Identifying Patterns of Crop Water Consumption in the Imperial Valley, California using Remotely Sensed Estimates of Evapotranspiration and NDVI

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EXECUTIVE SUMMARY

Since the Quantification Settlement Agreement of 2003 was enacted, the annual volume of water delivered to the Imperial Valley of California has decreased which could negatively impact the Salton Sea. Without a water-use mitigation plan, 500 million cubic meters (Mm^3) of inflows to the sea are anticipated to decrease each year after 2017. Satellite-derived maps of ET from the Earth Engine Evapotranspiration Flux (EEFlux) and Landsat Normalized Difference Vegetation Index (NDVI) were used to map 2010 water use (ET) and relative ET footprints (REF) at the field unit for potential water conservation management opportunities.

Annual EEFlux ET had an RSMD of 308 mm $year^{-1}$ (mean annual percent difference = 25%) when compared to a six-year surface water balance. Using a linear regression correction method, RSMD reduced to 90 mm $year^{-1}$ (mean annual percent difference = 6%).

Two methods were used to identify areas with potential for water conservation: highest water use (HWU) and highest REF (HREF) both of which identified the total area that collectively consumed a total 500 Mm^3 $year^{-1}$, the anticipated reduction of inflows. Conservation efforts would focus on 14% and 20% of the valley area under HWU and HREF methods, respectively.

PROJECT OBJECTIVES

Since the Quantification Settlement Agreement (QSA) of 2003 was signed, there has been a decrease of annual water delivery to the Imperial Valley (IV). A decrease in water delivery could negatively affect the Salton Sea which relies on IV return flows (Cohen, 2014). Efforts to mitigate Salton Sea deterioration include direct water transfers of Colorado River water to the sea however this will end in December 2017 (State Water Resources Control Board, 2002). Without a mitigation plan after 2017, inflows to the Salton Sea are projected to decrease by 500 Mm^3 $year^{-1}$ until 2026 (Table 1 from Cohen and Hyun, 2006).

Satellite-derived maps of evapotranspiration (ET) and relative ET footprints (REF) across the IV were used to identify croplands where increased efficiencies and/or reallocation could help continue mitigation inflows into the Salton Sea after December 2017. ET maps from the Earth Engine Evapotranspiration Flux (EEFlux) application and vegetation vigor maps from Landsat calculated using the Normalized Difference Vegetation Index (NDVI) were used. ET and NDVI maps were generated to address the original, overarching questions: *What is the accuracy of EEFlux ET when compared with a valley water balance? What volume of water could be conserved in the Imperial Valley using two conservation methods?* However, the latter question was adjusted to ask: *Where are areas of HWU and HREF? How much of a total area is required to generate ET equivalent to the anticipated reduction of inflows to the Salton Sea?* A slight change to the objectives allowed the internship to address potential areas for water conservation in addition to mapping patterns of water use across the IV.

Essential to the internship was the understanding of remote sensing and surface energy balance modelling. The general tasks of the project included downloading and processing satellite imagery, assessing the validity of the satellite-derived ET maps, and generating scripts to perform statistical analyses of data for faster processing.

Skills gained during the internship reflected many of the requirements for a Hydrologist position with the USDA and US Army Corps of Engineers (USACE). The agency sought someone who had courses in hydrology, physical and atmospheric sciences, meteorology, and management or conservation of water resources. Additionally, specialized experiences included knowledge of hydrological processes and geographic information systems (GIS), remote sensing and imagery analysis, database management, data visualization, and hydrological modeling.

PROJECT APPROACH

Study Region

The Imperial Valley is located within Imperial County, California and is bordered by Mexicali, Mexico to the south and the Salton Sea in the north (Figure 1). The area is semi-arid with minimal annual precipitation (Allen et al., 2005). Agriculture in the valley is primarily sustained by imported Colorado River water via the All-American Canal (Clemmens, 2008) and all water not stored in the soil or consumed through ET becomes overland flow and enters the New and Alamo river entries. Croplands in the area cover 1,730 km^2 (71% of valley area) and were based on the 2010 United States Bureau of Reclamation (USBR) crop dataset.

