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Agricultural Irrigation Induced Evaporation in a Temperate Study Area: A Stable Isotope Approach

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Agricultural Irrigation Induced Evaporation In a Temperate Study Area: A Stable Isotope Approach

by

Lincoln Grevengoed

A thesis submitted to the Graduate College
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Thesis Committee:

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Agricultural Irrigation Induced Evaporation
In a Temperate Study Area:
A Stable Isotope Approach

Lincoln Grevengoed, M.S.

Western Michigan University, 2020

In regions where groundwater is used for irrigation, significant water losses take place due to evaporation. Previous studies demonstrated the utility of stable oxygen and hydrogen isotopes in estimating evaporative water loss experienced during return flow back to an aquifer. Unlike arid regions where the other studies took place, this study examined the region around Kalamazoo, Michigan, the United States, which experiences a more temperate climate. Irrigation in the Kalamazoo area primarily uses center-pivot systems supplied by wells, unlike flood irrigation in previous study areas. Water samples were taken periodically from wells close to center-pivot irrigation systems. Water losses due to evaporation were estimated using stable oxygen and hydrogen isotopes, which are effective tracers for water. This approach was possible in the Kalamazoo area since the distribution of oxygen and hydrogen isotopes in local precipitation, which is the source of groundwater recharge, is known based on years of measurements. Isotope analyses during the irrigation season suggest water loss due to evaporation is approximately 14.3%. This is less than what was estimated by previous studies in arid climate zones. Evaporative water loss was greater at wells near cornfields than at wells that supplied other crop types. There was little expected correlation between the groundwater's isotope ratio values and the change in chloride concentration. This is likely due to an external input of chloride from road salt used in winter months.

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1. INTRODUCTION

Water has long been a critical resource for human development, prosperity, and survival. Recently, increasing human populations and the onset of climate change have increased the strain on the earth’s water resources. As a result, water scarcity is increasingly preventing water managers from meeting the needs of their community (Postel, 2000) This has prompted some governments to conserve their water resources by taking actions such as regulating the amount of water that can be used for agricultural irrigation. While this method does conserve water, it can also have a deleterious effect on food availability and quality. Therefore, understanding the water balance is essential in water management.

The stable isotopes of oxygen and hydrogen are arguably the best tracers suited for water studies. This is due to these two elements being the components of a water molecule, H_2O (Clark, 2015; Kendall and McDonnell, 2012). There are processes in the hydrologic cycle that significantly affect the stable isotope ratios of hydrogen and oxygen. During these processes the isotope ratio will change in the reactants and products due to fractionation. One of the important relationships between oxygen and hydrogen isotope ratios in precipitation is known as the Global Meteoric Water Line (GMWL) that represents a straight line on a plot of hydrogen vs oxygen isotope ratios, based on the assumption that all precipitation is derived from the oceans (Dansgaard, 1964; Machavaram and Krishnamurthy,1994; Merlivat and Jouzel, 1979; Rozanski, et al., 1993; Rozanski, et al., 1982). However local precipitation does not always follow this relationship which can be modified by secondary processes (Clark and Fritz, 1997; Hurst and Krishnamurthy, 2018). Since precipitation is the main source of recharge for ground and surface waters, it is imperative to know the distribution of oxygen and hydrogen isotopes in precipitation in an area where subsequent hydrological studies are to be carried out.

Some novel applications of stable isotopes have been demonstrated in regional studies in Egypt and the UAE (Mohammed, et al., 2016; Murad and Krishnamurthy, 2008). In these arid regions, intense agricultural activity relied on irrigation. Researchers sampled ground water from agricultural fields and estimated evaporative loss due to water usage prior to infiltration. In contrast to those previous studies, this study took place in a region that experiences a temperate climate and that utilizes pivot irrigation. Center-pivot irrigation systems consist of sprinklers attached to a metal arm that rotates around a pivot. Sprinklers on the arm distribute water to the crops from above. Some of the water is lost to the atmosphere via evaporation and wind drift, some is absorbed by plants, and some returns to the groundwater (i.e., return flow). Samples from wells supplying various crops and other wells nearby were taken to see if different crop types influenced the evaporative water loss experienced. The main objective of this study was to estimate evaporative loss prior to return flow to be compared with estimates from arid regions.

