Appendix D - Central Sands Lake Study Technical Memorandum: Recharge

A description of the conceptual model of recharge for the Central Sands Lake Study, how it was derived, what data was used, and what we learned from this estimation process.

Introduction

The Central Sands Lake Study (CSLS) tasks the DNR with quantifying the impacts that groundwater withdrawals have on three lakes in Waushara County. The three study lakes are located within the Central Sands. The Central Sands region of Central Wisconsin is an area of relatively shallow depth to water and a thick sand and gravel aquifer. The region also supports a significant amount of irrigated agriculture, and the predominant use of groundwater pumping in the area of interest for this study (near the three named study lakes) is for irrigated agriculture. To understand the impacts of irrigated agriculture on the groundwater system, however, we cannot focus solely on the amount of water pumped. Rather it is important to understand how the water budget associated with irrigated agriculture differs from other land uses and how that change can result in different amounts of water from the land surface reaching the groundwater system; this water entering the groundwater system is called “recharge”.

Groundwater recharge is difficult, if not impossible, to measure directly at the local and regional scales required for the CSLS. There are, however, alternate methods available to estimate recharge amounts. This report describes two approaches we used to estimate recharge and compare irrigated agriculture to non-irrigated areas in the Central Sands: A simplified annual water balance model, and a more complex Soil-Water Balance (SWB) Model. Both approaches rely on the concept of a water balance, which accounts for sources of water coming into and leaving the area above the water table. The basic components of the water balance are shown in Figure 1. Major sources of water include precipitation and applied irrigation, and major losses of water include evapotranspiration (water transpired by plants or evaporated into the atmosphere), surface runoff, and recharge that goes to the water table. These sources and losses of water are balanced by the change in water within the soil above the water table. We can measure or calculate the flux (the rate of water movement) of these components of the water balance more easily than measuring recharge directly, and with these fluxes we can estimate recharge.

For comparing irrigated agriculture to non-agricultural areas with the Central Sands, a straight comparison of recharge under irrigated agriculture to recharge under non-agriculture doesn’t tell us much. We expect total recharge to be higher for irrigated agricultural areas because those areas rely on pumping which is applied back to the land. But total recharge doesn’t account for the amount of water leaving the groundwater system from pumping, only the amount being applied back to the land. A more helpful comparison is to look at the *effective* recharge for irrigated agriculture, which is the total recharge minus the amount of water pumped. By comparing effective recharge for irrigated agriculture to total recharge for non-agriculture, we can better understand what the total impact from irrigated agriculture is, both from pumping and recharge.

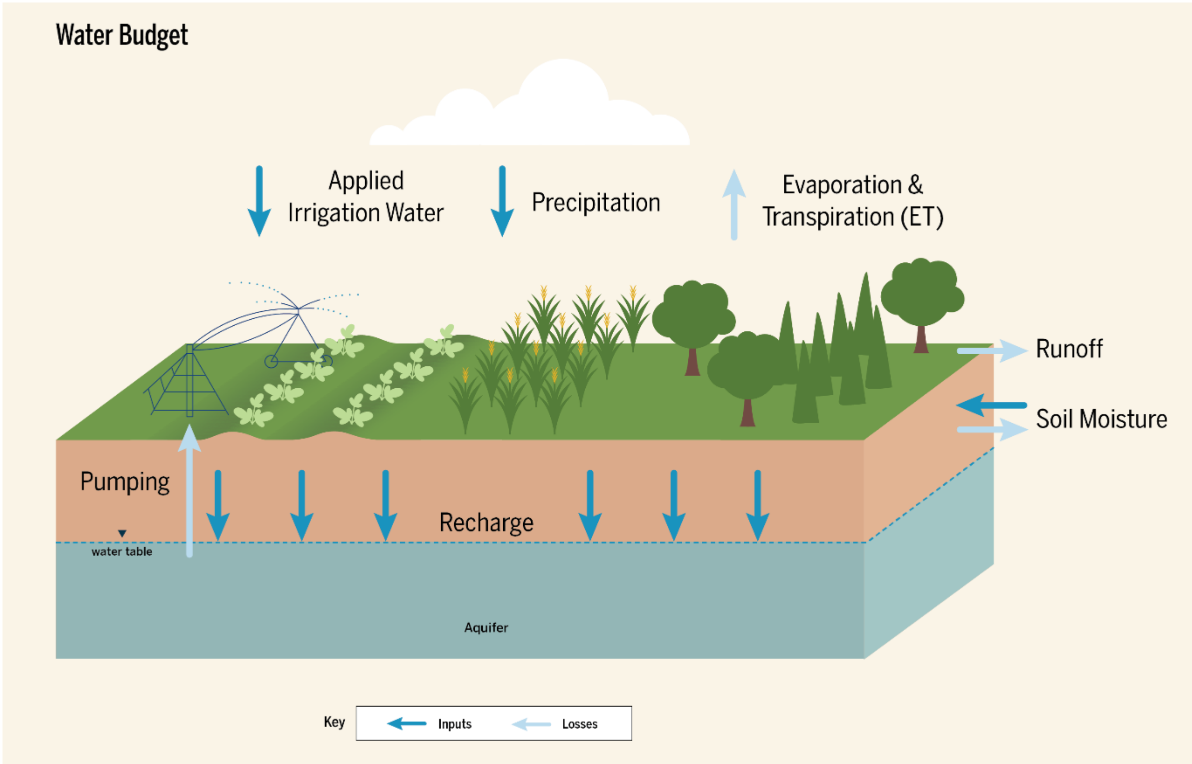

Figure 1. Components of a simplified water balance to estimate groundwater recharge.

Below, we describe the two methods for estimating recharge – the simplified annual water balance model and the SWB model. The SWB method is further described in Fienen et al. (2021). The effective recharge estimates derived using these methods help establish our conceptual understanding of how irrigated agriculture may affect the groundwater-surface water system, and the SWB model results provide inputs for our groundwater flow model.

Water Balance Theory

Both approaches used here for estimating recharge are based on the idea of a water balance or water budget, in which the inputs to the system and the outputs to the system are balanced by the change in volume of the system:

$$Change\ in\ Volume = In - Out$$

For estimating recharge, we apply this water balance approach to the unsaturated soils above the water table, so that all the major sources and losses of water are accounted for:

$$Change\ in\ Soil\ Storage = Precip. - ET + Irrig. - Runoff - Recharge$$

Soil storage is the amount of moisture held in the unsaturated soils above the water table. ET, or evapotranspiration, is a combined term including water directly evaporated and water released to the atmosphere through plant transpiration. Runoff is water flowing over the surface of the land, and irrigation is the amount of water applied through groundwater pumping. Since we are interested in estimating recharge, we can rearrange the equation as:

$$Recharge\ = Precip. - ET + Irrig. - Runoff - Change\ in\ Soil\ Storage$$

We can use estimates or measurements for everything on the right-hand side of this equation to estimate recharge. The components used in the simplified annual water balance model and the SWB model diverge, with the simplified model taking this equation and making simplifying assumptions and the SWB model taking this equation and adding more detail.

Simplified Annual Water Balance Model Theory

The simplified approach is to assume that over a long period of time, such as a year, the change in soil storage approaches zero. With that assumption, our equation becomes even simpler:

$$Recharge = Precip. - ET + Irrig. - Runoff$$

Because of the assumption of no change in soil storage, this approach can only be used for longer periods of time when we can assume that the change in soil storage is at least approaching zero.

SWB Model Theory

The SWB model takes the same water balance equation and adds more detail to it. The model runs on a daily timestep, with changes in soil storage being calculated every day, and can also account for additional, smaller components of the water balance such as snowmelt and interception by tree canopy (Westenbroek et al., 2018; Figure 2).