Data Acquisition and Processing

ET maps (30 m) were downloaded using EEFlux beta version 1.2.1 (http://eeflux-level1.appspot.com) and encompass the period from December 2009 to January 2016 for Landsat scene path 39 row 37 (Table 1). NDVI maps of the same dates were downloaded from the USGS Landsat repository of surface reflectance products. Some maps were derived from the Landsat 7

(ETM+) satellite (as highlighted in grey in Table 1) and contain data gaps. All gaps in the maps used for the analysis were spatially interpolated using a spline interpolation tool in ESRI ArcGIS software. Spatially-interpolated maps were linearly interpolated to derive daily values of ET and NDVI for each year from 2010 – 2015. Annual ET sums and NDVI means were calculated and used to make six annual maps each.

EEFlux ET Validation with an Annual Water Balance

Estimates of ET using EEFlux were compared to ET calculated from an annual surface-water balance using discharge data from the United States Geologic Survey (USGS). The gauges (Figure 1) used in the water balance solve ET as a residual of surface inflow less surface outflow (Eq. 2)

$$ET\ (Mm^3\ yr^{-1}) = (PK - CC) + NR1 + \ P + \ UG - \ NR2 - AR1 \qquad (2)$$

where *ET* is in million cubic meters per year (Mm^3), *PK* is the gauge on the All-American Canal below Pilot Knob (09527000), *CC* is the gauge on the Coachella Canal above Pilot Knob (09527590), *NR1* is the gauge on the New River at Calexico (10254970), *UG* are any ungauged flows that flow into the New and Alamo rivers at the study area boundary, *NR2* is the gauge on the New River at Westmorland (102555550), and *AR* is the gauge on the Alamo River at Niland (10254730). On average, 11% of *PK* measured water is delivered to farms east of the Coachella Canal each year before measurement at *CC* (Clemmens, 2008) so the difference between volumes recorded at *PK* and *CC* must be considered before quantifying ET.

P was mean annual precipitation collected by the California Irrigation Management System (CIMIS) at three meteorological stations within the IV: Calipatria/Mulberry, Meloland, and Seeley (Figure 1). *UG* flows were all areas of the Salton Sea Watershed that flowed into the study area and were not included in the watershed defined by the *NR1* gage (depicted white in Figure 1), because they were assumed to be insignificant. The surface-water balance is supported by the literature (Allen et al., 2005; Burt, 1999; Clemmens, 2008) however neglecting seepage and ground water storage would overestimate ET using the water balance method.

The water balance area was 2,047 km^2 and was used to calculate area-normalized ET rates to compare with original EEFlux ET data. Wetlands in the study region were excluded when EEFlux ET was calculated. ET maps were converted to volumes by multiplying by the spatial area of each pixel (900 m^2) then the root mean squared deviation (RMSD) from the canal water balance was calculated.

EEFlux ET Correction

EEFlux ET annual values were linearly regressed against water balance ET to derive a single correction factor that was applied to the annual EEFlux ET maps. Corrected ET (ET_{CF}) was compared to water balance ET to derive corrected RMSD.

Mapping Highest Water Use (HWU)

The annual 2010 ET map was used to calculate the highest water using (HWU) fields in the IV. 2010 was selected as it was matched the available USBR crop data. HWU fields were defined as those which consumed 500 Mm^3 of water through ET after field mean ET values were sorted in descending order.

Mapping Highest Relative ET Footprints (HREF)

The relative ET footprint (REF) was designed to identify areas that have high ET and low NDVI, which could be priority areas for management. REF was calculated as

$$REF_i = \frac{M_{ET} \times 100}{n} - \frac{M_{NDVI} \times 100}{n} \qquad (3)$$

where the REF_i is the difference between the ET percentile and the NDVI percentile for the 2010 maps at field i, M_{ET} and M_{NDVI} are the rank order of mean annual ET (mm year^{-1}) and NDVI sorted from lowest to highest, n is the total number of observations, and 100 is a constant to normalize values from 0 to 100. The volumetric ET total per field was cumulatively summed according to descending REF values. “Highest” REF pixel and field areas were those which contributed to the first 500 Mm^3 of ET once REF values were organized in descending order.

PROJECT OUTCOMES

EEFlux ET Validation and Correction

EEFlux ET overestimated water balance ET each year over the six-year period (Figure 2) but correlated well (R^2=0.80). RSMD of uncorrected EEFlux ET was 308 mm year^{-1} with a mean absolute percent difference (MAPD) of 25%. After applying a correction factor of 0.76 (ET_{CF}) the RSMD reduced to 90 mm year^{-1} (MAPD = 6%) with largest errors in 2014 and 2015 (Table 2)\. The mean bias after correction is similar to results of other automated ET models (Messina, 2012; Morton et al., 2013b) and shows that EEFlux can estimate regional ET when ground data is limited which may be beneficial for water resource managers.