2 METHODS

2.1 Study area

The study area consists of wells located throughout Kalamazoo County(42.24° N, -85.53° W) and a few wells located just outside of the county borders (Fig. 1). Kalamazoo County has a wide range of agricultural activity with 23,470 hectares of corn, 12,900 hectares of soybeans, and 850 hectares of wheat being planted in 2017 (USDA, 2019). Kalamazoo experiences a temperate climate with an annual temperature range between 35 °C and -27 °C, and with 96.2 centimeters total precipitation in 2019 (NOAA, 2019). Surface geology in the study area consists primarily of sand and gravel from glacial outwash, glacial lake, glacial moraine, and marsh and river deposits. Glacial drift deposits are the main source for well water in the county (Monaghan and Larson, 1982). These unconsolidated deposits form both an unconfined aquifer that covers most of the county and confined aquifers found in approximately a third of the county (Allen, et al., 1972). In the northeastern section of the county, where the glacial drift deposits are thinner, the Marshall Sandstone aquifer is also utilized for well water (Rheaume, 1990).

Well depth and lithologies were obtained via Michigan's Scanned Water Well Record Retrieval System. Samples were taken either from wells that were pumped or that were close to irrigated fields. Fields irrigated with groundwater primarily contained corn, but some grew gourds, soybeans, mint, and grass. Wells were between 12 m and 46 m in depth with most wells being over thirty meters deep (Table 1). Screens were set in either sand, gravel, or a mix of both.

Table 1. Well sites and features

Well Name	Well Depth(m)	Crop Type	Supplying Center Pivot
KH 1	31.09	Grass	N
KH 2*	16.76	Corn, Soybeans	N
KH 3	21.95	Mint (2018) Corn (2019)	N
F	19.2	Corn	N
SV	22.86	Corn, Gourds	N
V1	36.58	Corn, Hay, Gourds, Soybeans	Y
V2	47.55	Corn, Hay, Gourds, Soybeans	Y
V3	37.8	Corn, Hay, Gourds, Soybeans	N
SC	NA	Corn	N

Table 1 - continued

R1	NA	Corn	N
3R*	NA	Corn	N
S1*	NA	Corn	N
E1	NA	Corn	N
E2	NA	Corn	N
SF1	NA	Corn, Gourds	N

Table. 1 Depths of wells that were sampled for isotope analysis. *indicates well was located outside of Kalamazoo County.

Figure 1. Location of the study site in the United States in the state of Michigan. Inset of the location of the state of Michigan in the North American continent. Map created in ArcGIS.

2.2 Experimental

From June 2018 through October 2019, samples were collected from wells using airtight centrifuge tubes to avoid post-collection evaporation. Isotope ratios were obtained using Los Gatos Research (LGR) Off–Axis Integrated Cavity Output spectroscopy (Off–Axis ICOS) technology (Berman, et al., 2013). Working standards that had been calibrated with respect to international standards were utilized during runs. Isotope ratios are reported in the delta (δ) notation where

$$\delta‰ = \left(\frac{Rsample}{Rstandard} - 1\right) * 1000 \qquad 1.$$

R represents the ratio of $^{2}H/ ^{1}H$ or $^{18}O/ ^{16}O$. The international standard for both hydrogen and oxygen is Vienna Standard Mean Ocean Water (VSMOW). For quality control purposes, an internal standard was analyzed alongside the samples, which for our runs had standard deviations of 0.1‰ and 1.4‰ for $\delta\ ^{18}O$ and $\delta\ ^{2}H$, respectively. Chloride samples were analyzed using a LaMotte direct titration kit that uses argentometric titration to determine the chloride content.