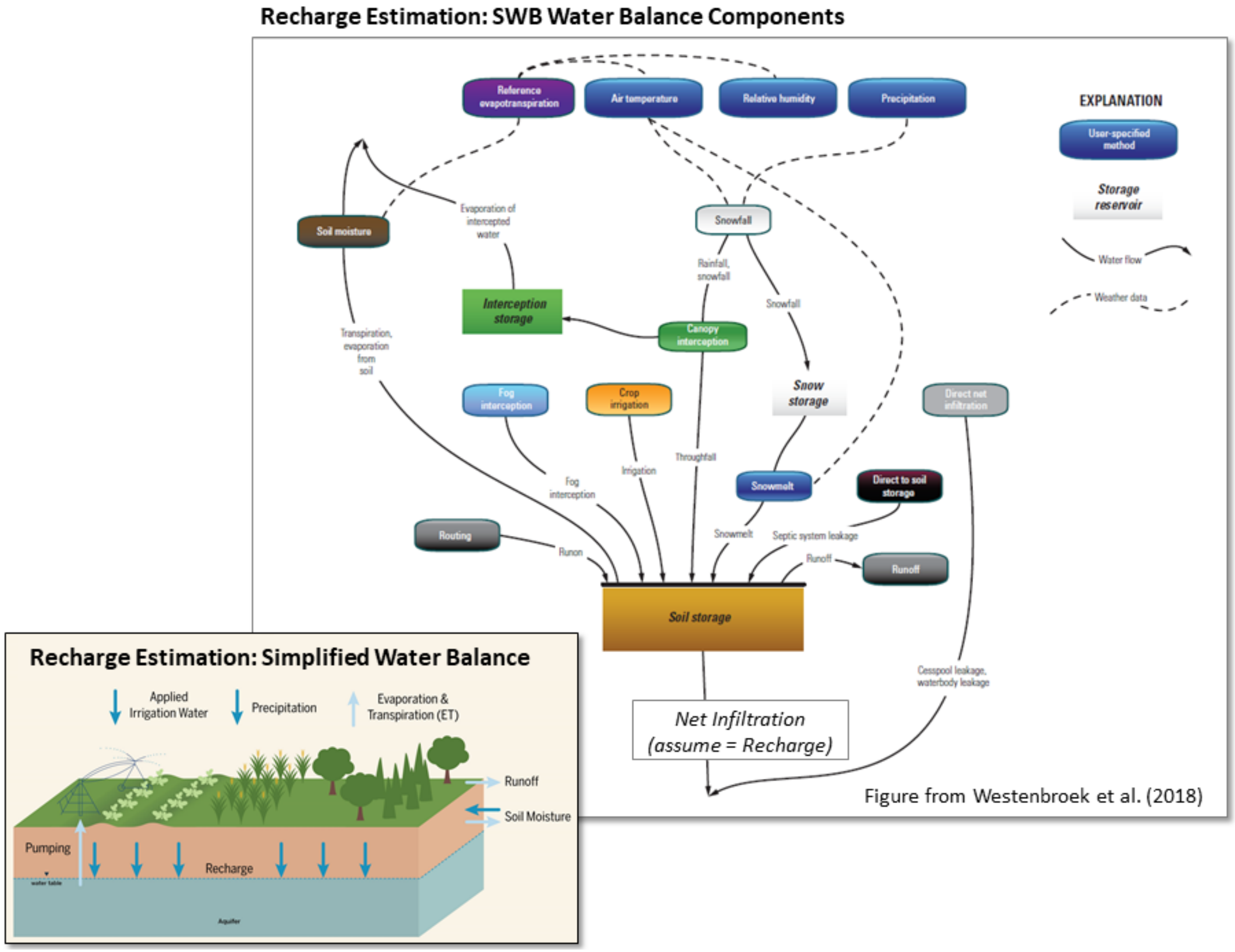

Figure 2. Contrasting the simplified and SWB water balance methods. The simplified annual water balance estimate lets us look at large-scale trends in recharge and identify the main drivers in the system. The Soil-Water Balance Model considers additional factors in the water balance.

Effective Recharge

While total recharge is an important component of the overall water balance, for irrigated land uses, we are primarily interested in the net impact of irrigated agriculture on the groundwater system. This impact can be expressed as the "Effective Recharge", which under a given agricultural field is the amount of recharge coming in minus the amount of water pumped for irrigation:

$$Effective\ Recharge = Total\ Recharge - Irrigation$$

Data Sources

Both approaches share many of the same data sources for precipitation, evapotranspiration, irrigation, and runoff. The sources for these datasets are described below.

Precipitation

Precipitation in our calculations comes from the Parameter-elevation Regressions on Independent Slopes Model (PRISM Climate Group) from Oregon State University. PRISM uses available weather station data as an input for a model that accounts for observation bias and missing measurements, topographic and coastal proximity effects on precipitation patterns, and known climatological patterns to produce daily precipitation estimates on a 30-second grid (approx. 800 meters).

Evapotranspiration

One source for evapotranspiration comes from the Moderate Resolution Imaging Spectroradiometer (MODIS) dataset, a NASA product of remote-sensed data. Specifically, we are using the 8-day net evapotranspiration MODIS dataset on a 500-meter grid (MOD16A2; Mu et al., 2011). The ET value in any given cell is representative of the entire landscape within that cell, based on the majority of landcover within the cell. Which means the ET value from a cell may be called "irrigated agriculture", but might actually be representing ET from irrigated agricultural as well as roads, farm structures, non-irrigated areas at the edges of the fields, etc. Studies show that this evapotranspiration dataset compares reasonably well with field-specific measurements of evapotranspiration at sites in the upper Midwest (Smail, 2020).

The SWB model can use MODIS evapotranspiration estimates as a direct input for actual evapotranspiration rates, or the model can estimate evapotranspiration using the FAO-56 methodology (Allen et al, 1998).

Irrigation

Irrigation withdrawal amounts in our simplified annual water balance model are based on monthly pumping amounts reported to the DNR's Water Use Section since 2011. The SWB model also estimates "irrigation demand" using the FAO-56 methodology (Allen et al, 1998), which is the amount of irrigation water needed to maintain soil moisture at predefined levels necessary for irrigated agricultural crops, and predicts the amount of water pumped for irrigation.

Runoff

Runoff is estimated using curve numbers and is calculated as part of the SWB model.

Simplified Annual Water Balance Model Results

The annual effective recharge to groundwater was estimated for each of the cells in the regional groundwater flow model domain from 2011-2018. This approach uses the same cell configuration as SWB so that results of the two methods can be easily compared. The average effective recharge for irrigated corn, irrigated potatoes, non-irrigated deciduous forests, non-irrigated grass/pasture, and non-irrigated evergreen forests are shown in Figure 3. Corn and potatoes represent 54% of all irrigated agriculture within the Central Sands region, or about 8% of the entire region. Deciduous forests, grass/pasture, and evergreen forests account for about 36%, 4%, and 6%, respectively of the entire region.

