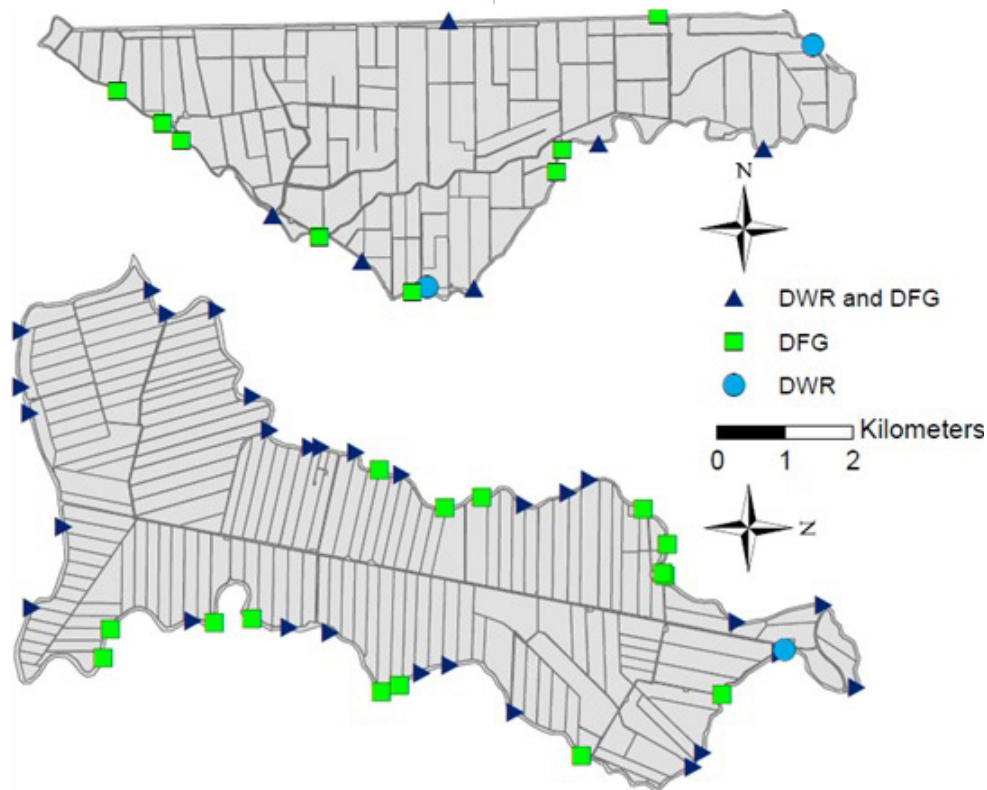


Figure 4 CDFW and CDWR published locations on Fabian Tract (top map) and Staten Island (bottom map)

if the location appeared to be in poor condition, the site was assumed to be inactive. Additionally, while traversing Fabian Tract, we found two previously unidentified diversions. Piping for these diversions was laid over the top of the levee that surrounds Fabian Tract, and appeared to be mobile (Siegfried 2012). For this study, all validated locations were assumed to be permanent, at least during the irrigation season.

We combined the ground-truthed CDFW and CDWR diversion and return locations with the confirmed return locations from LiDAR (Figure 5). On Fabian Tract, with the exception of one predicted return spaced between other predicted returns on the northern edge, the predicted returns were valid and located where expected. Most published diversions were valid, with the exception of one listed but non-existent diversion, two new permanent locations, and two mobile diversions along southern Fabian Tract. On Staten Island, all predicted returns were valid and

no unpredicted returns existed. Additionally, all verified (through Google Earth) published diversion locations and one unpublished diversion location, located through Google Earth, existed.

3. Model Incorporation

We developed hydrologic models and performed water budget simulations with data from distinctive water years to estimate daily volumes of water diverted to and returned from Fabian Tract and Staten Island.

We selected the IDC model to simulate water demands and returns from Fabian Tract and Staten Island based on its capabilities, ease of use, applicability, and consultations with CDWR (Siegfried 2012). IDC here refers to the generic IDC model, whereas IDC-FT and IDC-SI refer to the IDC model applications to Fabian Tract and Staten Island, respectively.

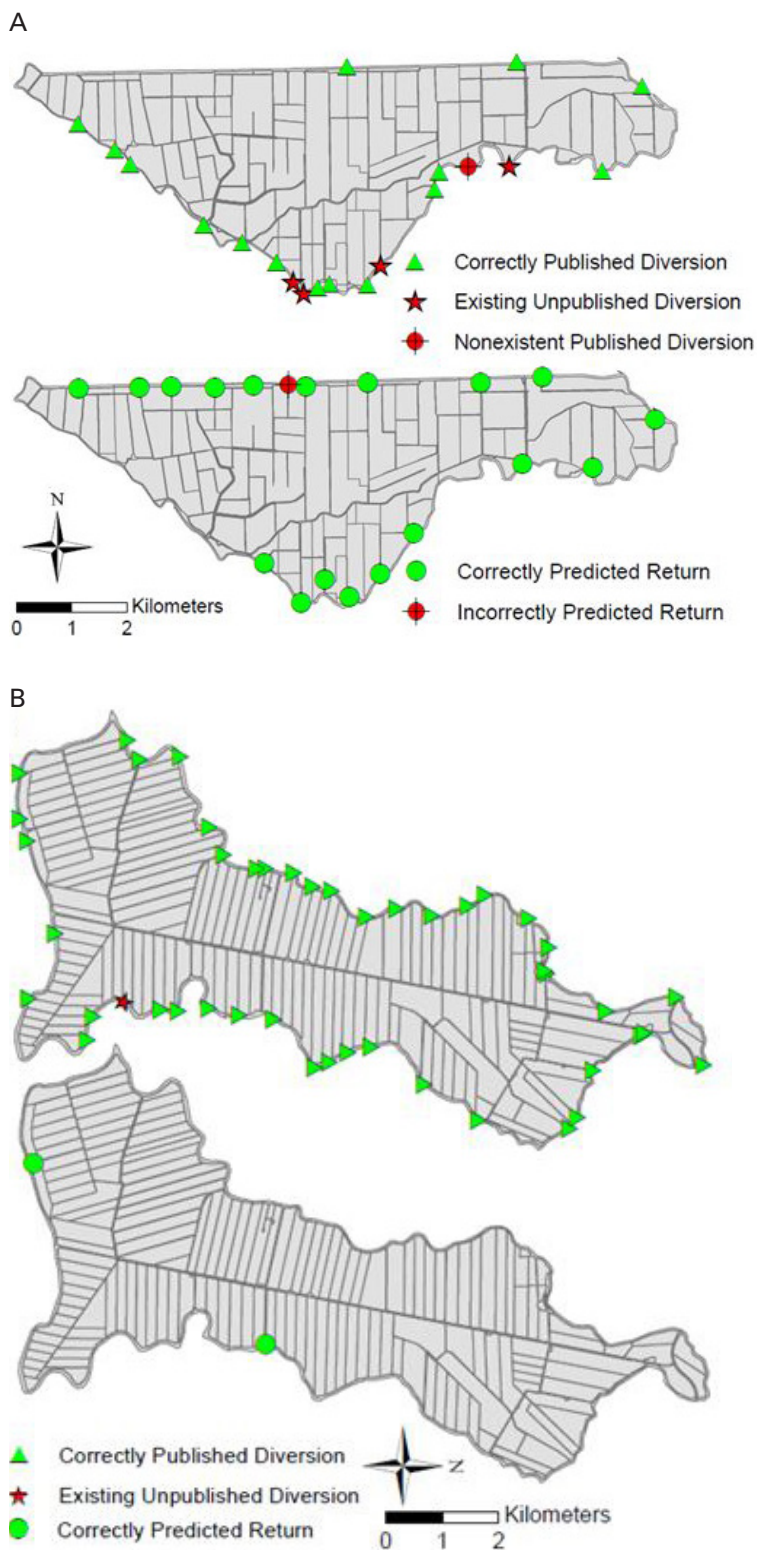


Figure 5 Ground-truthed diversion and return locations on Fabian Tract (A) and Staten Island (B)

Using Esri ArcGIS we manually divided Fabian Tract and Staten Island into subregions, representing fields, levees, ditches, and roads. Then we used Aquaveo SMS to generate grids on Fabian Tract and Staten Island, representing the developed subregions to be used in IDC (Ballard 2012; Siegfried 2012). We used the technique described in the IDCv4.0 documentation (2011) to apply physical soil properties to each grid element.

We used the Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) to compile the soil physical properties (Figure 6). Soil physical properties including field capacity, total porosity, saturated hydraulic conductivity, and soil hydrologic group were averaged over soil horizons for each soil component. Each component-defined soil property was then averaged for each soil map unit. The defined map units were then intersected with the simulation grid cells. For grid cells intersecting multiple map units, we averaged the physical soil properties over each grid cell to attain a single value that defined each soil property for each element. Arithmetic mean values of the pore size distribution index described by Rawls et al. (1982) were assigned to match the dominant soil textures. Additionally, the wilting point for each cell was set to zero.

Monthly ET data from the CalSim 3.0 project for a northern region of the Central Valley of California was assumed to be valid, and we applied it to the IDC models (Integrated Hydrological Models Development Unit 2011). This ET data was divided into four land-use categories used for modeling with IDC:

1. Non-ponded, including grain, cotton, sugar beets, corn, dry beans, safflower, alfalfa, pasture, tomatoes, cucurbits, onions and garlic, almond and pistachios, subtropical, fallow and idle, other deciduous, other truck and other field land-use types;
2. Ponded, including rice and refuge land-use types;
3. Urban, including developed areas; and
4. Native and riparian vegetation.