3 Results and Discussion

Table 2. Groundwater stable isotope ratios

Sample Name	$\delta\ ^{18}O$ ‰	$\delta^{2}H$ ‰	Crop Type	Chloride (ppm)	Collection Date	Well Name
LG-1	-8.7	-59.8	Corn		5/5/18	E1
LG-3	-8.9	-60.8	Corn		6/9/18	E1
LG-4	-9.7	-64.6	Corn		6/9/18	E2
LG-5	-9.2	-59.4	Corn		6/9/18	F1
LG-6	-9.2	-59.3	Corn		6/9/18	F2
LG-7	-9.2	-59.2	Corn		7/3/18	F2
LG-8	-9.8	-64.0	Corn		7/3/18	E1
LG-9	-9.7	-64.5	Corn		7/3/18	E1
LG-10	-10.2	-68.2	Corn/Soybeans		7/27/18	KH2
LG-11	-9.7	-63.8	Corn/Soybeans		7/27/18	KH2
LG-12	-9.0	-62.1	Mint		7/30/18	KH3
LG-13	-9.8	-64.0	Mint		7/30/18	KH3
LG-14	-9.5	-62.9	Corn		8/2/18	R1
LG-15	-9.5	-62.0	Corn		8/2/18	R1
LG-16	-9.3	-60.2	Corn		8/4/18	SC1
LG-17	-9.2	-61.5	Corn		8/4018	SC1
LG-18	-10.2	-66.6	Corn		8/16/18	R1
LG-19	-9.5	-61.4	Corn/Soybeans		9/1/18	KH2
LG-20	-10.2	-67.3	Corn		9/15/18	R1
LG-21	-10	-65.7	Corn/Soybeans		9/27/18	KH2
LG-22	-9.6	-62.7	Grass/Pasture		10/1/18	SK1
LG-23	-9.3	-60.6	Corn		9/29/18	R1
LG-24	-9.2	-59.4	Corn		10/1/18	F1
LG-25	-10.2	-66.0	Corn		10/2/18	S1
LG-26	-9.8	-64.7	Corn		10/4/18	3R
LG-27	-9.5	-61.2	Corn		10/10/18	R1
LG-28	-10.2	-66.1	Corn		10/19/18	S1
LG-29	-10.2	-67.2	Corn/Soybeans		10/20/18	KH2
LG-30	-10.0	-64.4	Grass/Pasture		10/20/18	KH3
LG-31	-10.0	-66.2	Corn		05/01/18	3R
LG-32	-10.1	-64.6	Grass/Pasture		10/28/18	KH3
LG-33	-10	-65.2	Corn/Soybeans		11/3/18	KH2
LG-34	-10.1	-67.2	Mint		11/03/18	KH3
LG-35	-9.5	-62.4	Corn		11/03/18	R1
LG-37	-10.3	-65.8	Corn		12/08/18	3R
LG-38	-10.5	-68.3	Corn		12/18/18	S1
LG-39	-9.5	-62.4	Corn		01/08/19	R1
LG-40	-9.3	-64.5	Corn		01/08/19	S1
LG-41	-9.1	-61.5	Corn		01/03/19	R1
LG-42	-10.2	-66.9	Corn		02/06/19	S1
LG-43	-9.7	-63.8	Corn		02/21/19	3R
LG-44	-9.4	-61.0	Corn		04/03/19	R1