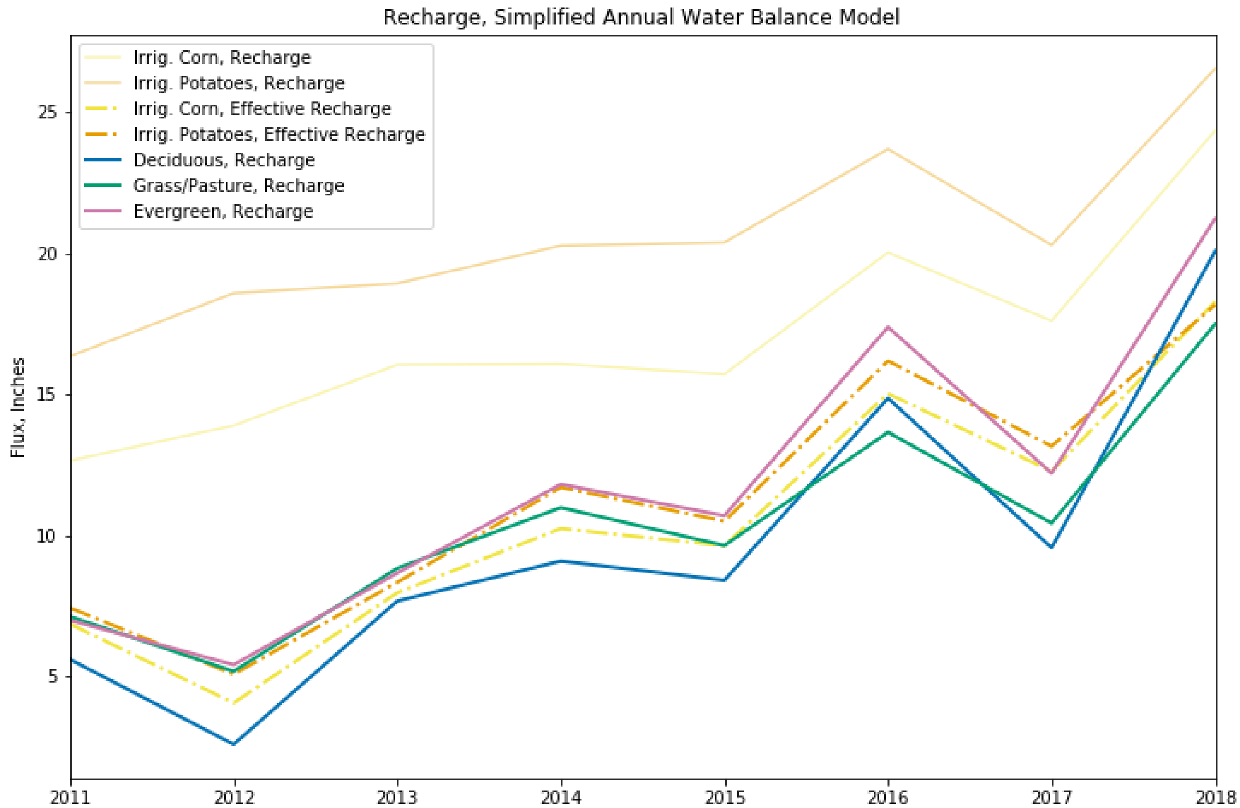

Figure 3. Annual average effective recharge to groundwater for selected land uses within the Central Sands based on simplified annual water balance model. Also shown is the total recharge or irrigated agriculture, which does not account for the irrigation amounts which also affect the groundwater system.

The total recharge for irrigated crops is estimated to be significantly higher than non-agricultural land uses because the irrigated water is being applied to the field. When looking at impacts to the groundwater system, however, it is more appropriate to compare recharge under non-agricultural land uses to the effective recharge under irrigated crops. Making this type of comparison, we see that recharge under deciduous forest tends to be lower than any of the other selected land uses on an annual basis and recharge under evergreen forests tends to be the highest. Effective recharge under crops is typically somewhere in between evergreen forests and deciduous forests.

Effective recharge for all land uses tends to track together and has a generally increasing trend between 2012 and 2018; this corresponding to increasing precipitation trends during the same time period. The precipitation-driven variation we see from year-to-year is much greater than the differences between estimated recharge for different land uses within any given year. For example, the effective recharge difference during the wettest and driest years (2012 and 2018, respectively) was 14 inches for irrigated corn (increasing from 4 inches in 2012 to 18 inches in 2018) and 17.5 inches for deciduous forests (2.5 inches in 2012 to over 20 inches in 2018). By contrast, the maximum difference between land uses within any single year differed by less than five inches. This suggests that precipitation is the primary driver of the recharge water balance, with land use having a smaller role.

When examining the effects of different factors on recharge amounts, we also need to consider the spatial variability of recharge. The recharge estimates shown in Figure 3 have been averaged spatially across the entire model domain and do not reflect the considerable degree of recharge variability that occurs across the landscape. In the real world, recharge patterns are controlled by a variety of factors (e.g., wind patterns, precipitation patterns, soil coarseness, crop planting, plant growth, etc.). This often results in recharge amounts that vary considerably even within a single agricultural parcel (Nocco, et al., 2018), potentially varying even more at a larger scale. To quantify this variability, we can look at the range of recharge estimates by land use type across the model domain. In Figure 4, we plot two standard deviations above and below the mean annual value to understand how much variability there is in our calculations across the entire area (95% of our calculated values fall within two standard deviations of the mean value).

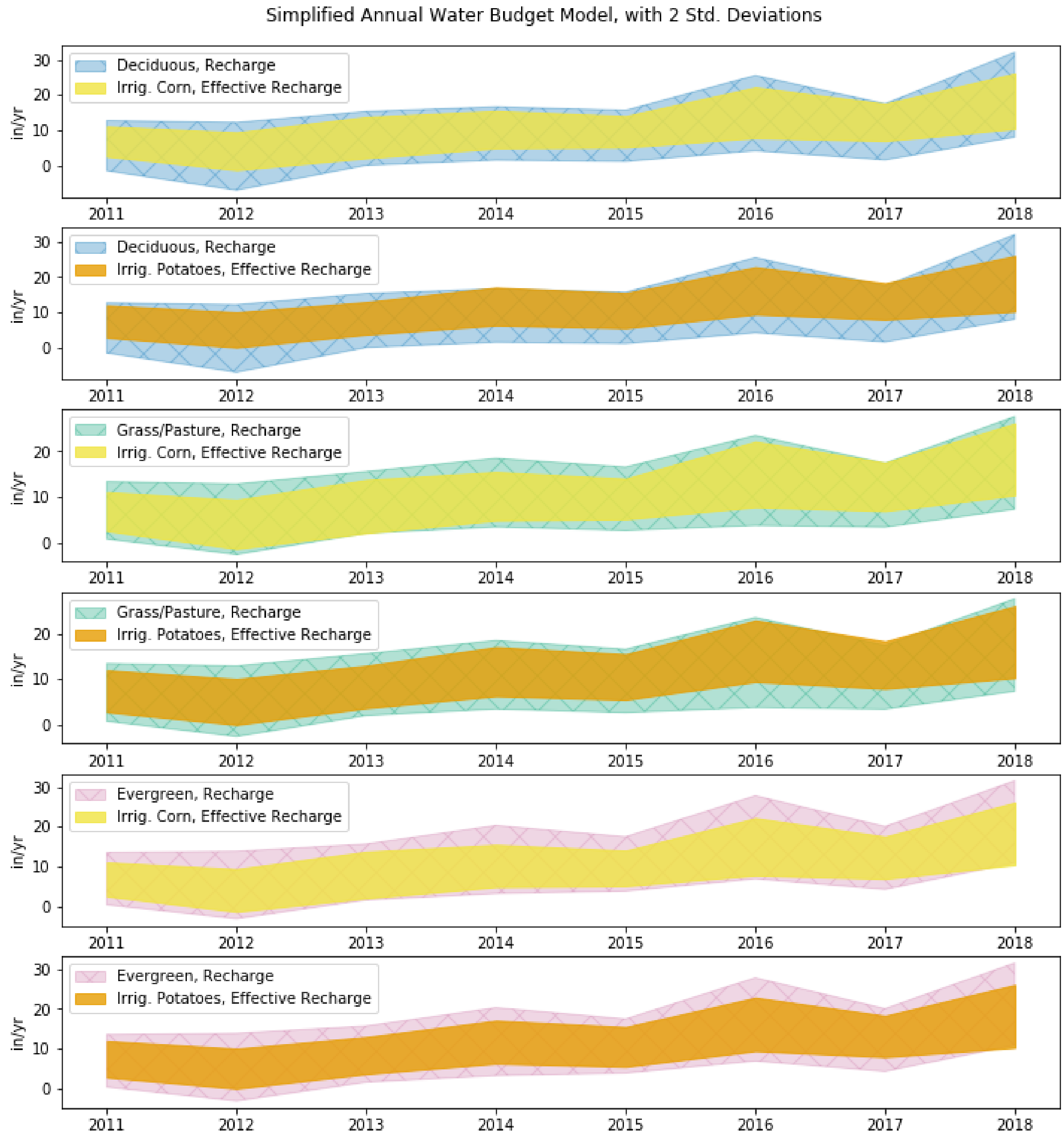

Figure 4. Spatial variability in annual recharge estimates per land use type.

Accounting for the spatial variability in recharge shows that the difference within a single land use type is much greater than the average differences between different land use types. For instance, in 2012, the difference between the average effective recharge under irrigated corn and under deciduous forest is just under 1.5 inches. But in the same year, estimates of irrigated corn recharge varied by over 5 inches across the model domain, and deciduous recharge varied by over 9.5 inches.

Soil Water Balance Model Results

Calculating the water balance on an annual timestep helps us better understand the system on a very broad scale under 2011-2018 conditions. However, for the analyses run as part of the Central Sands Lake Study, we need a more refined tool that can estimate recharge on a smaller timestep and also allow us to investigate recharge for hypothetical situations where we cannot use reported groundwater pumping data, for example. The Soil-Water Balance Model (SWB) can estimate recharge at the level of detail necessary for our study.

The SWB model calculates recharge with a water balance approach similar to the annual water balance calculation, but it calculates that water balance on a daily time-step; it also tracks precipitation, estimates evapotranspiration and irrigation demand (using the FAO-56 methodology), calculates soil moisture storage, and estimates net infiltration (water leaving the soil zone that will eventually flow to the water table). Additionally, the SWB model accounts for smaller components of the water cycle that were ignored in the simplified annual water balance model – components such as rejected net infiltration (when the water table is above the land surface and therefore water cannot recharge), snow storage and snow melt. These components are typically small compared to the primary drivers of the system such as precipitation and evaporation, but can, in aggregate, amount to small but significant differences between land uses.