Most of Fabian Tract is designated as “field.” “Field” areas were assigned land-use values based on data

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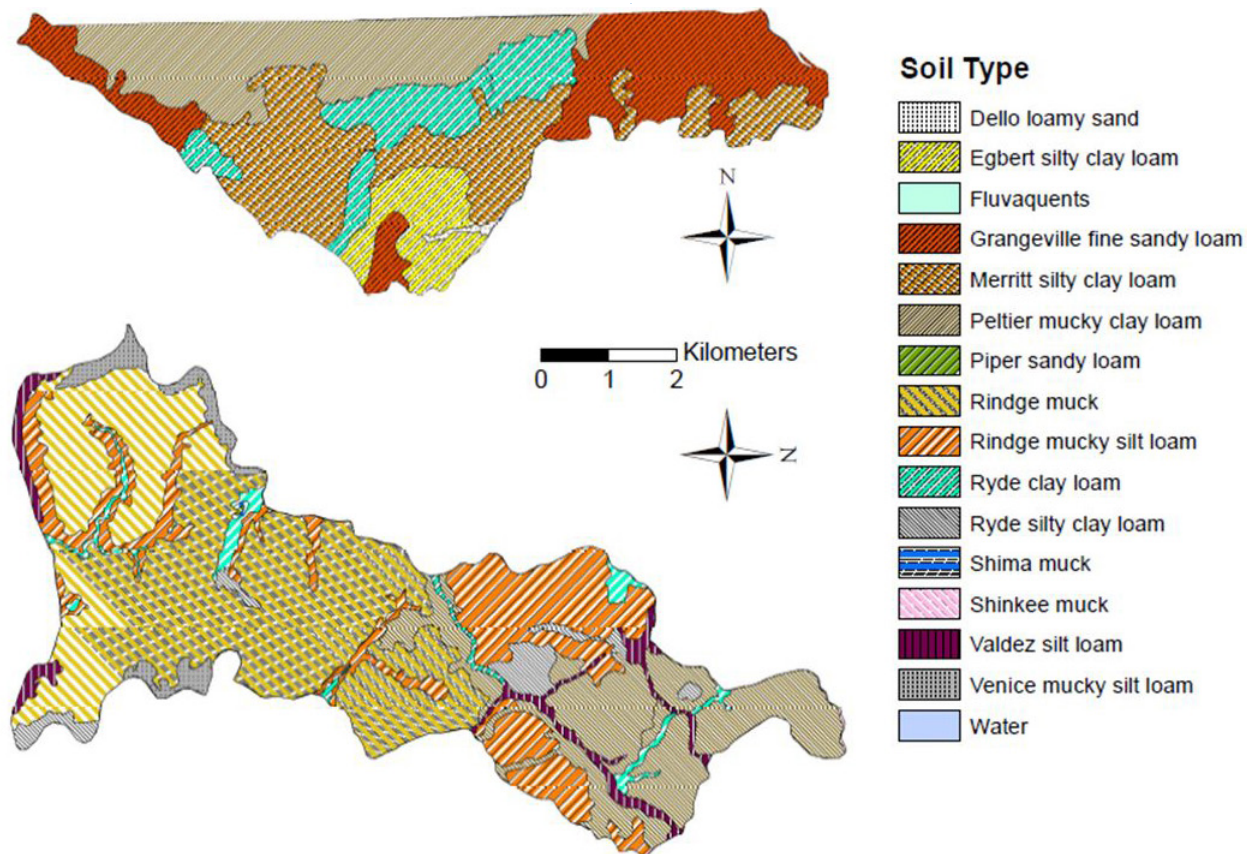


Figure 6 Soil types present on Fabian Tract (top map) and Staten Island (bottom map)

from the National Agricultural Statistics Service (USDA 2011), which provided GIS land-use data for 2007 and 2010. However, elements designated as “road” were assigned to be 90% developed and 10% idle and fallow; elements designated as “gravel road” were assigned to be 60% developed and 40% idle and fallow; elements designated as “levee” were assigned to be 15% riparian, 60% native vegetation, and 25% developed; and elements designated as “ditches” were assigned to be 50% riparian and 50% idle and fallow. Values for areas designated as “road”, “levee”, or “ditches” were based on visual observations made while ground-truthing. Regions designated as “open water” were insignificant (less than 0.05% of the total area), and were incorporated into the riparian land-use category. From intersecting the National Agricultural Statistics land-use map with the “field” elements and assigning land-use values to all other grid elements based on their designation, the primary land-use types on Fabian Tract were corn and alfalfa

whereas the primary land-use type on Staten Island was corn (Figure 7).

Using Thiessen polygons and considering topographical variations, we used meteorological data from the Tracy Weather Station for IDC-FT; we used meteorological data from the Twitchell Weather Station for IDC-SI. To have realistic initial soil-water mixture storage for each model year based on irrigation and precipitation before the model run, we input historical meteorological data into IDC-FT and IDC-SI, allowing for model spin-up. We then used meteorological data for a dry year, 2007, and for a wet year, 2010, for each model simulation respectively (Figure 8). Here, a model year refers to a water year (e.g., October 1, 2006 through September 30, 2007 is water year 2007). Precipitation trends between the meteorological stations remain the same, but the scale of the precipitation events changes between the stations.

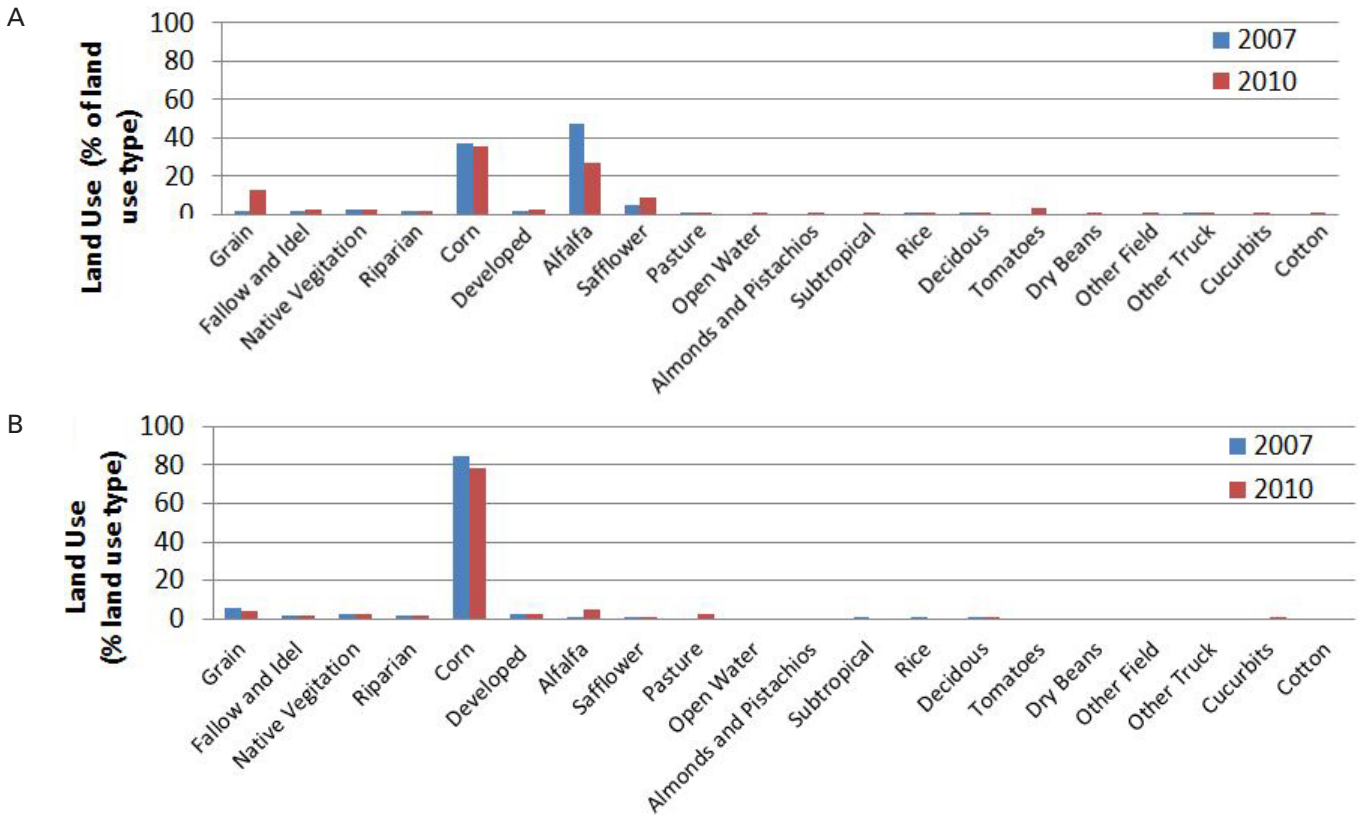


Figure 7 Land use on Fabian Tract (A) and Staten Island (B)