Table 2 - continued

LG-45	-10.1	-66.5	Corn		04/09/19	S1
LG-46	-9.4	-61.4	Corn		04/12/19	R1
LG-47	-9.7	-65.1	Corn		04/24/19	3R
LG-48	-10.2	-67.4	Corn		04/27/19	S1
LG-49	-9.4	-61.9	Hay/Corn/Beans		04/29/19	V1
LG-50	-9.6	-62.1	Hay/Corn/Beans		05/15/19	V1
LG-51	-9.7	-63.0	Hay/Corn/Beans	40	05/24/19	V2
LG-52	-9.6	-61.6	Hay/Corn/Beans		05/24/19	V3
LG-53	-10.0	-65.7	Hay/Corn/Beans		05/24/19	SV
LG-54	-10.0	-66.0	Corn/Soybeans		05/24/19	KH2
LG-57	-10.0	-65.8	Corn/Soybeans		05/24/19	KH2
LG-59	-10.1	-66.0	Corn/Soybeans		05/29/19	KH2
LG-60	-10.1	-65.6	Corn		06/03/19	KH3
LG-62	-10.1	-63.6	Corn/Soybeans		06/12/19	KH2
LG-63	-10.1	-66.7	Corn		06/12/19	KH3
LG-64	-9.52	-63.2	Corn	36	6/12/19	R1
LG-65	-9.83	-65.9	Corn		06/12/19	SC
LG-66	-9.64	-63.3	Corn		05/11/19	R1
LG-67	-9.0	-63.1	Various		6/25/19	SV
LG-68	-10.03	-65.7	Various		6/28/19	SV
LG-69	-10.06	-65.4	Corn		6/12/19	SC
LG-71	-9.7	-63.1	Corn		6/19/19	R1
LG-72	-10.08	-65.7	Corn/Soybeans		6/30/19	KH2
LG-73	-10.04	-66.3	Corn/Soybeans		6/30/19	KH2
LG-74	-9.5	-62.0	Corn	38	6/29/19	R1
LG-75	-10.33	-67.4	Corn	39	6/28/19	SC
LG-76	-10.35	-68.3	Corn		7/11/19	SC
LG-77	-9.42	-61.5	Corn	50	7/14/19	R1
LG-78	-9.6	-61.8	Hay/Corn/Beans		7/12/19	V1
LG-79	-9.62	-62.1	Hay/Corn/Beans	52	7/12/19	V1
LG-80	-9.7	-62.9	Hay/Corn/Beans		7/12/19	V2
LG-81	-9.79	-65.2	Hay/Corn/Beans		7/12/19	V2
LG-82	-9.63	-62.9	Hay/Corn/Beans	54	7/12/19	V3
LG-83	-9.67	-62.7	Hay/Corn/Beans	83	7/12/19	V3
LG-84	-10.26	-67.8	Corn		7/14/19	KH3
LG-87	-9.86	-64.7	Corn/Soybeans	24	7/11/19	KH2
LG-88	-10.03	-66.2	Corn		7/11/19	KH3
LG-89	-9.81	-63.7	Corn/Soybeans		7/11/19	KH2
LG-90	-9.26	-59.7	Grass/Pasture		7/11/19	KH1
LG-91	-9.16	-59.1	Grass/Pasture		7/11/19	KH1
LG-95	-9.6	-62.5	Soybeans	40	8/8/19	F2
LG-96	-9.53	-62.0	Soybeans	84	8/8/19	F1
LG-97	-9.76	-64.1	Soybeans		8/8/19	F3
LG-98	-9.81	-63.8	Corn	30	8/8/19	E1
LG-99	-9.34	-59.9	Corn	38	8/8/19	SF1
LG-100	-9.41	-61.9	Corn		8/8/19	SF1
LG-103	-10.08	-66.9	Corn/Soybeans		8/8/19	KH2
LG-104	-10.11	-66.3	Corn/Soybeans		8/8/19	KH2
LG-105	-9.98	-65.7	Corn	24	8/8/19	KH3
LG-106	-10.18	-65.2	Corn	17	8/8/19	KH3
LG-108	-10.11	-65.7	Corn	28	8/20/19	KH3
LG-109	-10.16	-66.5	Corn	104	8/20/19	KH3
LG-111	-9.7	-62.6	Corn	39	7/26/19	S1
LG-112	-10.1	-66.1	Corn	20	7/26/19	SC
LG-113	-9.4	-62.6	Corn		7/27/19	R1
LG-114	-8.9	-60.4	Corn		8/7/19	S1
LG-115	-10.2	-65.4	Corn	44	9/12/19	SC
LG-116	-10.0	-65.3	Corn		8/10/19	R1
LG-118	-9.5	-61.9	Corn/Soybeans	90	8/20/19	KH2

Table 2 - continued

LG-119	-9.3	-60.4	Corn/Soybeans		8/20/19	KH2
LG-120	-9.9	-64.0	Corn		8/28/19	KH3
LG-122	-10.0	-64.2	Corn		9/14/19	R1
LG-123	-9.7	-62.1	Corn	28	8/17/19	KH3
LG-124	-10	-66.3	Gourds/Corn	42	9/1/19	SV
LG-125	-9.6	-64.2	Gourds/Corn		9/8/19	SV
LG-126	-9.9	-67.4	Corn		9/3/19	S1
LG-127	-10.8	-69.1	Corn		9/12/19	SC
LG-128	-9.9	-62.6	Corn/Soybeans		9/27/19	KH2
LG-129	-9.9	-64	Corn	20	9/14/19	R1
LG-130	-9.7	-62.4	Corn		10/26/19	R1
LG-131	-9.7	-63.2	Corn	44	10/1/19	S1
LG-132	-10.3	-68.8	Corn	16	10/10/19	SC
LG-133	-9.2	-61.9	Corn		9/28/19	R1
LG-134	-10.5	-66.23	Corn/Soybeans		9/30/19	KH2
LG-137	-9.5	-66.31	Corn		8/17/19	KH3
LG-138	-9.3	-62.71	Corn		8/17/19	KH2
LG-140	-9.1	-63.86	Corn		10/17/19	S1
LG-142	-9.7	-62.88	Corn		10/26/19	R1
LG-143	-9.4	-69.14	Corn		10/29/19	SC
LG-144	-10.1	-64.12	Corn		10/31/19	S1

Table 2. Measured water stable isotope ratios for irrigated fields in or by Kalamazoo County, MI.