The capabilities of the SWB model allow us to assess various land use scenarios and look at how recharge varies throughout the year under various land-use types. The SWB model provides recharge inputs for a groundwater flow model. Additional details on how SWB calculates various parts of the water balance and how the SWB results are incorporated into the groundwater model are described in the groundwater modeling appendix (Fienen et al., 2021).

The SWB model fills an important informational need by calculating recharge at a shorter (daily) timestep. Recharge and groundwater pumping vary throughout the year in ways that could potentially be important to assessing the impacts of irrigated agriculture on the groundwater-surface water system. The simplified annual water balance model is limited to looking at annual trends because it uses the simplifying assumptions such as zero net change in soil moisture, which may not always be true. Because data on seasonal soil moisture variability is not available on the scale of the entire Central Sands, we use the SWB model to assess the effects of the seasonal nature of recharge and groundwater withdrawals, as well as providing estimates of the longer-term trends without having to make all the simplifying assumptions needed for the simple annual water balance model.

A second important use of the SWB model is to calculate recharge distributions for hypothetical cases where we do not have direct measurements of evapotranspiration or reported groundwater withdrawals. In order to answer questions about the impacts of irrigated agriculture on Central Sands lakes, we need to assess various “what would have happened” scenarios. For instance we may want to ask “how would the lakes change if we removed this irrigation well and replaced the field it was irrigating with a forest?” or “what would the effects of current level of irrigated agriculture be over an extended time period?” Using the SWB model allows us to do this.

The SWB model calculations use various equations that include parameters which can be hard to verify in real life, such as crop-coefficients for transpiration, or plant rooting depths. Because we can define a reasonable range for each of these parameters but can’t definitively say what the “true” values are, the

USGS ran a Monte Carlo simulation where the SWB model was run several hundred times with different combinations of these parameters within set reasonable ranges based on literature values. This produces a range of recharge estimations. The goal of the Monte Carlo simulations is not to produce a single value of recharge, but to produce a range of reasonable results such that the true recharge amounts are likely to fall within that range. (See the groundwater modeling appendix [Fienen et al, 2021] for further discussion of Monte Carlo simulation).

To ensure that the Monte Carlo SWB results were reasonable, we compared the suite of recharge estimations to our simplified annual water balance model estimates of recharge. The simplified annual water balance model has its own set of simplifying assumptions and uncertainties and shouldn't be interpreted as the "true" value of recharge, but it should serve as a reasonable estimation of annual recharge in the Central Sands. In addition, we compared evapotranspiration and irrigation rates calculated by SWB runs to evapotranspiration values calculated from MODIS observations and to Water Use reported withdrawal volumes. It should be noted that, similar to the annual calculated recharge values, recharge results for each set of input parameters in the Monte Carlo run has significant spatial variability.

Soil-Water Balance vs. Annual Calculation Recharge Estimates

As an overall check on the SWB model, we compared the modeled recharge to the annual water balance recharge estimates. These simplified annual water balance model estimates of recharge are imperfect – the estimates require simplifying assumptions, such as no net change in soil storage from one year to the next, and the measured input values have some amount of inaccuracy, especially at broad, regional scales. Nevertheless, the simplified annual water balance model estimates provide a good starting point for comparison.

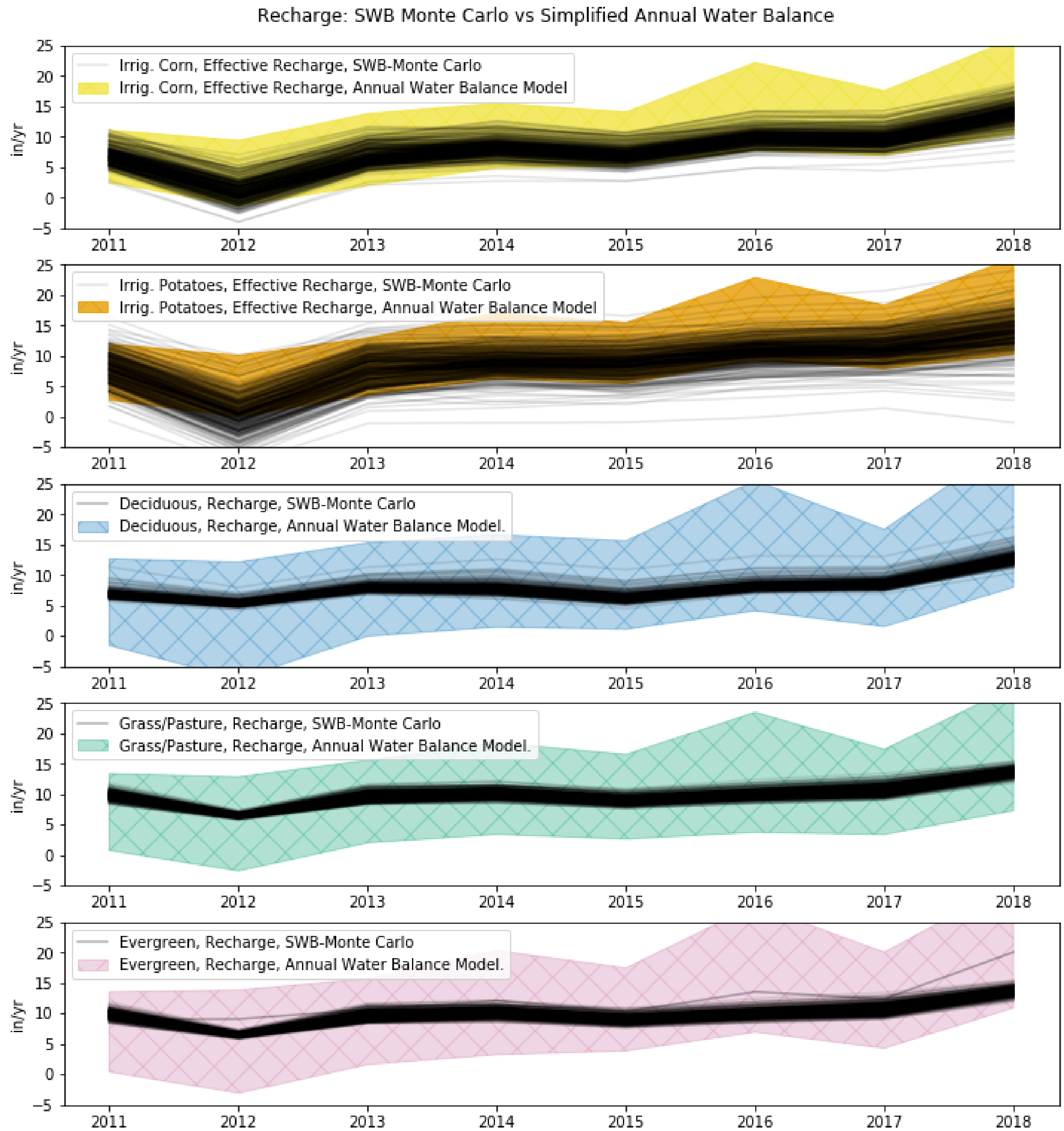

Figure 5. The range of recharge from the simplified annual water balance model (hatched area) compared to the recharge estimated by the Monte Carlo SWB model (lines).

Figure 5 illustrates two comparisons of the Monte Carlo SWB estimates and simplified annual water balance model estimates for deciduous and irrigated corn recharge. The values for recharge calculated using each method fall within the same range. The Monte Carlo SWB has a wider range of estimates for irrigated ag than for non-irrigated. This is primarily because the Monte Carlo approach had more parameters for agricultural crops, which vary over a greater range and have a direct impact on the ET estimation. For instance, in the SWB model, planting and harvest dates have to be explicitly specified for agricultural crops, and irrigation rates can be varied by changing the amount of irrigated water that is applied to a crop whenever the soil zone gets too dry and by changing what that "too dry" threshold is to trigger an irrigation event. None of these parameters is relevant to a non-irrigated land cover like deciduous or evergreen forests.