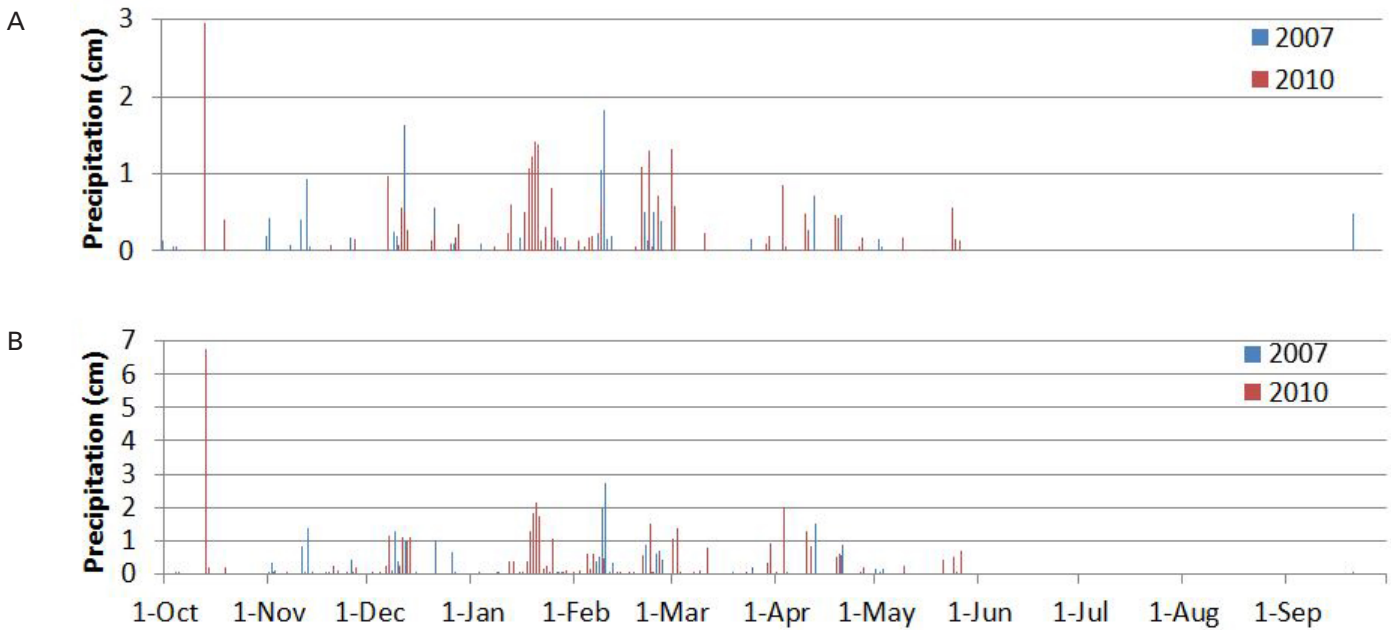


Figure 8 Daily precipitation at the Tracy (A) and Twitchell Island (B) meteorological stations

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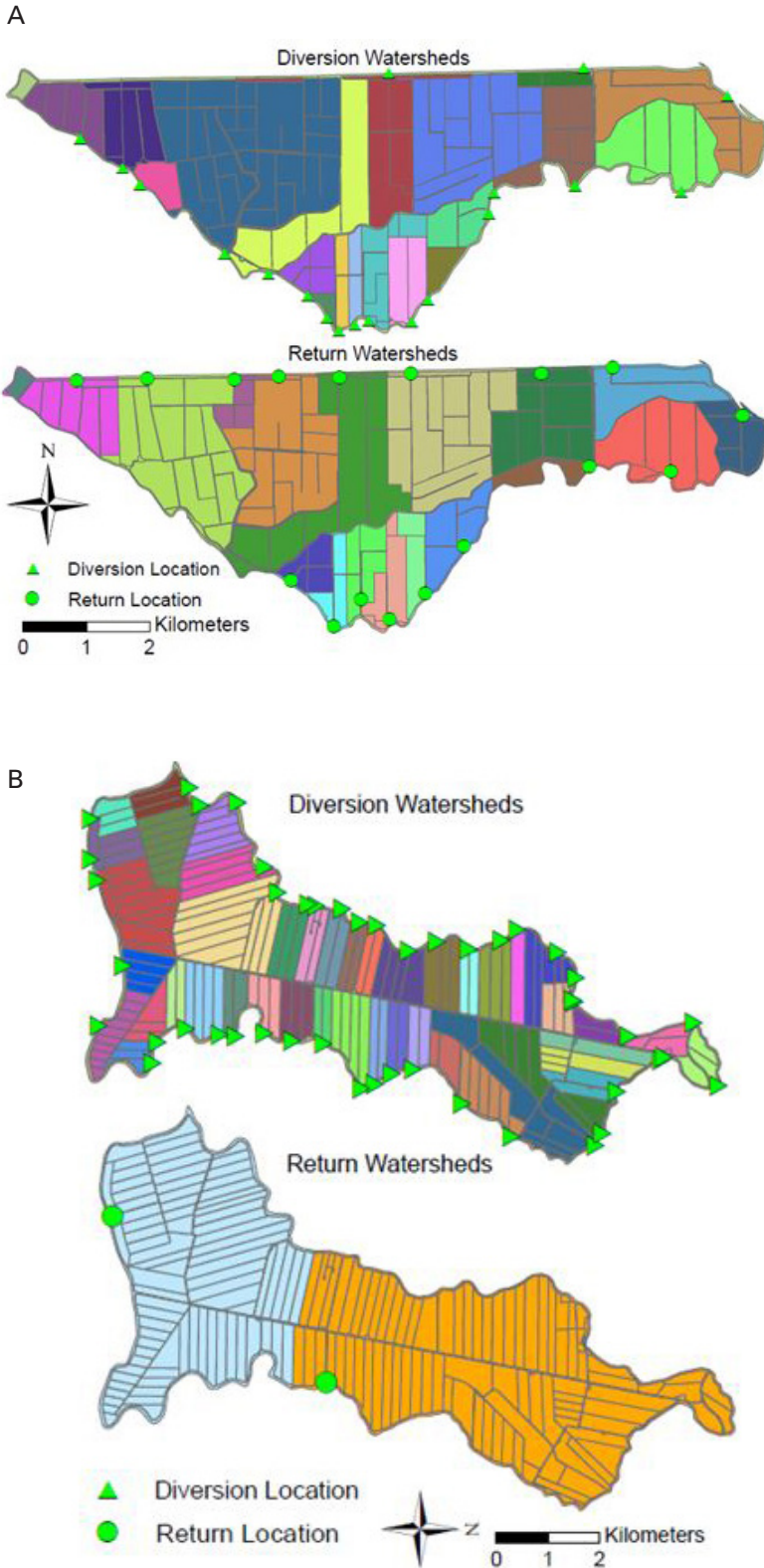


Figure 9 Diversion and return subregion allocations for Fabian Tract (A) and Staten Island (B)

Using the method described in the Development of Delta Island Topography section, we determined diversion and return locations for Fabian Tract and Staten Island sub-regions. Combining sub-regions based on their allocated diversion and return locations, we delineated diversion and return watersheds that represented the total area fed by a diversion source or the total area draining to a return sink, respectively (Figure 9).

The ratio of consumed applied water to the amount of water supplied through irrigation, termed irrigation efficiency, is not user-defined in IDC. Rather, IDC uses a user-defined return flow fraction (the ration of applied water returning to the source, and a reuse fraction, the fraction of applied water assumed to be reused), along with deep percolation values computed dynamically based on soil characteristics, to compute a unique irrigation efficiency for each grid element. For IDC model runs presented here, was assumed the return flow fraction to be 0.2 and the reuse fraction to be 0.05.

To test the performance of IDC-FT during dry and wet conditions, we initially ran the model using precipitation data for 2007 and 2010, input parameters determined from the SSURGO, and land use data for 2007 and 2010. Applied water demands for ponded crops were sensitive to changes in saturated hydraulic conductivity, as suggested by Dogrul et al. (2011). We calibrated the IDC-FT model using a mid-range saturated hydraulic conductivity of $0.05 \mu\text{m s}^{-1}$ for all IDC elements with ponded crops (Siegfried 2012). Diversion and return trends for 2007 and 2010 were similar, however the volume and timing of water diversions between the water years varied (Figure 10). For 2007 and 2010, we observed large spikes in diverted water, signaling that the root zone water content reached a critical state that required diverted water to recharge the root zone water content, and they were followed by smaller slightly offset spikes in returned water. As expected, more diverted water was required for the dry year, 2007, than for the wet year, 2010.

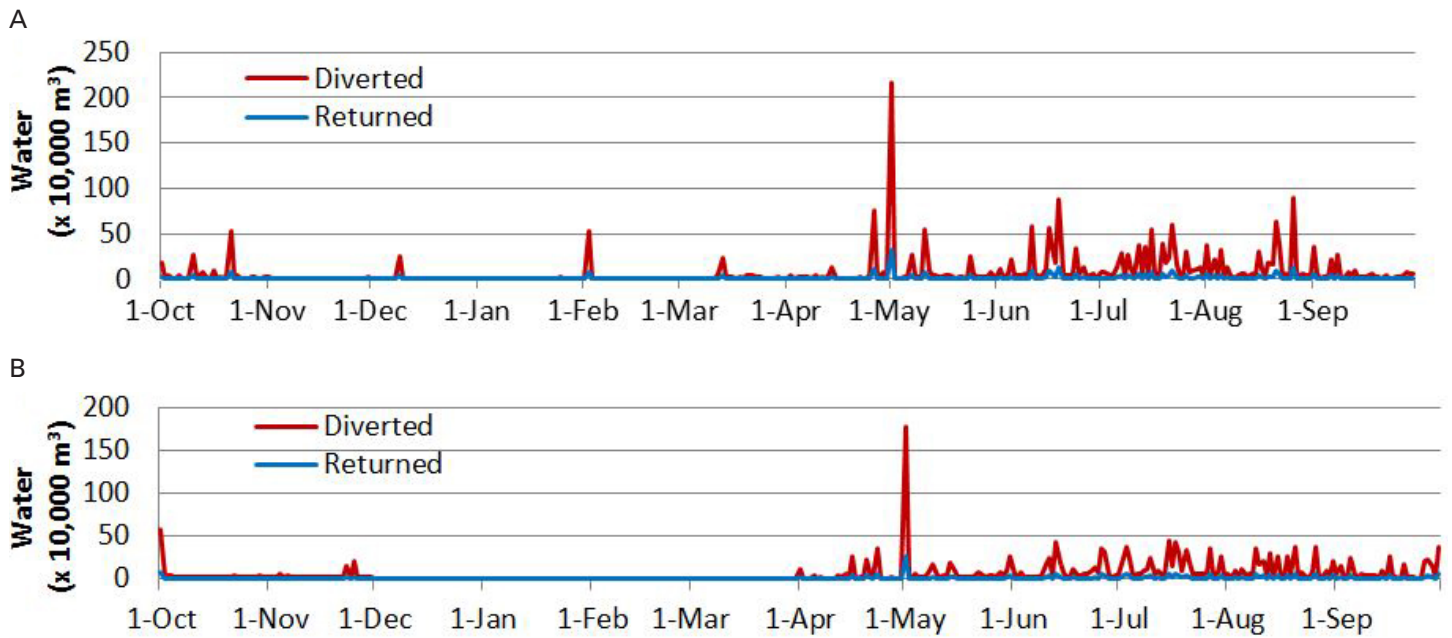


Figure 10 2007 (A) and 2010 (B) total daily diverted and returned water on Fabian Tract