Isotopic results are shown in Table 2. along with chloride and other data.

The isotope values of precipitation from around the world are linearly related (Craig, 1961). This relationship is called the Global Meteoric Water Line, and can be described by the equation

$$\delta\,^{2}H = 8\,\delta\,^{18}O + 10 \qquad 2.$$

The slope of 8 reflects the vapor pressure differences of the oxygen and hydrogen isotopologues at normal earth surface temperatures. It is also suggestive of the equilibrium nature of condensation. For regional scale studies it is more desirable to obtain a Local Meteoric Water Line (LMWL). LMWL may or not mimic, depending on various factors, the GMWL. The intercept of 10, often termed “deuterium excess”, results from the differential fractionation of deuterium compared to ^{18}O at the source of global precipitation, mostly tropical oceans (Dansgaard, 1964; Merlivate and Jouzel, 1979). Differences in the intercept often indicates post precipitation processes or incorporation of secondary moisture to the primary ocean-derived moisture. (Bowen, et al., 2012; Clark, 2015; Machavaram and Krishnmurthy, 1994.). Previous studies of precipitation in the study area have produced a LMWL (Hurst and Krishnamurthy, 2018; Machavaram and Krishnamurthy, 1994). The Kalamazoo-area LMWL is

$$\delta\,^{2}H = 7.7^{*}\,\delta\,^{18}O + 12.9 \qquad 3.$$

As long as secondary evaporation does not occur, groundwater isotopically retains the average of the precipitation that recharges it. This can be observed in Fig. 2, which shows the isotope ratios of local ground water samples that have not undergone evaporation alongside the Kalamazoo LMWL.

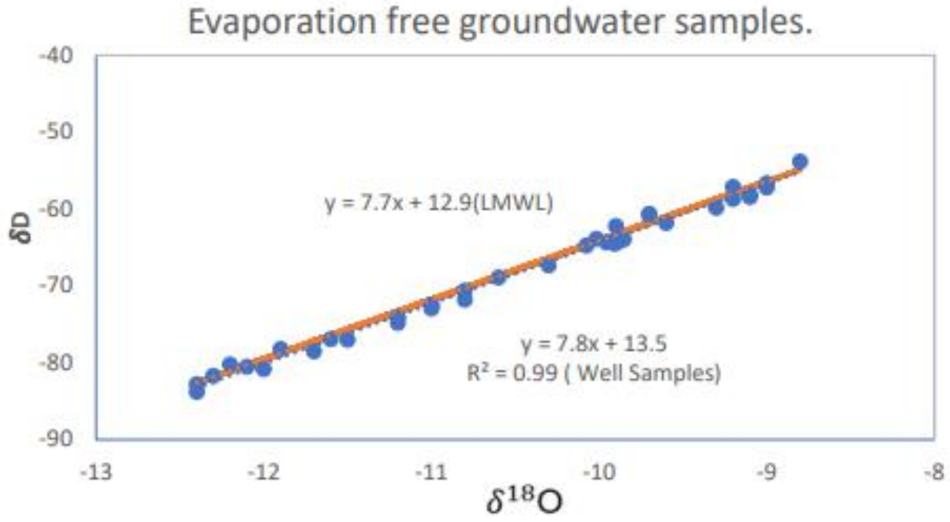

Figure. 2 West Michigan groundwater samples from wells relatively free from evaporation alongside the Kalamazoo Local Meteoric Water Line (LMWL). Isotope ratios were based on samples collected locally and those published by a previous study (Bowen, et al., 2012). The circles represent well isotope ratios while the solid line is the LMWL for Kalamazoo.

Fig. 3 shows the δ ^{18}O-δ ^{2}H plot for the samples of ground waters that were used for pivot irrigation. It is evident that the slope deviates from the LMWL significantly and points to secondary evaporation.