Soil-Water Balance vs. MODIS Evapotranspiration

Another check on the SWB model is to compare the model's estimated evapotranspiration rates to other estimates of evapotranspiration over the same time period. One source for evapotranspiration estimates is NASA's remote-sensed MODIS dataset. The MODIS dataset provides regular snapshots of the movement of heat from the earth's surface due to evapotranspiration (latent heat flux). The gridded heat data is used to estimate actual evapotranspiration using the logic of the Penman-Monteith equation. Because it is a global-scale dataset, many users of MODIS and other remoted-sensed ET datasets have found that they need to adjust these ET estimates to align with more direct measurements of evapotranspiration. We have not made any corrections to the MODIS evapotranspiration estimates. However, MODIS evapotranspiration has been found to perform reasonably well in the upper Midwest, including in the Central Sands (Smail, 2020).

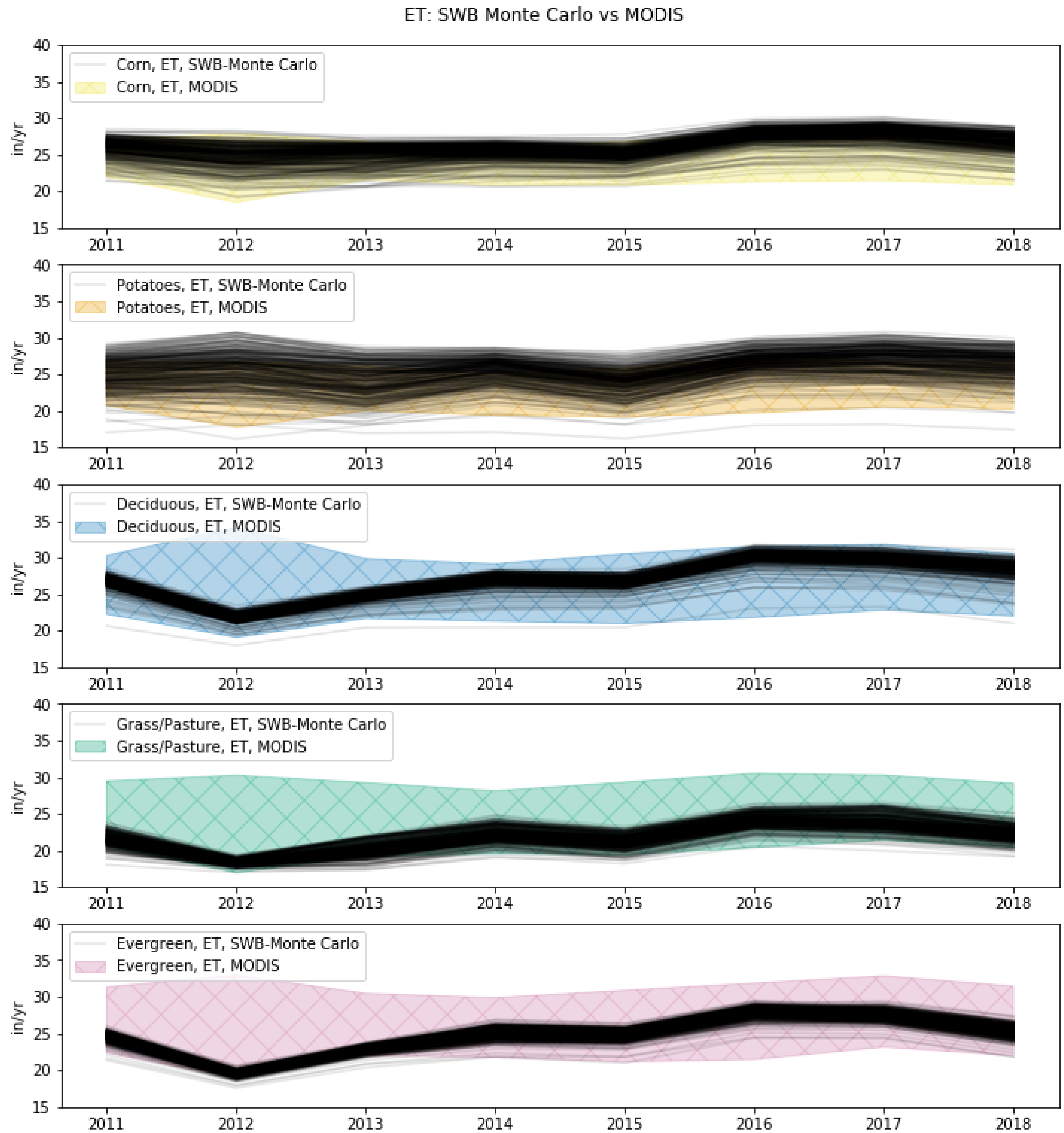

Figure 6. Range of evapotranspiration estimates from the Monte Carlo SWB model (lines) compared to the range of estimates from the MODIS remote-sensed model (hatched area).

The evapotranspiration estimates from the Monte Carlo SWB model generally fall within the range of values from the MODIS remote-sensed model (Figure 6). The Monte Carlo SWB model generally produces a wider range of estimates for irrigated crops than for non-agricultural land uses. As described above, this is mainly because irrigated lands have a greater number of parameters within SWB that we can vary as compared to non-irrigated land use types.

The Monte Carlo SWB model estimates ET rates within the range of modeled MODIS ET rates. The non-agricultural land uses tend to have ET rates which are more responsive to precipitation trends, with lower ET during drier years such as 2012. This is because irrigation allows crops to have their water needs met even under low precipitation conditions, while deciduous forests may become water-stressed in drier years as lower precipitation produces a lack of water in the soil zone.

Soil-Water Balance vs. Water Use Reported Pumping

Another check on the performance of the Monte Carlo SWB model is how well the model estimates irrigation demand. The SWB model automatically applies a set amount of water whenever the soil moisture drops below a certain amount. The amount of water applied per event and the minimum soil moisture that triggers irrigation are both parameters that were adjusted during the Monte Carlo simulations in order to better match reported irrigation water withdrawals. The final estimated irrigation demand can be compared to reported water use data from high capacity wells in the Central Sands. We expect the reported irrigation and modeled irrigation demand to be similar but not to match perfectly. This is because the SWB model applies irrigation water only to maintain transpiration rates of the crops, while real-world irrigators may have other reasons for applying additional irrigated water at other times (for example, farms may add water for fertigation, but this would not be simulated in the SWB model).