Areas for Potential Water Conservation

Implementing remotely sensed products, such as EEFlux ET and Landsat NDVI can be useful to identify variabilities of water use at the field unit and to identify areas for potential water conservation as exemplified in the HWU and HREF methods.

When mapped, HWU and HREF fields displayed similar spatial distributions. Both methods highlighted fields in the centered north of the valley and east of the Alamo River however HWU fields (Figure 3) were not as concentrated in these parts of the valley as much as HREF fields (Figure 4). A total of 906 fields were HWU in 2010 and occupied 244 km^2 (14% of the valley area). Using the HREF method, I identified 1,382 fields as priority areas for management. HREF fields had a larger total than HWU fields, occupying 351 km^2 of the total valley cropland area (20% of the IV).

CONCLUSIONS

EEFlux ET correlated well to a valley water balance (R^2=0.80) and its biases, once corrected, display the module’s ability to reliably estimate water consumption when ground observational data is unavailable.

Using HWU and HREF methods, I identified fields which could potentially be focused on in future water conservation efforts. HWU and HREF areas were associated with fields which contributed to the first 500 Mm^3 of cumulatively distributed values however there are differences amongst the methods. HWU highlights fields with the highest ET while HREF find high ET fields with low relative vigor (NDVI). Conservation efforts to generate Salton Sea mitigation flows using HWU and HREF methods would focus on 20% or less of the total IV cropland area.

The internship project relates to my interest in reducing water use across semi-arid environments, particularly in California landscapes. Prior to the internship, I expressed interest in water resource management and remote sensing, primarily to increase my skills to become a competitive candidate for hydrology and remote sensing positions. One hydrologist position with the USACE implemented knowledge of hydrologic processes, GIS, and remote sensing. The USDA-WRPI internship was an experience to better my skills for a career such as the USACE Hydrologist.

OUTREACH AND FUTURE RESEARCH

Mapping areas of water consumption can ensure availability of water resources however, the methods do not consider other variables, namely, socio-economic impacts. Generating additional mitigation flows for the Salton Sea using HWU and HREF methods implies a removal of or decreased water-use in fields which may impact economic return to the valley and/or employment opportunities. Future research could include HWU and HREF impacts on related economic productivity and how societal values are reflected in water management strategies.

Presented research will be expanded into two separate papers which will be prepared for publication. The two papers: “Validating and Correcting EEFlux ET for Regional Water Resource Management” and “Opportunities for Water Conservation in Imperial Valley, California using EEFlux ET and Landsat NDVI” will be submitted to the Journal of American Water Resources Association (JAWRA) and the International Journal of Remote Sensing (IJRS).

After discussing our research with Michael Cohen, senior research associate at the Pacific Institute, we plan to submit the findings to Tina Shields of the Imperial Irrigation District.