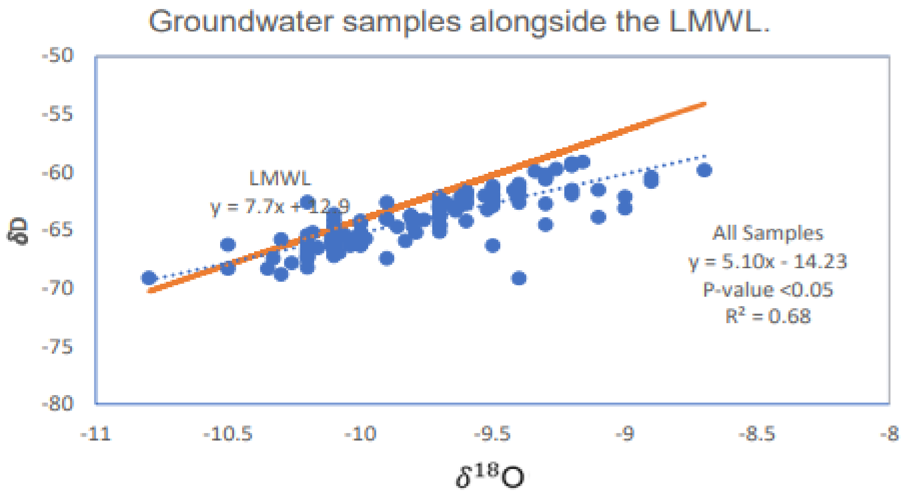

Figure. 3 Isotope ratios for groundwater samples taken during the 2018 and 2019 irrigation seasons. The circles represent well isotope ratios while the solid line is the

Local Meteoric Water Line (LMWL) for Kalamazoo.

Several models are available to explain the kinetic process involved in evaporation. A widely-used one was proposed by Craig and Gordon (Craig and Gordon, 1965; Gonfiantini, 1986). In these models, there is a thin layer at the air- water interface where isotopic equilibrium exists. Evaporation out of this layer is kinetically controlled. Thus, the models take into account both equilibrium and kinetic fractionation. A simple and usable form of this model considering the oxygen isotope is given by the equation

$$\delta^{18}O_{gw} - \delta^{18}O_{prec} = \varepsilon\ ^{18}O_{total} * \ln f = \Delta\ ^{18}O \qquad 4.$$

where $\delta\ 18Ogw$ is the δ 18O of groundwater, $\delta\ 18Oprec$ is the δ 18O of precipitation, ε $18Ototal$ is the isotope fractionation during evaporation (kinetic and equilibrium), f is the residual water fraction, Δ 18O is the change in 18O content in the groundwater obtained by using δ 18O $final$ − δ 18O $inital$, and 1 - f is an indicator of evaporative flux. The robustness of this model is critically linked to the quality of the $\delta\ 18Oprec$ data available. Decades of previous sample collection and analysis has provided a robust data base for the $\delta\ 18Oprec$ in precipitation in the study area (Hurst and Krishnamurthy, 2018; Machavaram and Krishnamurthy,1994).

Use of the Craig-Gordon model and its variations permits estimating evaporative loss in surface water systems. Two previous systems used the Craig-Gordon model for this purpose. The first of these studies took place in the United Arab Emirates, where the researchers used stable isotopes alongside other tracers to investigate groundwater quality and salinity. In this study, evaporative water loss in the area was approximately 21% (Murad and Krishnamurthy, 2008) The second study was carried out in the Nile Valley where the groundwater was heavily affected by agricultural irrigation and experienced evaporative water loss between 31% and 36% (Mohammed, et al., 2016). Both studies took place in regions that extensively used flood irrigation.

In the present study, use of the evaporative model for the 2018 and 2019 irrigation seasons provides an estimated evaporative loss. For this an average relative humidity of 0.73 for the irrigation season can be assumed (Weather Underground, an equilibrium fractionation of 9.5‰ and kinetic fractionation of 3.86‰ at ambient temperatures during the irrigation season. Equilibrium fractionation was calculated using the following equation.

$$\varepsilon\ ^{18}O_{\text{equilibrium}} = 0.0004\ T^{2} - 0.103T + 11.64 \qquad 5.$$

Where T is the ambient temperature (Clark & Fritz, 1997). Kinetic fractionation was calculated using

$$\varepsilon^{18}O_{\text{kinetic}} = -\ 14.2\ (1 - h) \qquad 6.$$

Where h is the relative humidity (Gonfiantini,1986). Calculations suggest an evaporative water loss of 14.3% (Weather Underground, 2019). The higher numbers derived for the other regions might be due to the arid climate, irrigation method used, and/or the type of crop that was irrigated.