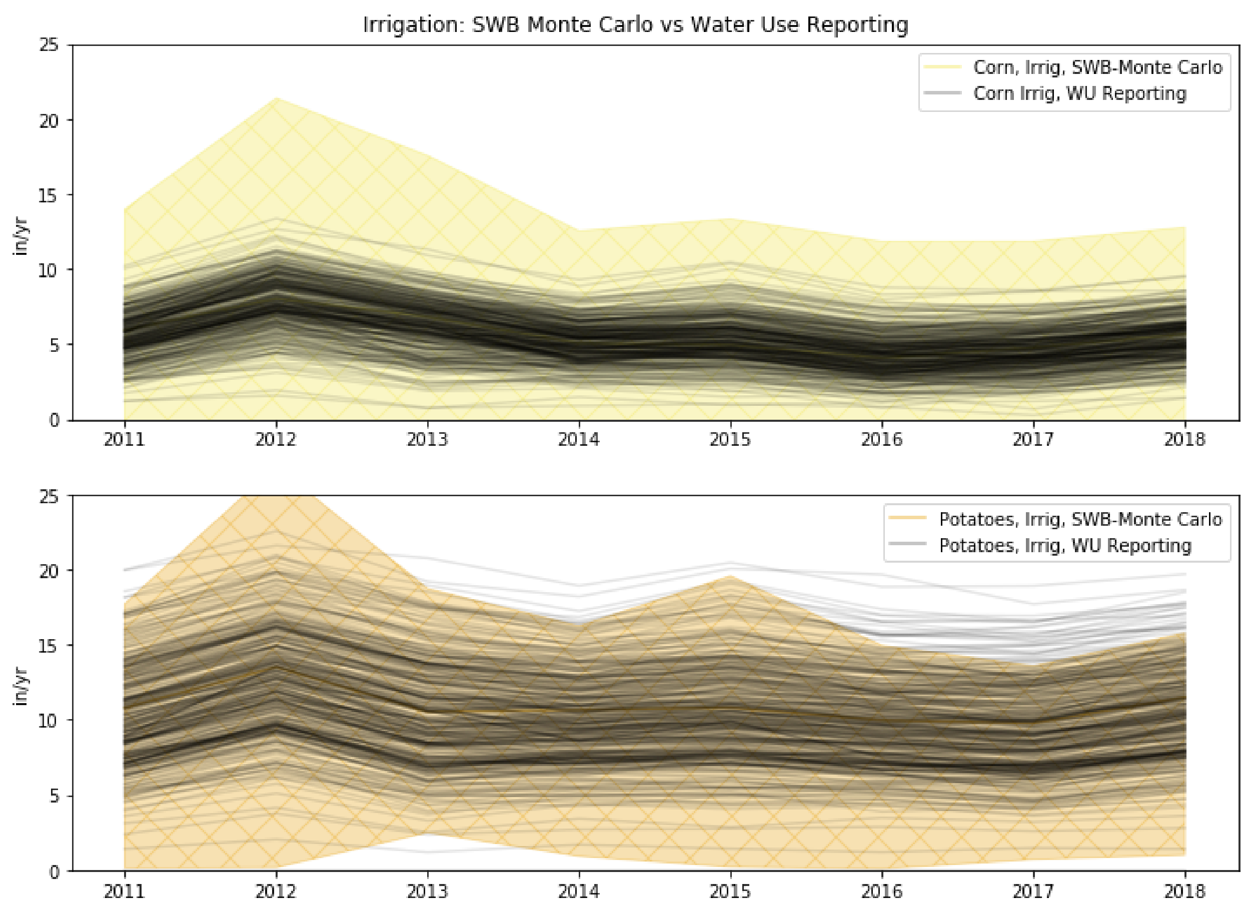

Figure 7. Reported Water Use withdrawal amounts (hatched area) compared to SWB model estimated irrigation demand (lines).

Irrigation demand amounts from the SWB model for corn are all within the range of reported estimates, typically between 2 and 10 inches per year. There is more variability in the estimated Monte Carlo SWB irrigation rates for potatoes. While there is a good deal of overlap between the model-predicted and reported irrigation amounts, bias in the Soil-Water Balance estimated irrigation rates for potatoes err towards the side of under-irrigation of crops.

Annual Trends in Soil-Water Balance Modeled Recharge

Some of the comparison datasets used to validate the SWB model are only available for a short period of time. Reported Water Use withdrawal amounts, for example, are only available since 2011. The Monte Carlo SWB model, however, can be extended outside this time period to provide estimates of recharge for the entire 38-year period used in the modeling scenarios (Figure 8).

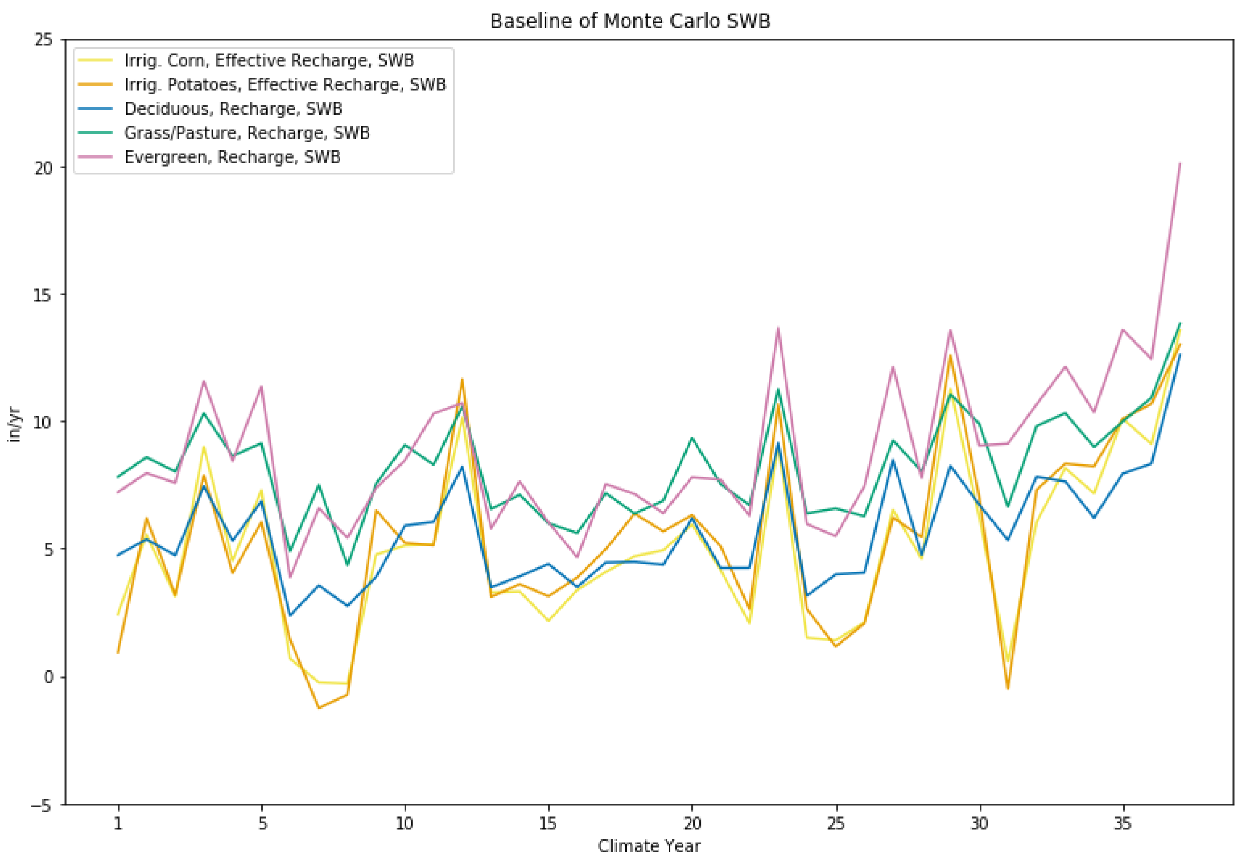

Figure 8. Annual average recharge from the Monte Carlo SWB using the initial parameters within the SWB model.

The SWB estimates of recharge for evergreen and grass/pasture tend to be highest of any land use. Deciduous recharge and the irrigated agriculture tend to track together for most years, but irrigated agriculture recharge drops significantly in dry years, such as climate years 7-8, 24-26, and 31 (corresponding to precipitation trends in 1987-1988, 2005-2007, and 2012). These results suggest that switching irrigated crops to deciduous forests (one of the most common land use types within the Central Sands) would result in increased recharge during dry summers, with little change in recharge during other years.

The advantage of the Monte Carlo approach to using SWB, however, is that it produces a range of estimates for recharge that is based on the range of “reasonable” parameters, and we do not have to rely on a single SWB estimate for recharge that comes from using the initial, “base” parameters. The SWB model was run 349 times with combinations of parameters, to provide a range of recharge estimates used by the groundwater model. The groundwater modeling and lake ecosystem response efforts have identified particular runs within this suite of 349 runs that are representative of “large-drawdowns” and “small-drawdowns” to lake levels, and all three of these representative combinations (large-drawdown, small-drawdown, and baseline) were used for determining lake ecosystem impacts (further discussion in Voter et al., 2021). These ranges of recharge are shown in Figure 9.