APPENDICES

Figures

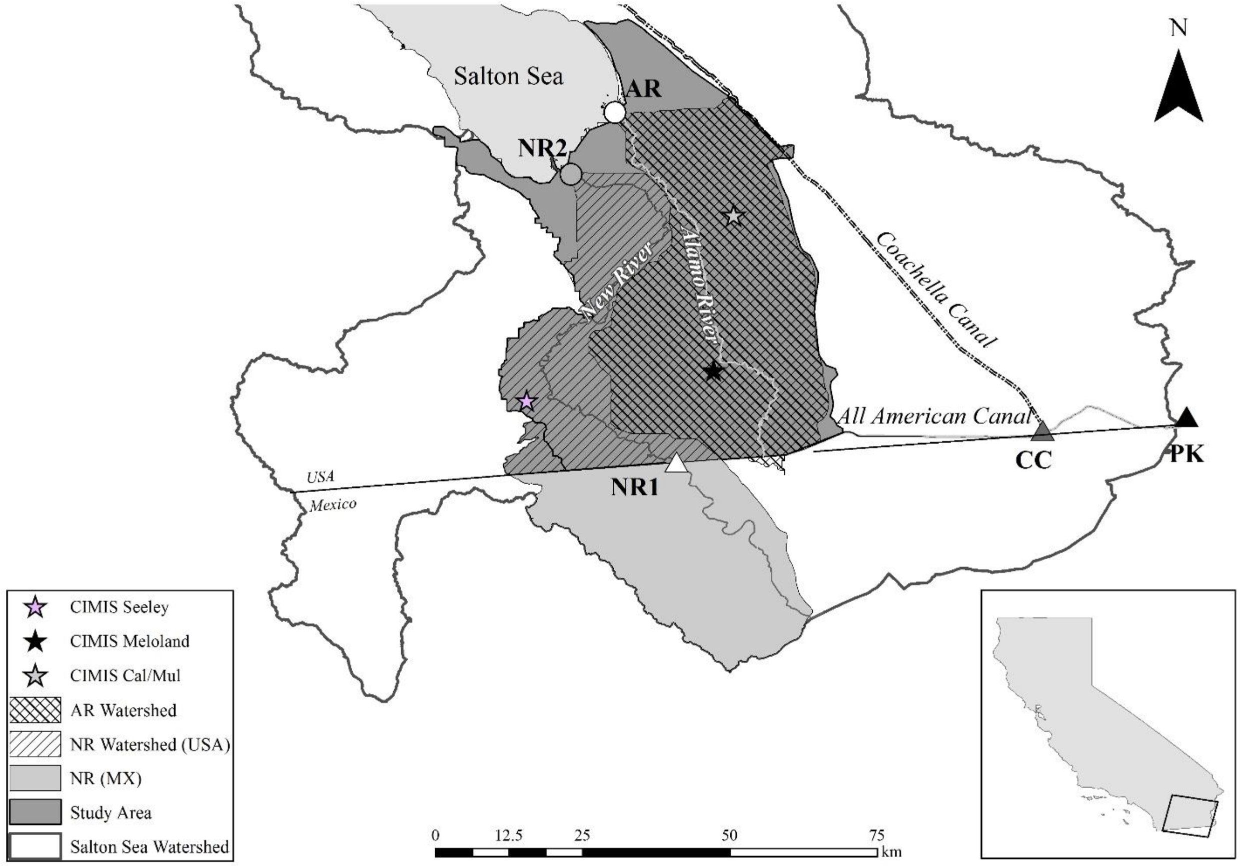

Figure 1: The Imperial Valley is within the south end of Imperial County, California. Subwatershed boundaries (New and Alamo) were used to determine water balance area for validation. The valley is near the center of Landsat scene Path 39 Row 37 (inset).