Wells that irrigated corn fields (63% of the crops in the county) provided the majority of samples used for this study. In order to examine if crop type had an effect, the calculations were performed for fields where other types of crops were raised. In contrast to the all-inclusive values, groundwater taken from non-corn fields had a $\Delta\ ^{18}O$ of .6 (Fig. 5) and experienced 4.3% evaporative water loss during the irrigation seasons.

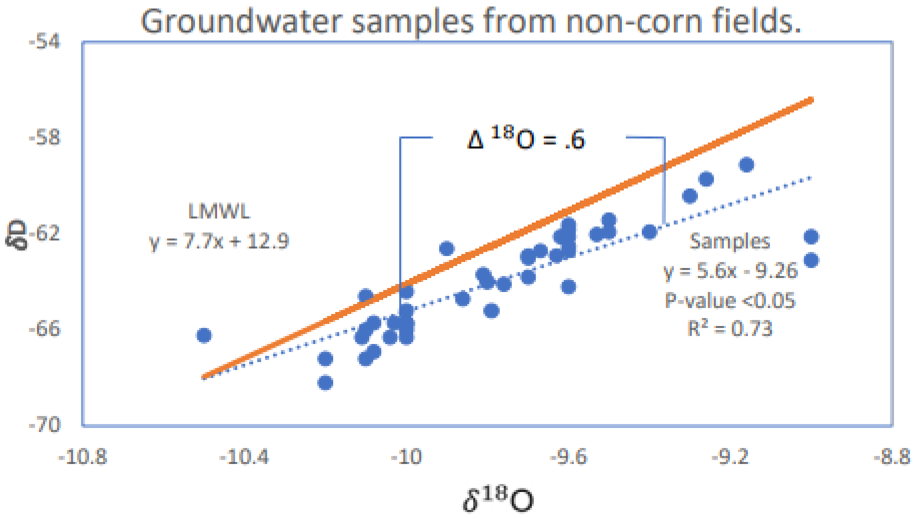

Figure. 5 Isotope ratios of samples from fields that grew crops besides corn. The solid line is the Kalamazoo Local Meteoric Water Line (LMWL) while the circles represent individual samples. Crops grown in these fields included soybeans, hay, gourds, and mint.

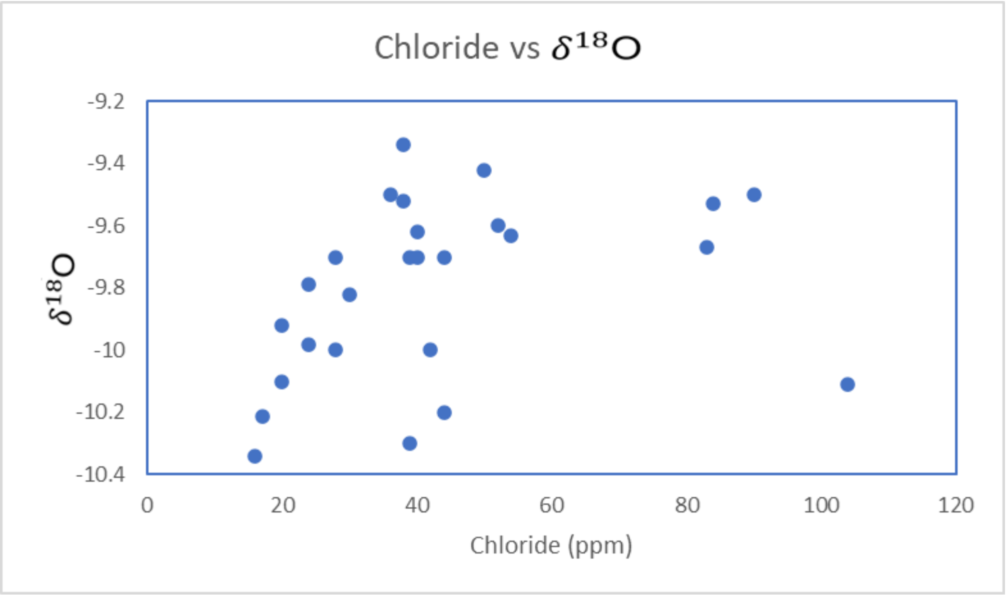

Figure. 6 Chloride concentration vs $\delta^{18}O$ ratios of groundwater used in pivot irrigation.