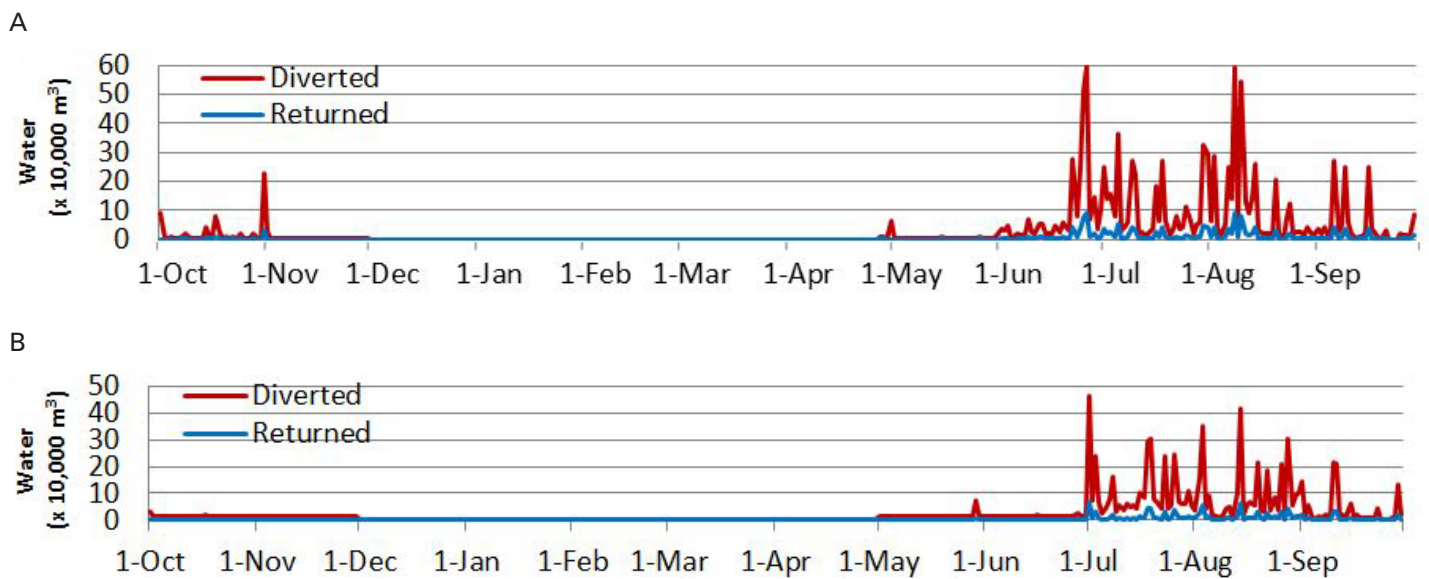


Figure 11 2007 (A) and 2010 (B) total daily diverted and returned water, assuming a constant seepage rate onto Fabian Tract of 0.21 cm m^{-1} rooting depth per month

Owen and Nance (1962) and others have suggested that groundwater seeps from Delta island channels as a function of the soil characteristics and hydraulic gradient. Historically, however, CDWR has assumed a uniform seepage rate across the Delta of 0.21 cm m⁻¹ rooting depth per month (2012 email from T. Kadir to L. Siegfried, unreferenced, see "Notes"). For consistency, we applied this value to IDC-FT (Figure 11). The general trends remained the same: large spikes in diverted water were followed by smaller slightly offset spikes in returned water. However, the irrigation period was significantly reduced and the initial large spikes of diverted water at the beginning of the irrigation period were eliminated, leading to significant reductions in diverted water that appear valid.

We assumed IDC-FT parameters developed through the calibration process described above to be valid for IDC-SI, and applied them to the model.

RESULTS AND DISCUSSION

Diversion and return locations from existing data and ground-truthing were coupled with IDC to model diversion and return flows on Fabian Tract and Staten Island. In the following sections, we present and discuss results of the Delta island topography analysis and IDC-FT and IDC-SI simulations.

Delta Island Topography

Table 1 Summary of diversion and return locations. Near matches to ground-truthed in parentheses ().

	Fabian Tract		Staten Island	
	Diversions	Returns	Diversions	Returns
Ground-truthed	19	17	46	2
Water atlas	13 (10)	13 (10)	45 (40)	2 (1)
DICU	12 (10)	11 (10)	11 (9)	2 (0)

We found undocumented diversions and returns on Fabian Tract and Staten Island. Significant differences in the location and number of diversions and returns exist between the ground-truthed data and

those listed in the Sacramento–San Joaquin Delta Atlas (CDWR 1995) as well as the CDWR DICU models (Table 1). However, the general pattern of diversion and return locations in the Delta Atlas and the current CDWR DICU model were similar to that ground-truthed and are not expected to affect diversion and return flow patterns (Siegfried 2012).

IDC-FT and IDC-SI Model Results

We developed IDC models and integrated them with ArcGIS data, along with cropping and irrigation schemes, to perform a water budget analysis of Fabian Tract and Staten Island (Figure 12). We estimated the daily volume of water diverted and returned from each ground-truthed location (Siegfried 2012). The volume and timing of water diverted and returned at each location varied and are correlated to each other; however, the volume of water returned at a given location is not necessarily determined by the volume of water diverted from a given diversion. For example, a large spike in withdrawn water at a single location may correlate to spikes in returned water at several locations.

The initial IDC models assumed no limiting rates for water diversion or return, allowing unrealistic daily volumes of water to be modeled as diverted or returned. We applied maximum daily flow rate capacities—estimated from pump unit use coefficients, pump horsepower ratings, and given flow rate capacities—at each location. For unrated locations, rate capacities were assumed to be the average of the known pump or siphon capacities of a similar size. For diversion siphons or pump diversions of an unknown size, we assumed the flow rate capacity to be enough to meet annual demand.

Applying flow rate capacities at each location while maintaining the total volume of water modeled by IDC as diverted and returned significantly flattens and broadens the diversion and return peaks. The volume and timing of water diverted and returned at each location still varies with peaks in diverted water followed by smaller offset peaks in returned water. However, flow rate limitations reduce peak diversion and return rates (Figure 13). To maintain the same volume of water being diverted or returned, the dura-

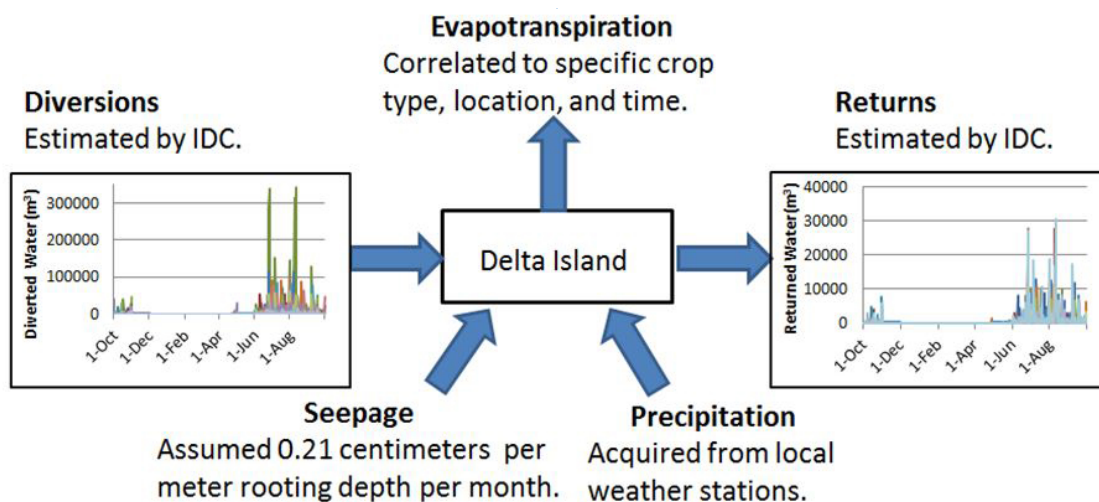


Figure 12 Summary table of water budget analysis

tion of peak withdrawals and returns is increased, allowing smaller daily rates of diverted and returned water to meet demands.

To visually examine the volume of water diverted and returned from Fabian Tract and Staten Island, we integrated IDC-FT and IDC-SI results into ArcGIS. On Fabian Tract in 2007 and 2010, most diverted water on Fabian Tract was withdrawn from the southern side of the island, and most agricultural runoff was returned on the northern side of the island. On Staten Island in 2007 and 2010, water was fairly evenly diverted from around the island and returned from the two given return locations.

The diversion and return patterns of Staten Island significantly differ from those modeled on Fabian Tract. In part, this difference results from subsidence differences on the two tracts. Fabian Tract is less subsided, making siphoning difficult or infeasible for some areas. Additionally, the locations where siphoning is possible are generally at the lowest point on the island, so siphoned water at these locations would need to be piped—and possibly pumped—uphill to irrigate crops. So, water is generally pumped onto the highest parts of Fabian Tract and then drains to the lower regions for irrigation and return (Figure 14A). Conversely, Staten Island is so subsided that water for irrigation can easily be siphoned onto the island at most locations; irrigation runoff then drains to a central ditch for return water, which runs the entire

length of the island. As a result, Staten Island has many more diversion locations than Fabian Tract, but Fabian Tract has more returns than Staten Island (Figure 14B).