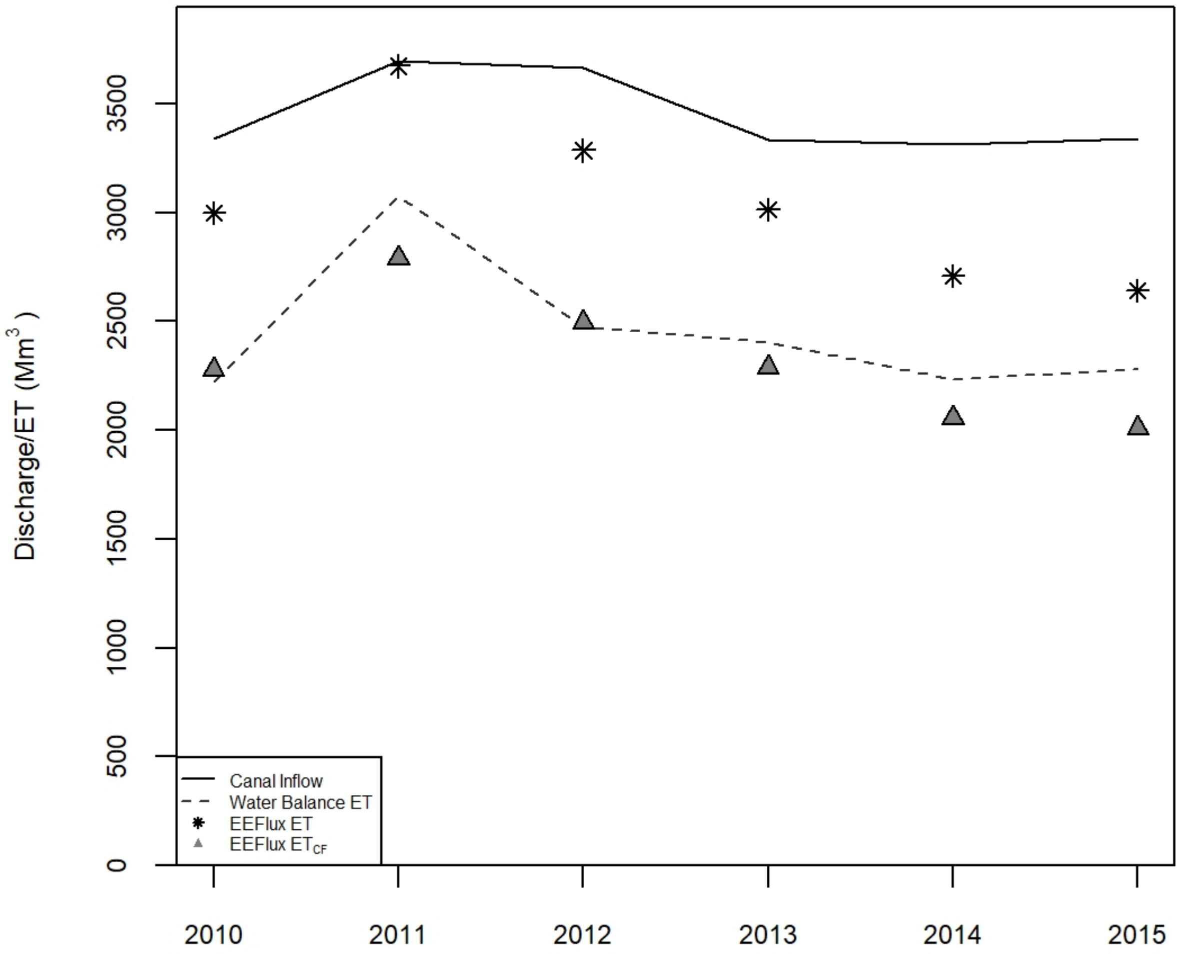

Figure 2: Uncorrected EEFlux ET maps overestimate water balance ET on average by 25%. Corrected maps (ET$_{CF}$) decrease biases to 6%, underestimating in all but 2010 and 2012 years.