Isotope values were compared with chloride concentrations since normally they are correlated in an evaporation scenario. Fig. 6 demonstrates a lack of correlation between chloride concentrations and $\delta^{18}O$. This is likely due to the influence of other processes. For example, many of the sample wells were located close to streets which were treated with salt-based deicers during the winter. Deicing chemicals used in the county have previously been shown to have infiltrated groundwater during the spring and have been linked to increased chloride concentrations in nearby lakes (Koretsky, et al., 2012; Sibert, et al., 2015). The increase in chloride concentrations during the winter months would likely obfuscate rises caused by summer evaporation.

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4 Conclusion

This study supports the validity of using stable isotopes to ascertain evaporative water loss rates induced by agricultural practices in temperate regions. While the difference in evaporative water loss for corn and other crops fields is indicated, it is premature to offer an explanation at this time. Any explanation will have to take into account the volume of crop cultivated, water use efficiencies of different plant types and other plant physiological factors. Lack of correlation between oxygen isotopes and chloride is likely due to an external input of chloride from road salt. As expected, evaporative water loss was lower in a temperate region that featured pivot irrigation compared to the arid-regions previously studied.

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Appendix

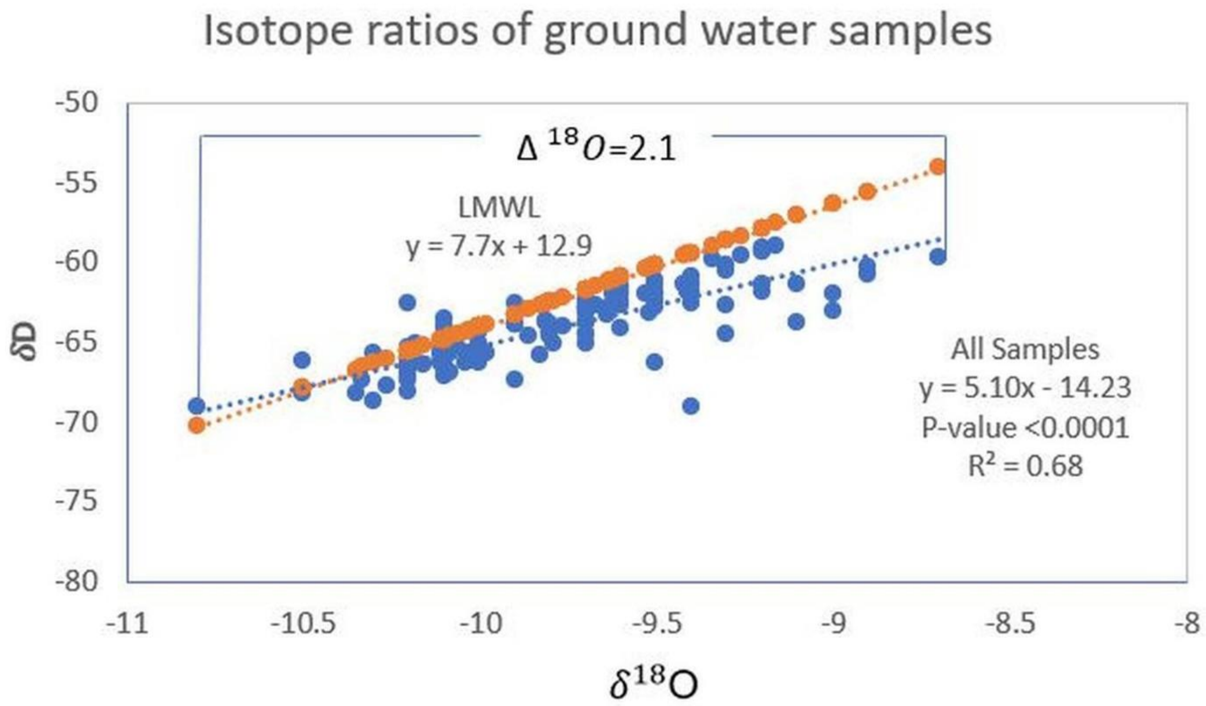

Figure. 7 Groundwater samples and the $\Delta\ ^{18}$O.

$\Delta\ ^{18}$O is the change in ^{18}O in the groundwater during the sampling. $\Delta\ ^{18}$O can be determined from the location of the end samples on the graph.