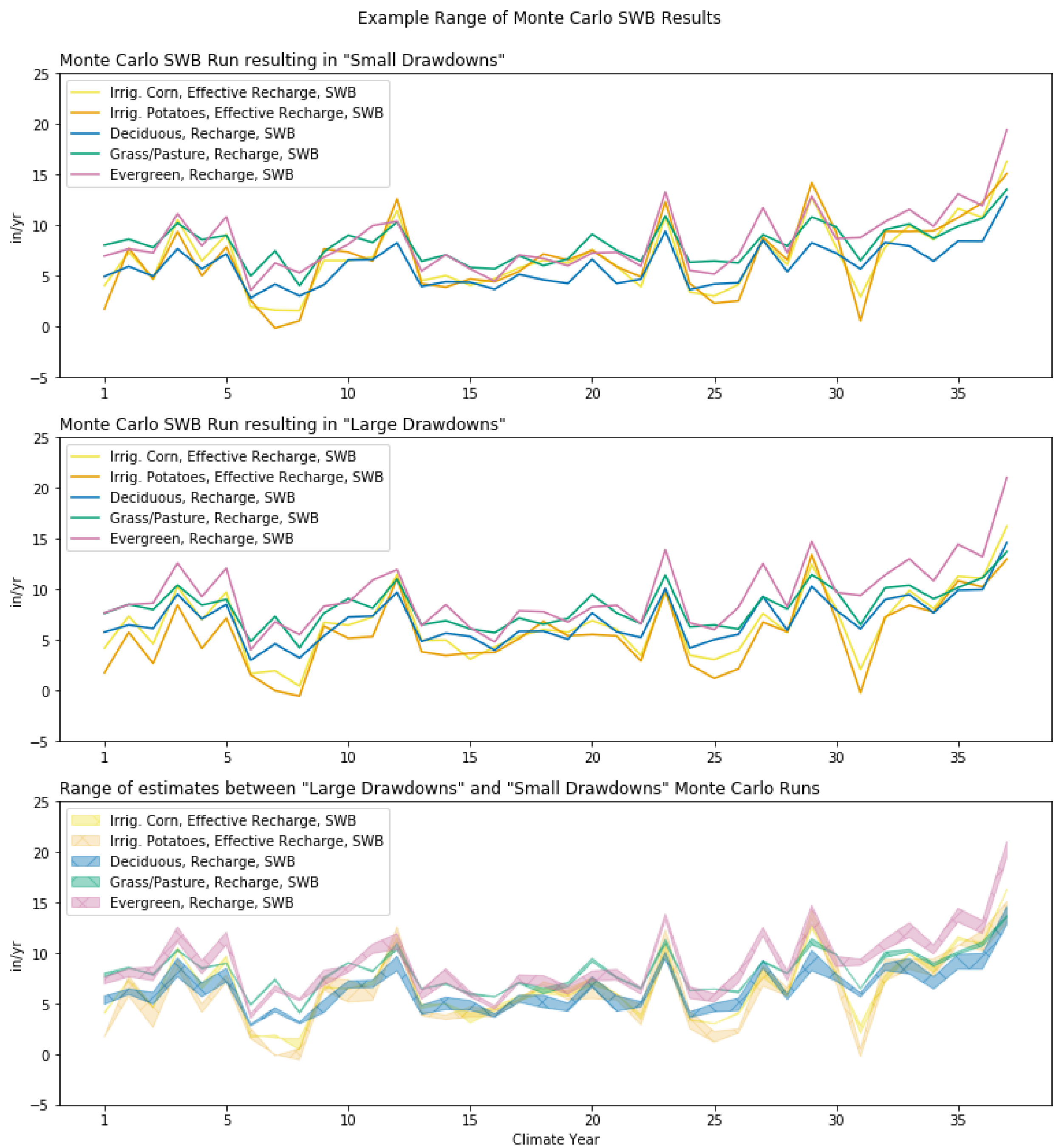

Figure 9. Range of annual average recharge calculated by the Monte Carlo SWB runs. The upper two graphs show recharge for individual SWB runs that resulted in "small" and "large" drawdown amounts (as defined in the Voter et al., 2021). The lower graph shows the range of recharge estimates obtained from the suite of Monte Carlo SWB runs.

The Monte Carlo SWB approach produces the widest range of effective recharge for irrigated potatoes. The range of annual recharge estimates for all the other land uses tend to be small compared to irrigated potatoes, and the differences in the irrigated potato recharge estimates are likely produced by the variability in the Monte Carlo SWB estimates for ET (Figure 6), and irrigation (Figure 7).

Seasonal Trends in Recharge

One other advantage of using the Soil-Water Balance model is that it enables us to estimate recharge at timesteps shorter than an annual calculation, which lets us examine the seasonal nature of recharge. While annual differences in total recharge between different land uses can be illustrative, they do not capture the full story. Groundwater recharge, depletion, and recovery occur at different times of the year and at different rates under various land cover types. Effective recharge to groundwater under irrigated land is much more variable throughout the year than recharge under non-irrigated land (higher in spring and fall, lower in summer), and it can take the groundwater system time to recover from the summer deficit of water, even if the total amount of recharge during the year for the two land use types is the same.

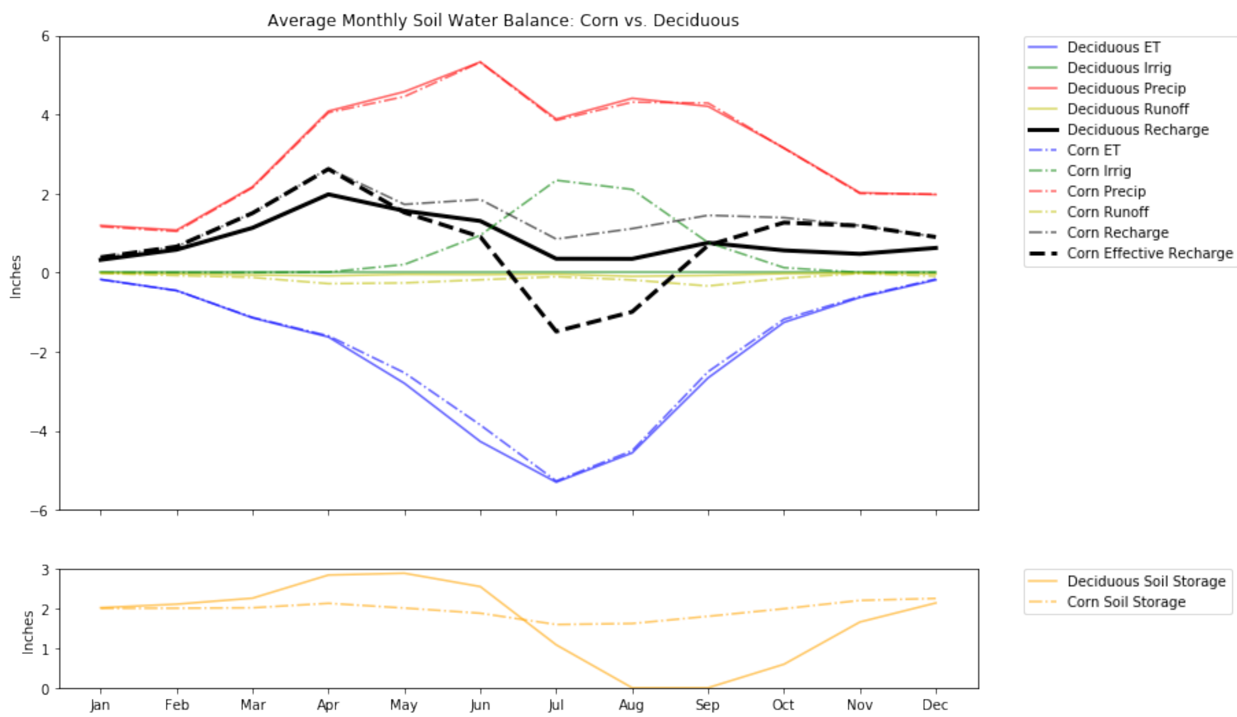

Figure 10. Average monthly components of the water budget.

Monthly averages from the Soil-Water Balance model for the period 2011-2018 for all the major components of the water budget show the differences between non-irrigated deciduous forests and irrigated corn fields (Figure 10). For better visualization, figures 10 and 11 depict results from a set of base parameters in Soil-Water Balance, rather than the full suite of Monte Carlo results. The average precipitation (red lines) and evapotranspiration (blue lines) generally track together, with slight deviation in evapotranspiration in the late spring/early summer months. Runoff (yellow lines) is very low in both land uses, as expected for the Central Sands' relatively flat, coarse soils, although there are slight increases in runoff from corn during the spring and autumn months, likely when fields are bare. Irrigation (green line) shows pumping peaking for irrigated corn in July and August. The recharge estimated for corn fields (dot-dash gray line) is slightly greater than the recharge for deciduous forests (solid black line) when totaled throughout the year. However, looking at the effective recharge for corn fields (black dashed line) shows that corn has more recharge during the early spring and the late fall, but results in a net deficit to groundwater during the summer months as the irrigation amounts exceed the recharge amounts during those months. The differences between corn and deciduous recharge in the spring and autumn are accounted for in the change in soil storage (orange line shown in the bottom panel). During the spring, corn fields are at field capacity, and SWB models precipitation or snow melt in that period going more to recharge for corn fields. For deciduous forests, however, the SWB model shows more of that springtime water going towards additional soil storage, resulting in relatively less recharge. During the summer, soil storage is maintained for corn fields due to irrigation, whereas deciduous soil storage goes to zero during this time as water is depleted from the soil zone to maintain deciduous transpiration rates. And during the autumn, the SWB model simulates deciduous soil zone refilling, which reduces the amount of water available for recharge for deciduous during this period. Note however that these soil storage values are the average across the 2012 to 2018 period; dry years can produce a net loss in soil storage across the year, while wet years can produce a net gain in soil storage across the year.