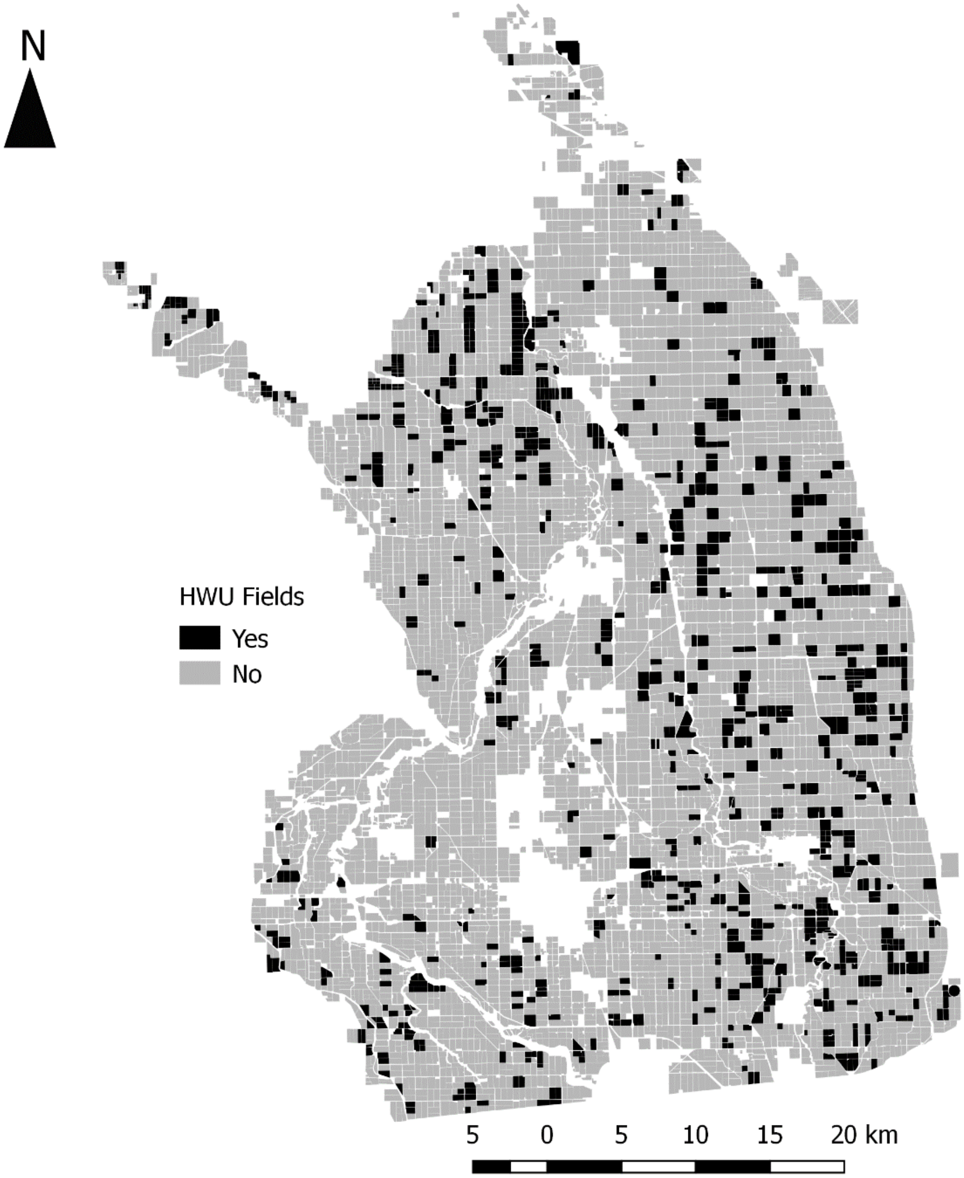

Figure 3: HWU fields are primarily located in the north and east however include some scattering of fields in the southwest.