Sufficient diversion and return data for model validation was inaccessible during the modeling effort presented herein. For this reason, we obtained post-processed model results of diversion, return, and seepage values for Fabian Tract and Staten Island for comparative purposes from the current DICU model used by the CDWR and a recently developed DICU model in DETAW, also developed by the CDWR (2012 email from L. Liang to L. Siegfried, unreferenced, see "Notes"). The results of the CDWR DICU and DETAW models needed to be post-processed to make them comparable to the IDC-FT and IDC-SI model results. These post-processed results are referred to as Post-DICU and Post-DETAW.

The annual fraction of water routed through each Fabian Tract and Staten Island DICU node was combined with GIS analysis to compare to IDC-FT and IDC-SI results (Figure 15). Post-DICU trends match fairly well to IDC-FT and IDC-SI trends of diverted water. On Fabian Tract, most water is withdrawn from the southern side of the island, whereas on Staten Island, a fairly even proportion of water is withdrawn from all sides of the island. However, the Post-DICU trends poorly match the IDC-FT and IDC-SI trends

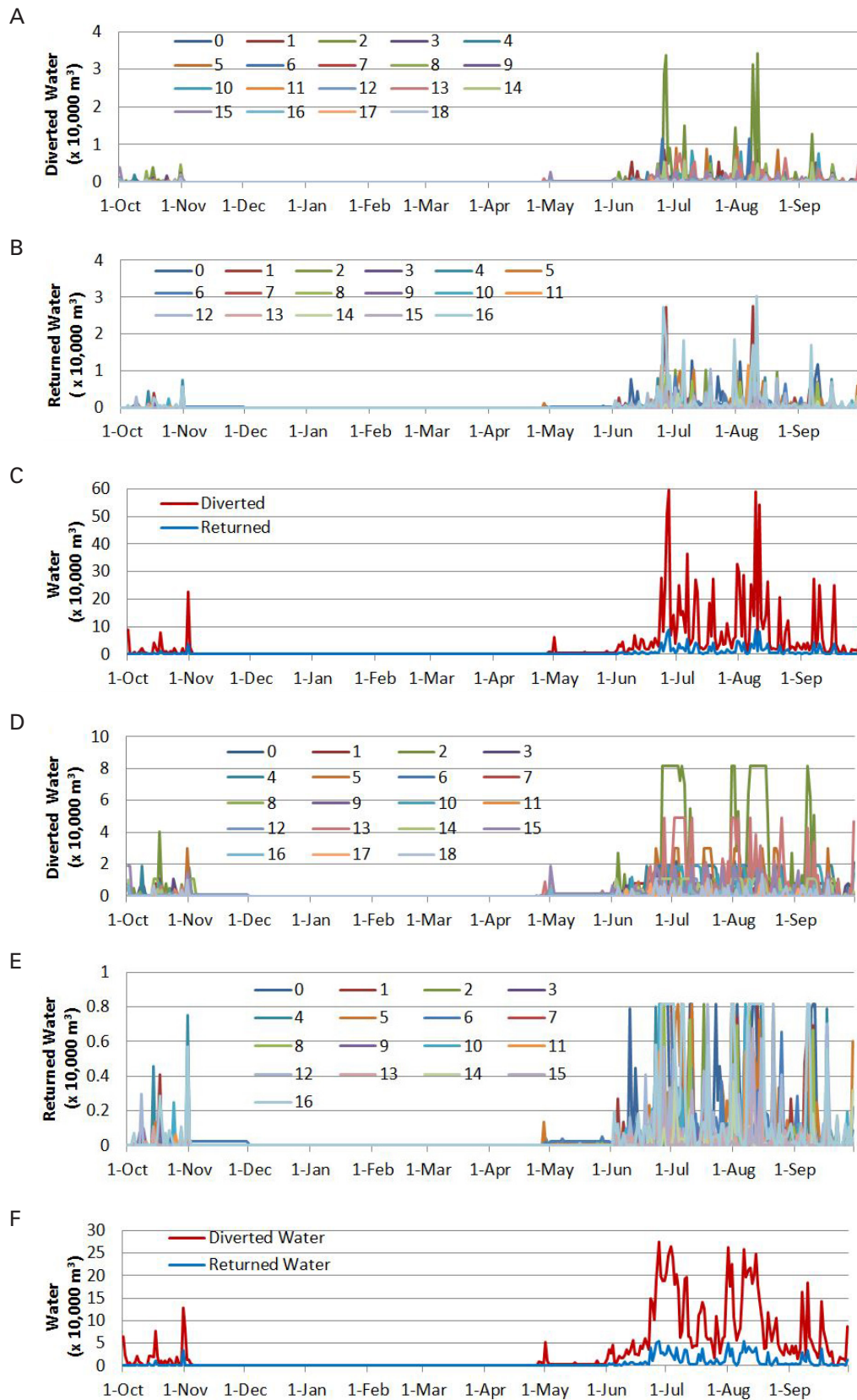


Figure 13 Daily diverted (A) , returned (B) , and total diverted and returned water (C) on Fabian Tract for 2007 from ground-truthed locations. Daily diverted (D), returned (E), and total diverted and returned water (F) on Fabian Tract for 2007 from ground-truthed locations applying diversion and return rate limits.

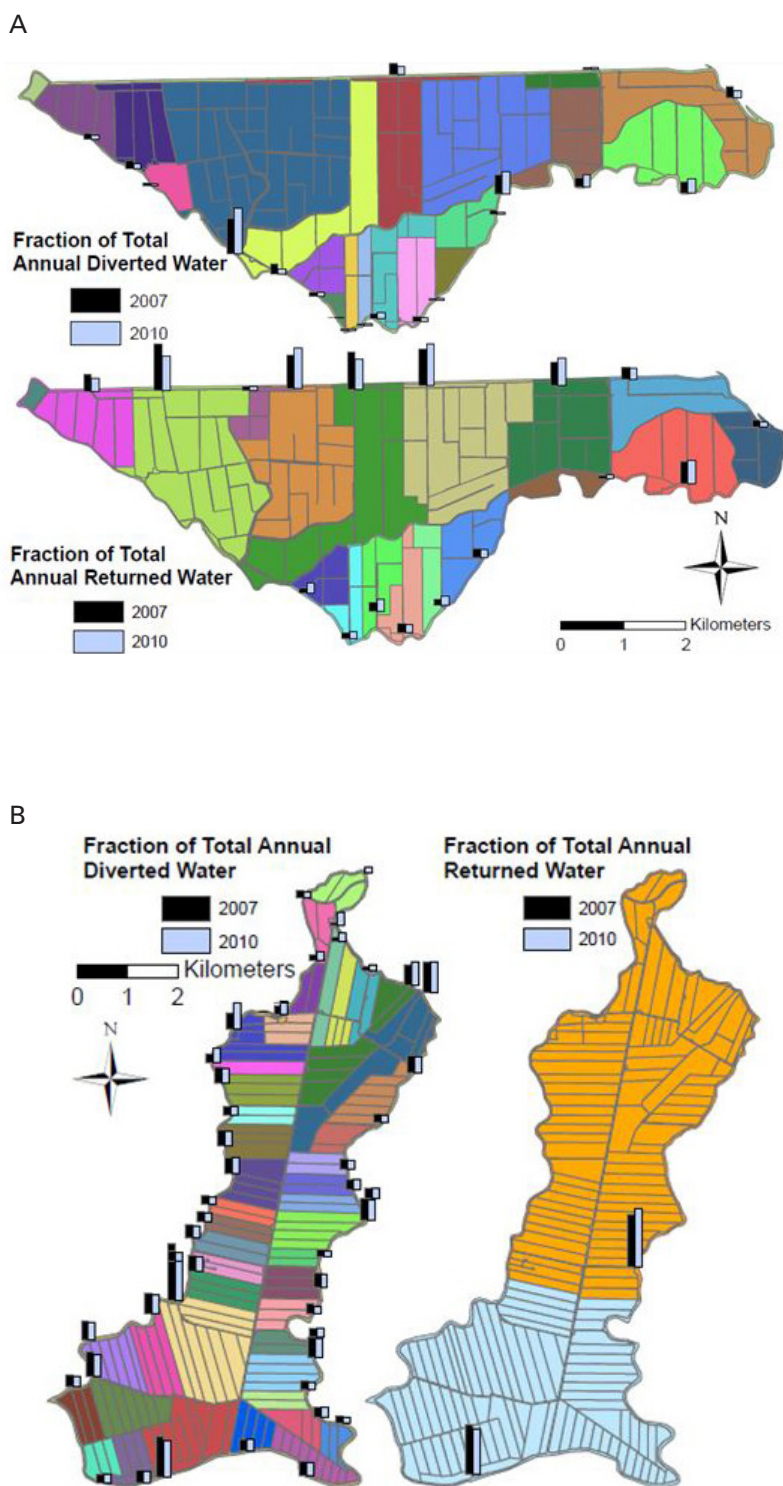


Figure 14 Fabian Tract (A) and Staten Island (B) diversion and return patterns, showing the annual fraction of total water diverted and returned at a given location per watershed for 2007 and 2010

of returned water. Post-DICU results indicate that most agricultural runoff is returned back to the southern side of the island, whereas IDC-FT shows most water returned to the northern side of Fabian Tract. Additionally, Post-DICU results indicate that most water is returned at the southernmost return on Staten Island, whereas IDC-SI shows a relatively even split of returned water at the two return locations on the island, which agrees with pump records and local understanding. Based on the topography analysis of Fabian Tract and Staten Island using LiDAR DEM data as previously described, Post-DICU results are expected to be less accurate than the IDC model results.

We also compared net channel depletion, diverted water, returned water, and seepage values for the IDC models to Post-DICU and Post-DETAW results (Figure 16). Since Post-DICU, Post-DETAW, and IDC-FT areas are of different size, we converted volume units into unit depths (hectare-meters per hectare).

General trends of net channel depletion and diverted water on Fabian Tract are the same across models, with most water estimated to be diverted during the peak growing season, May through September, as expected. However, the volumes and timing of net channel depletion and diverted water vary between the models. Post-DICU and Post-DETAW both divert water earlier in the agricultural season than IDC-FT; Post-DICU applies less water than IDC-FT and Post-DETAW at the end of the agricultural season. Additionally, post-DICU and post-DETAW divert water during winter, which can affect returned water volumes during these months (Figure 16). Post-DICU and Post-DETAW show a trend in peak return discharges offset from the peak growing season, which is not shown by IDC-FT. Some differences are caused by different model input values.

The IDC-FT and Post-DICU seepage estimates are fairly constant throughout 2007, with an exception in February for the Post-DICU results. The hydraulic gradient between Delta islands and

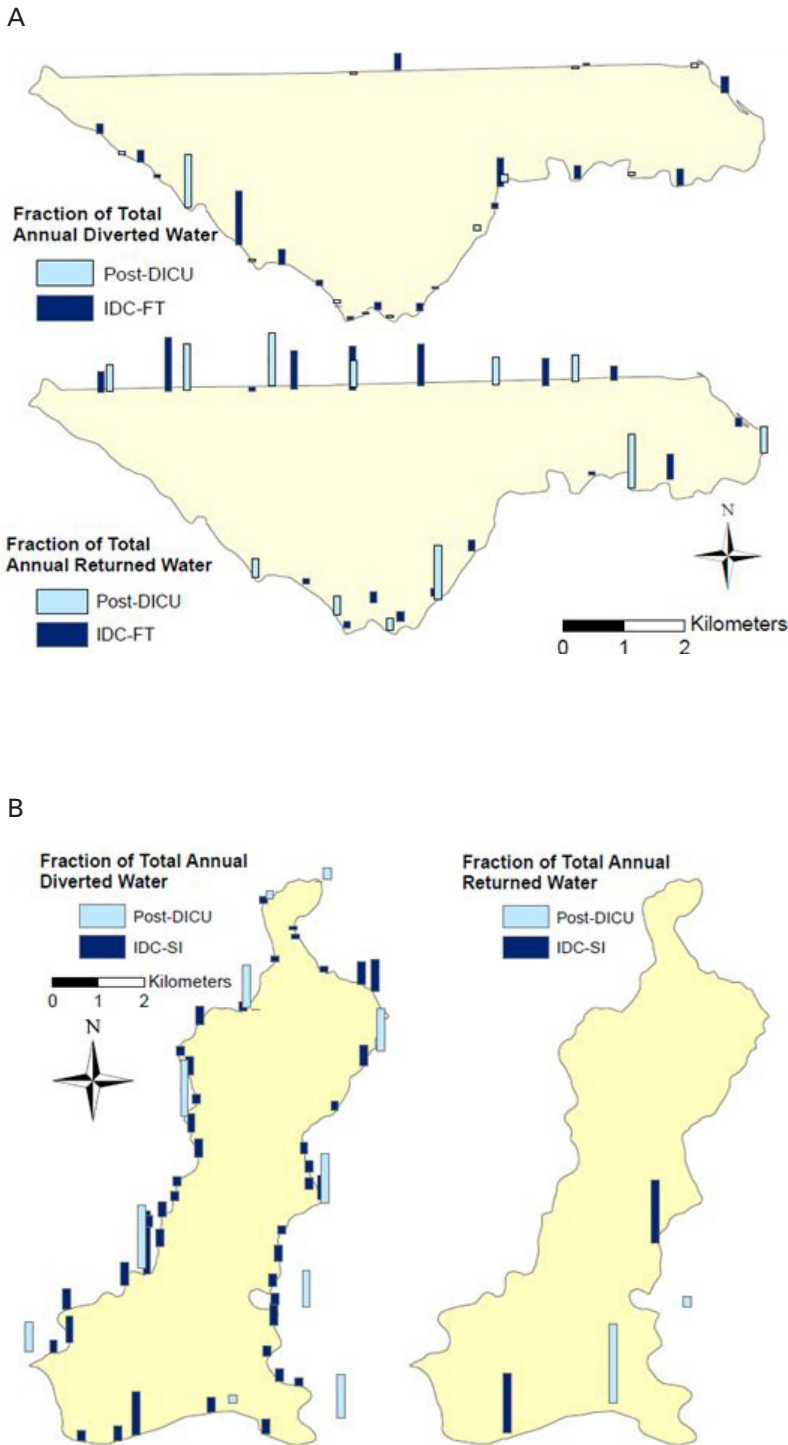


Figure 15 Comparison of IDC-FT to Post-DICU (A) and IDC-SI to Post-DICU (B) results for 2007, showing the total annual fraction of water diverted or returned at respective locations

neighboring channels does not change much seasonally, but the Post-DETAW results show seasonal seepage variations.

Post-DICU and Post-DETAW estimates roughly match the IDC-SI annual estimates of net channel depletion and diverted water. However IDC-SI return volume and seepage estimates are lower. Changing the return flow or reuse fractions would change the overall irrigation efficiency and could be used a calibration parameter; however, this may not represent actual farming practices. Varying seepage or precipitation values may also explain the difference. The assumed seepage rate—the same among IDC-SI, Post-DICU, and Post-DETAW—is a function of crop rooting depth. If the models used different types of crops during the same water year, different seepage volumes of water would be available for consumption (ET). This may explain differences in seepage. The same general trends of net channel depletion and diverted water on Fabian Tract are also on Staten Island. Again, the general trends of returned water and seepage on Fabian Tract are also on Staten Island. However, the return and seepage values of the post-DICU and post-DETAW results significantly exceed the IDC-SI model estimates.

The 1960 study of DICU on Twitchell Island conducted by Owen and Nance was the only report found during the literature review process that included measured seepage data along with diversion and return flow data. For this reason, we compared the Owen and Nance study and IDC model runs. IDC model runs were not made for 1960, but were performed for both a wet and dry water years and are assumed to bracket conditions similar to those in 1960. Since the Islands are of a different size, unit depths of water will be used to compare Owen and Nance’s 1960 study results to the IDC 2007 and 2010 model results for both Fabian Tract and Staten Island.

The annual volume of diverted water reported by Owen and Nance (1962) matches nicely with the IDC-FT and IDC-SI results, but differences in net channel depletions, returns, and seepage exist (Figure 17A). The most significant difference in

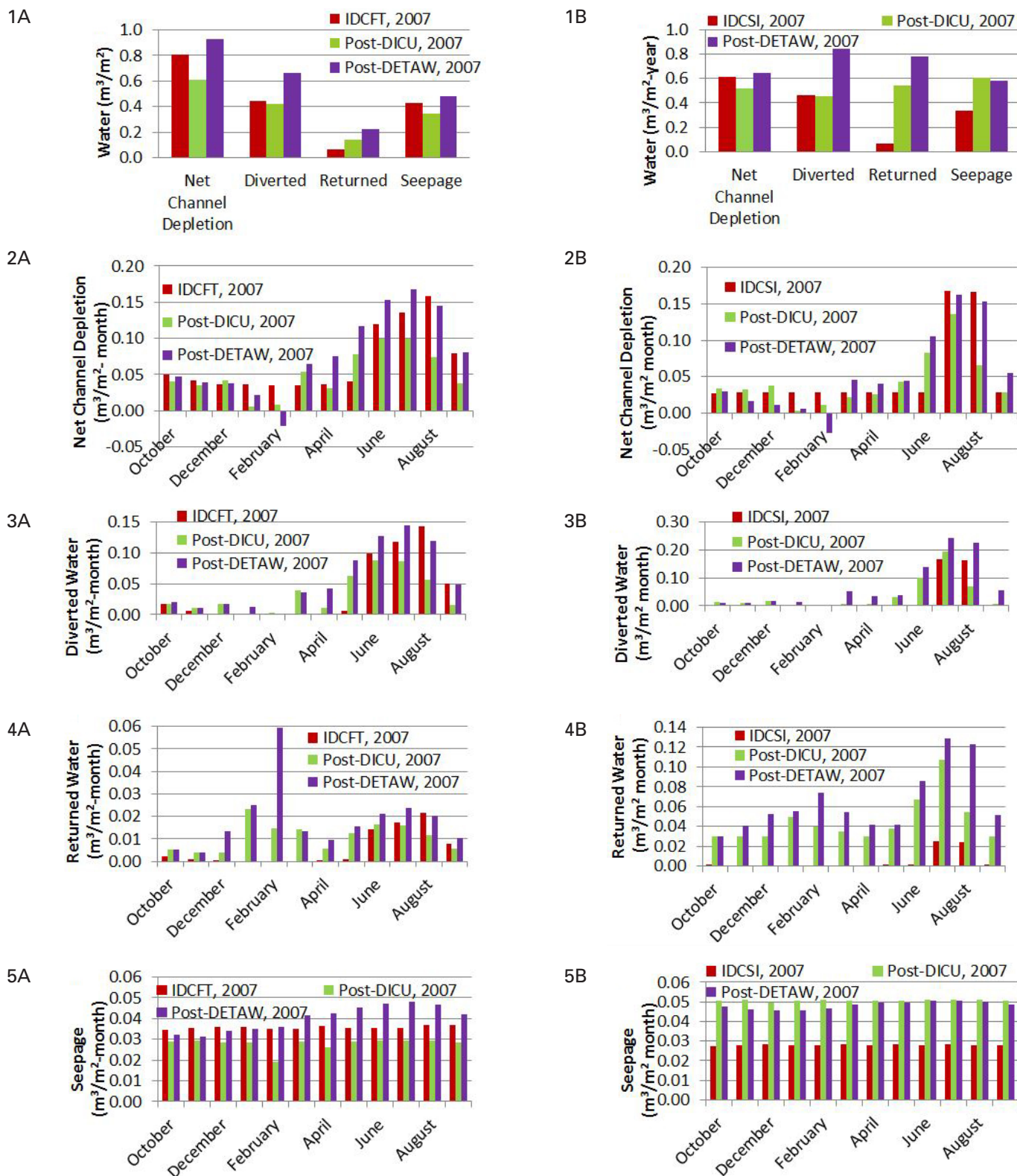


Figure 16 Model comparison of (1) annual net channel depletion, diverted water, returned water and seepage; (2) monthly net channel depletion; (3) monthly diverted water; (4) monthly returned water; and (5) monthly seepage on (A) Fabian Tract and (B) Staten Island

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estimated values and those reported by Owen and Nance are for returned water. This difference may be the result of the many parameters that affect agricultural practices such as soil characteristics, irrigation efficiency, precipitation, and leaching practices.