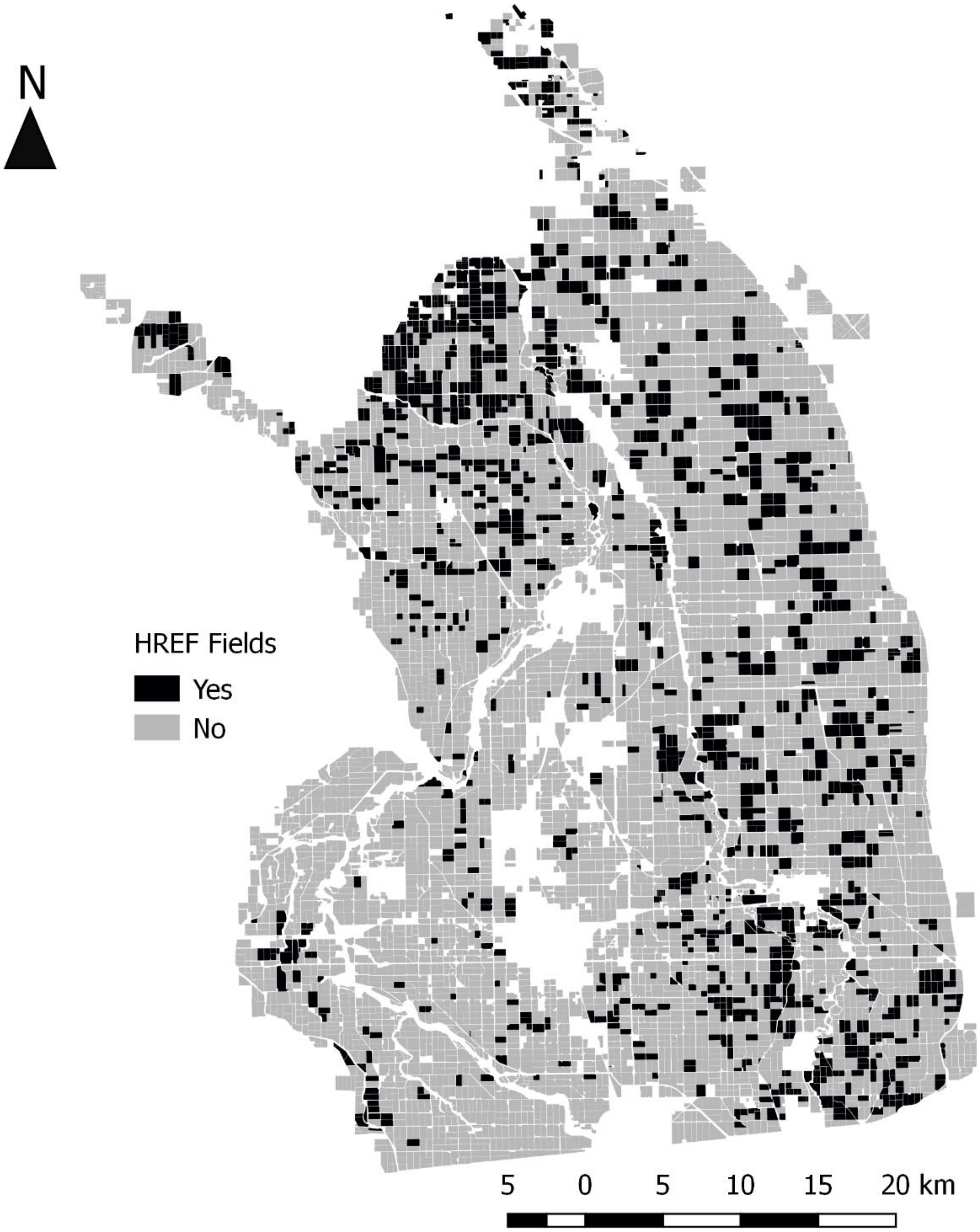

Figure 4: HREF fields are found in the north but are also located in along the eastern and southeastern parts of the valley.

Tables

Table 1: Image acquisition dates for EEFlux ET and Landsat NDVI products.

Image	**Dates**							▨ **ETM+**
2009								
12-14								
2010								
01-15	01-31	02-16	03-20	05-07	06-08	06-24	07-10	08-11
08-27	09-12	10-14	10-30	11-15	12-01			
2011								
01-18	02-03	▨ 02-11	▨ 02-27	03-07	▨ 03-15	▨ 03-31	04-16	05-10
05-26	06-11	06-27	07-13	▨ 07-21	▨ 08-06	08-14	▨ 08-22	08-30
▨ 09-07	09-15	10-01	▨ 10-09	10-27	▨ 11-26	▨ 12-28		
2012								
▨ 01-13	▨ 01-29	▨ 03-01	▨ 04-02	▨ 05-04	▨ 05-20	▨ 06-05	▨ 06-21	▨ 07-07
▨ 08-08	▨ 08-24	▨ 09-25	▨ 10-11	▨ 10-27	▨ 11-12	▨ 11-28	▨ 12-14	▨ 12-30
2013								
▨ 01-15	▨ 01-31	▨ 03-04	▨ 04-05	▨ 04-21	04-29	05-15	▨ 05-23	05-31
▨ 06-08	06-16	▨ 08-11	▨ 08-27	▨ 09-12	▨ 09-28	10-06	▨ 10-14	10-22
▨ 10-30	▨ 11-15	12-09	12-25					
2014								
▨ 01-02	01-10	▨ 01-18	01-26	▨ 02-03	03-15	▨ 03-23	03-31	04-16
▨ 04-24	▨ 05-10	▨ 05-26	▨ 06-11	▨ 07-13	▨ 07-29	08-06	▨ 08-14	08-22
▨ 08-30	▨ 09-15	▨ 10-01	10-09	▨ 11-02	▨ 11-18	11-26		
2015								
▨ 01-05	▨ 01-21	02-26	▨ 03-10	04-03	▨ 04-11	04-19	04-27	05-05
06-06	▨ 06-14	06-22	▨ 07-16	▨ 08-17	▨ 09-18	▨ 10-20	▨ 11-21	▨ 12-23
2016								
▨ 01-08								

Table 2: Mean and total annual EEFlux ET compared with water balance ET.

	2010	**2011**	**2012**	**2013**	**2014**	**2015**
Annual ET (mm)						
Water Balance	1089	1509	1214	1177	1096	1117
EEFlux	1473	1802	1612	1477	1328	1296
EEFlux$_{CF}$	1120	1369	1225	1123	1009	985
Annual ET (Mm^3)						
Water Balance	2220	3076	2475	2401	2235	2277
EEFlux	2998	3672	3285	3012	2707	2641
EEFlux$_{CF}$	2278	2791	2497	2289	2057	2007
Annual % Error						
EEFlux	35.02	19.37	32.72	25.43	21.11	15.99
EEFlux$_{CF}$	2.61	-9.28	0.87	-4.68	-7.95	-11.85

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