Net channel depletions and diverted water trends are similar between estimated values and those reported by Owen and Nance, with net channel depletions and diversions increasing during the summer and decreasing during the winter (Figures 17B and 17C). However, Owen and Nance report water being diverted during the winter whereas no winter diversions are estimated by the IDC model, perhaps because of leaching practices not accounted for in the current IDC models.

Returned water trends vary between estimated values and those reported by Owen and Nance (Figure 17D). Since Owen and Nance report water being diverted in the winter, runoff and returned water would be expected during the winter, as reported. The IDC model does not identify a need for diverted water during the winter, so the only water returned would be from overland flow of precipitation and seepage. If soil saturation is not reached from precipitation and seepage alone, no overland flow would occur, and so no water would need to be returned during the winter, as estimated by the IDC model runs.

Owen and Nance report a greater rate of seepage than the IDC models estimate; however, the seepage rates remain fairly constant, as expected (Figure 17E). This rate is a function of the hydraulic gradient and soil characteristics, which vary among Delta islands.

Where Delta water quality is related to DICU, future implementations of DICU models using IDC (DICU-IDC models) can improve Delta water quality estimates. Land-use effects can be estimated through GIS analysis, permitting better correlations between agricultural land-use type and return water quality. Unlike previous DICU models, these correlations can be directly incorporated into the DICU-IDC models. Additionally, these models would capture daily DICU variations missed in older DICU models (Figure 18).

DICU-IDC estimates daily diversion and return flows; however, the accuracy of these estimates is uncer-

tain because of a lack of data. Comparing measured return flow data (CALFED 2007) to modeled return flow estimates on Staten Island, we observed large deviations in the return flow patterns and rates (Figure 19). Methods to calibrate the IDC-DICU models exist: model coefficients can be used to adjust the volume and timing of flows and data can be post-processed on a field-by-field scale (Siegfried 2012). However, each Delta island is unique, and may require measured data to calibrate DICU-IDC models for each island.

For example, Staten Island is highly subsided and slopes downwards to the south. Thus, even though the island's crops for the model years were predominantly corn, the irrigation schedules were offset, with irrigation starting on the north and progressing to the southern side of the island. In addition, there are over 100 ha of return flow ditches, which provide significant temporary storage on Delta islands, so agricultural runoff is not immediately returned to channels.

Applying an offset irrigation schedule to the IDC-SI results in the post-processor, and monitoring temporary return ditch storage, the modeled Staten Island return flow pattern appears to better match the measured data (Figure 20). However, the return flow volumes are still significantly less than those measured, and the irrigation patterns still deviate. The difference in return flow volumes result from deviations in seepage rates, diversion rates, or a combination of the two. Model error was introduced by averaging soil characteristics and assuming a constant seepage rate across Delta Islands, this error may be shown here by the differences of measured and modeled flows on Staten Island. Agricultural irrigation practices are inherently stochastic, varying between locations and farmers. Since the stochastic nature of the irrigation practices on Staten Island and Fabian Tract cannot be determined non-invasively, they were not accounted for in this modeling effort. Such stochasticity may explain some of the variations between daily observed and modeled irrigation practices.

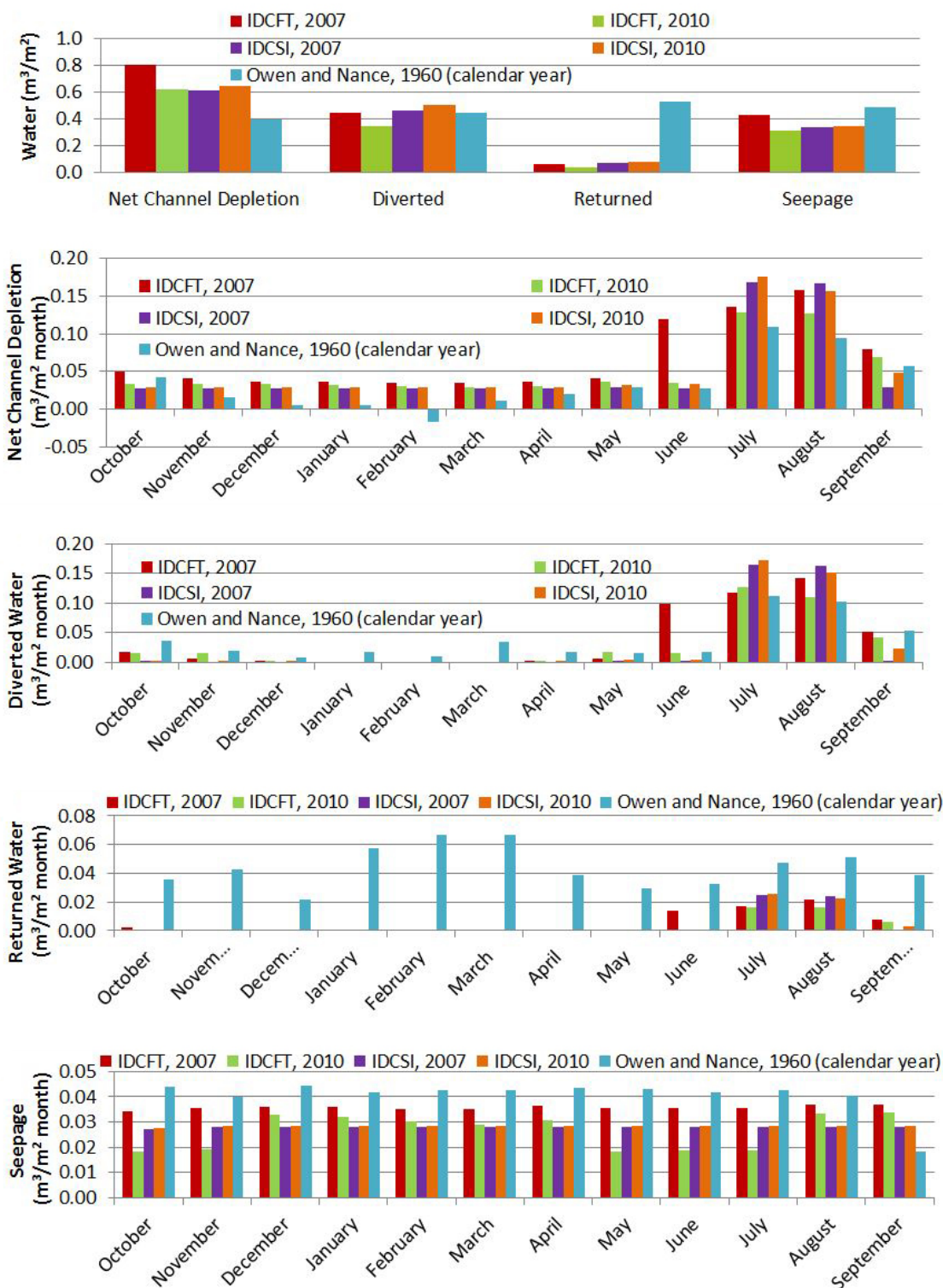


Figure 17 Comparison of (A) annual net channel depletion, diversion, returned, and seepage estimates to values reported by Owen and Nance (1962); (B) monthly net channel depletion estimates to values reported by Owen and Nance (1962); (C) monthly diversion estimates to values reported by Owen and Nance (1962); (D) monthly return estimates to values reported by Owen and Nance (1962); (E) monthly seepage estimates to values reported by Owen and Nance (1962).

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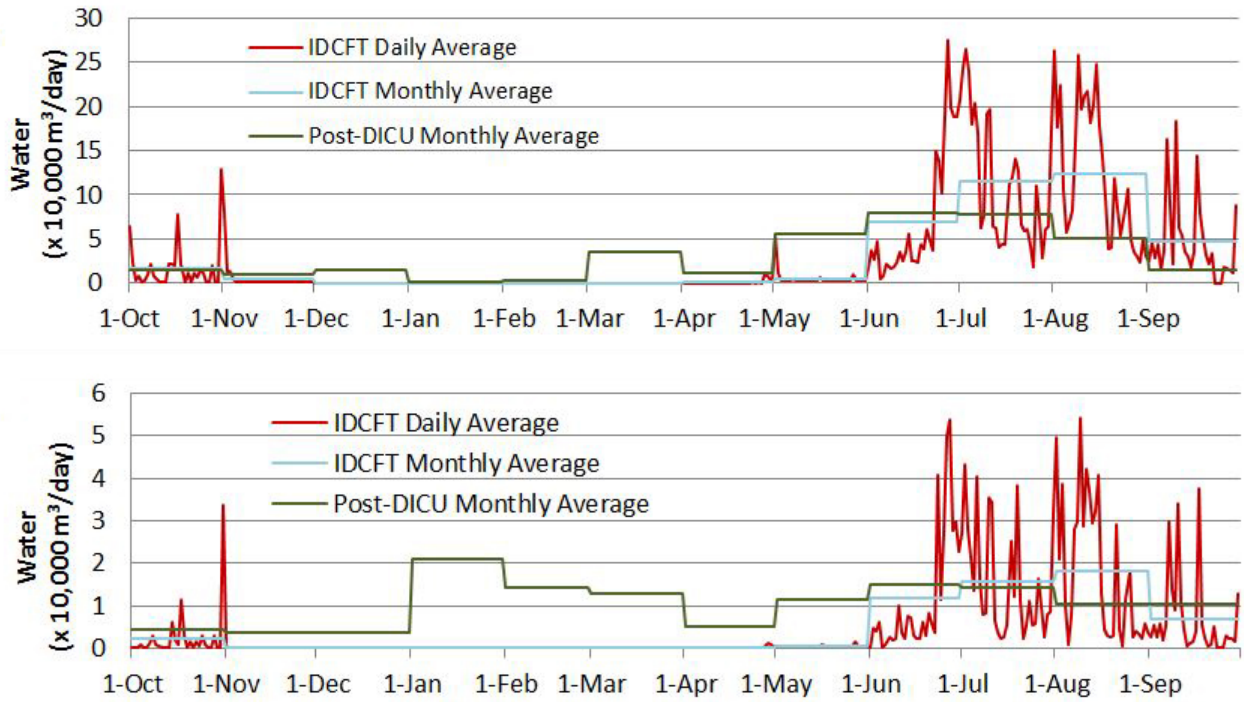


Figure 18 Comparison of Fabian Tract 2007 average daily vs. monthly diversion rates (A) and average daily vs. monthly return rates (B)

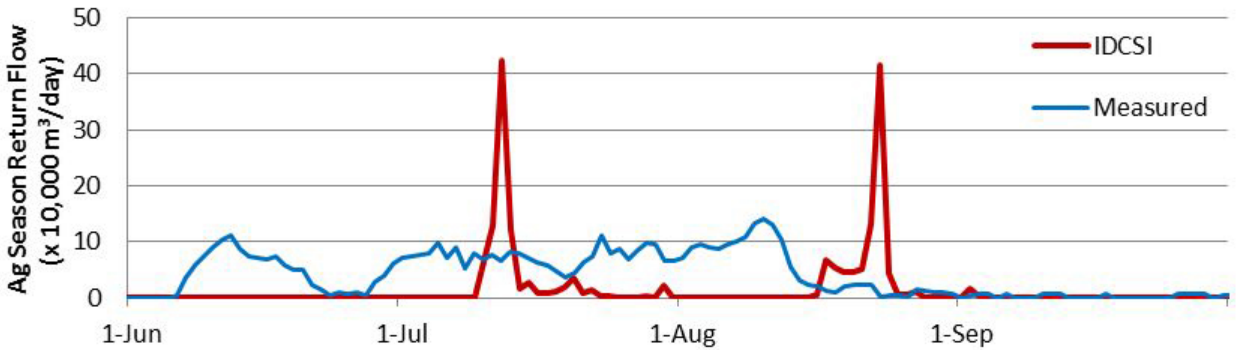


Figure 19 Measured vs. modeled daily return flow rates on Staten Island

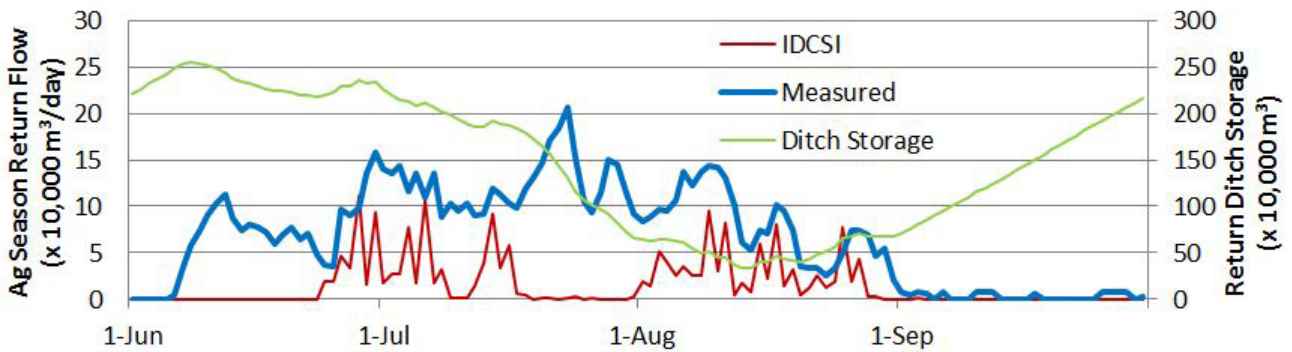


Figure 20 Measured return flow data vs. offset return flow estimates on Staten Island

Estimating Diversions and Returns for the Entire Delta

In-Delta diversions and returns are a significant source of uncertainty in water uses required for water quality modeling. Based on the requirements to analyze Fabian Tract and Staten Island using the methods described herein, a substantial, but not overwhelming, modeling effort would be needed to analyze the entire Delta. A larger requirement would be the collection and digestion of field data to improve and test model calibrations, and inform sensitivity analysis.

Such Delta-wide DICU-IDC modeling would improve upon current DICU models by more accurately modeling diversion and return sources, bracketing the maximum and minimum daily diversion and return volumes, and providing a method to link diversion and return volumes to water quality. However, without data to calibrate DICU-IDC models, such a modeling effort might not substantially improve current DICU estimates of diversion and return volumes.

CONCLUSIONS

To better understand and manage the Delta, a collaborative, integrated approach was used to estimate DICU on a higher resolution, and base diversion and return locations on topography rather than simple geographical approximation. Fabian Tract and Staten Island locations were selected.

The non-invasive method used to identify diversion and return locations appears to work well. Historical diversion and return data, which varied between data sets and did not document some diversion locations and most return locations, was improved upon through GIS analysis. GIS analysis accurately predicted most diversion and return locations. Differences exist between the ground-truthed diversion and return locations and those listed in the Sacramento-San Joaquin Delta Atlas (1995), as well as in the current DICU model. However the trend of diversion and return locations on Fabian Tract and Staten Island in the current DICU model is similar to the pattern observed from ground-truthing. The close proximity of incorrect diversion and return locations to existing

locations is not expected to significantly affect in-Delta diversion and return patterns but could cause local modeling errors.

However, the current DICU model allocation of agricultural runoff appears often to be incorrect and should be improved. The aggregate of such agricultural runoff errors would make even greater errors in local water quality estimates. When compared to historical DICU data and other models, DICU-IDC model net channel depletions and diversion estimates appear valid. However, DICU-IDC model return and seepage estimates varied from other existing models and historical data. The trends of return flow in the IDC models do not match the post-DICU trends well, probably because of different model inputs. The DICU-IDC models do not account for non-irrigation season practices, such as soil leaching and seepage rates, which vary among islands. Such practices could only be included through local ground-truthing from farm managers.

Diversions and returns in the entire Delta can be modeled using the methods described here in a moderate effort. The developed DICU-IDC model would improve upon current DICU models by more accurately modeling diversion and return sources; bracketing the maximum and minimum daily diversion and return volumes; and potentially providing a method to link diversion and return volumes to water quality. However, any new DICU model will likely not improve upon current DICU volume estimates without further field data collection to calibrate and test developed models.

Daily return flow rates from the IDC model correlated poorly to observed daily return flow rates on Staten Island. It seems likely that daily diversion rates from the IDC model are also poorly correlated to actual daily diversion rates. To improve upon these correlations, data concerning the stochastic nature of agricultural irrigation practices within the Delta need to be acquired and incorporated into model development. Such data collection was beyond the scope of this project, but is important for future work.

LIST OF ACRONYMS AND MODELS

ArcGIS—a geographical information system which provides a functioning geographic database to manage geographic information and provide a platform for geographic inquiries (Johnston et al. 2001).

Aquaveo SMS—Aquaveo Surfacewater Modeling System, serving as a graphical user interface to generate geographical information system objects, including nodes, vertices, arcs, and polygons, for model development (Ballard 2012).

CDWR—California Department of Water Resources

CDWR DICU—Delta Island Consumptive Use model currently in use by the California Department of Water Resources.

CDFW—California Department of Fish and Wildlife

DETAW—Delta Evapotranspiration of Applied Water model released by the CDWR and University of California, Davis to improve spatial and temporal estimation of consumptive water use in the Delta (Snyder et al. 2009).

DICU—Delta island consumptive use, referring to agricultural use of water within the Sacramento–San Joaquin Delta.

DICU-IDC models—Generically refers to Delta island consumptive use models using the Integrated Water Flow Model Demand Calculator.

ET—Evapotranspiration, the cumulative total of evaporation and transpiration.

Google Earth—a web based geographical information system which maps the Earth.

IDC—Integrated Water Flow Model Demand Calculator version 4.0 was released as a stand-alone, root-zone modeling tool to estimate irrigation water requirements and route the soil moisture through the root zone for integrated hydrologic modeling (Integrated Hydrological Models Development Unit 2011).

IDC-FT—Developed Delta island consumptive use model of Fabian Tract using the Integrated Water Flow Model Demand Calculator.

IDC-SI—Developed Delta island consumptive use model of Staten Island using the Integrated Water Flow Model Demand Calculator.

IGSM2—Integrated Groundwater–Surface water Model version 2, a groundwater–surface water model developed by the CDWR, which is the precursor to the Integrated Water Flow Model Demand Calculator (Integrated Hydrological Models Development Unit 2011).

IWFM—Integrated Water Flow Model that the CDWR released to the public in 2002 as a FORTRAN-based mathematical surface–subsurface hydrologic model using an irrigation-scheduling-type approach to simulate ground water interactions, including groundwater flow, stream flow, and surface flow (Dogrul et al. 2010; Integrated Hydrological Models Development Unit 2011).

LiDAR—Remote sensing technology which measures distance by analyzing reflected light illuminated on a target by a laser.

NRCS—Natural Resources Conservation Service.

Post-DETAW—Post-processed results for comparative purposes of a Delta Island consumptive use model developed by the California Department of Water Resources using Delta Evapotranspiration of Applied Water mode as the modeling platform.

Post-DICU—Post-processed results for comparative purposes of the Delta Island consumptive use model currently in use by the California Department of Water Resources.

SSURGO—Natural Resources Conservation Service Soil Survey Geographic Database.

ACKNOWLEDGEMENTS

This report would not have been possible without support from the State Water Resources Control Board, The Nature Conservancy, John Herrick, Tariq N. Kadir, Emin C. Dogrul, Josué Medellín-Azuara, and Angeles Casas Planes.

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