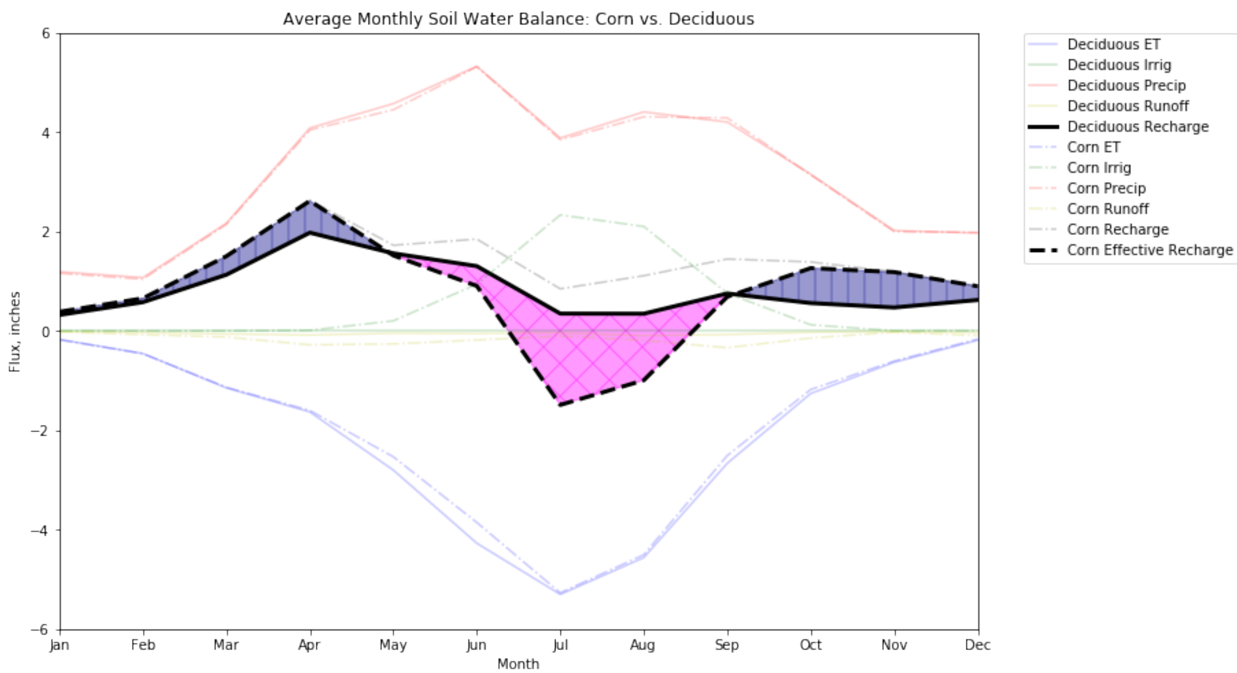

Figure 11. Components of the average monthly water budget with the difference between irrigated corn effective recharge deciduous forest recharge shaded. Blue shading indicates more irrigated corn effective recharge than deciduous recharge; pink shading indicates more deciduous recharge than irrigated corn effective recharge.

Using the base parameters in the SWB model, there is less than an inch of difference between the annual recharge under deciduous forest (an average of 10 inches per year) and the irrigated corn effective recharge (an average of 9.2 inches per year). However, the way recharge is distributed throughout the year can result in important differences in the way each land use type affects nearby surface waters. Figure 11 highlights the seasonal differences between deciduous recharge and corn effective recharge. Blue shading shows periods when corn effective recharge exceeds deciduous recharge; pink is where deciduous recharge exceeds the corn effective recharge. There is relatively more irrigated corn effective recharge in the shoulder seasons, typically when crops aren't being grown and irrigated. That additional recharge in the shoulder seasons is offset by the deficit in effective recharge during the summer months. Combining the excess effective recharge from spring and fall with the deficit during summer results in a total annual corn effective recharge that could be very close to the annual recharge under deciduous forests. However, the summer deficit can result in seasonal impacts to the groundwater and surface water systems near pumping centers, such as groundwater depletion at the end of summer when irrigation withdrawals would be at their maximum. In addition, the drawdowns caused by those summer deficits dissipate slowly rather than disappearing immediately when pumping stops; in some cases the time it takes for an aquifer to recover after the end of pumping can be longer than length of time pumping occurred (for example, if pumping occurred for one month, it could take several months for the aquifer to recover to pre-pumping levels). Figure 12 illustrates the way that impacts to streams and groundwater levels can extend beyond the period when recharge reductions are occurring, sometimes failing to fully recover before the next round of annual groundwater withdrawals start.

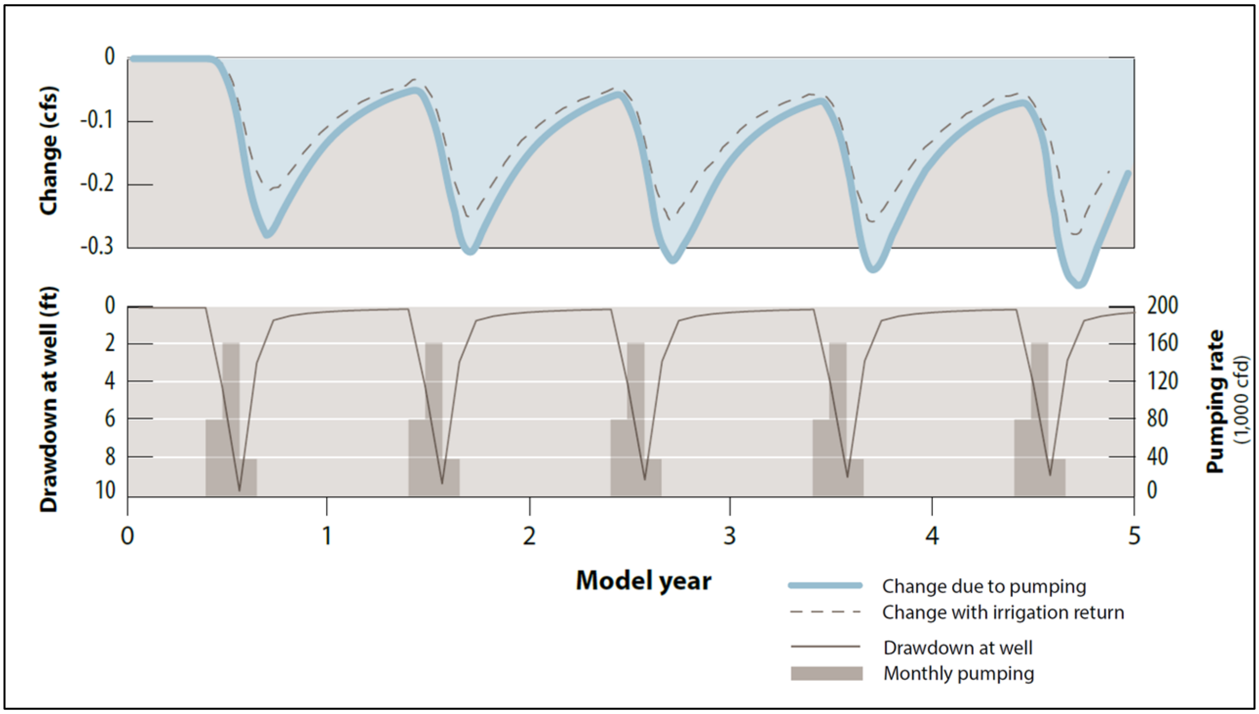

Figure 12. Timing of aquifer and surface water changes relative to timing of water withdrawals. Top: Hydrograph showing modeled changes to streamflow due to simulated summer water withdrawals from a well near the Little Plover River; Bottom: Simulated pumping schedule and related groundwater drawdown. (from Bradbury et al, 2017)

Small differences in total recharge, together with the seasonality of impacts from irrigation indicate that irrigated agriculture can cause a shift in the total amount and timing of water reaching the water table and nearby surface waters.

While determining recharge is a necessary step in understanding and quantifying changes to the groundwater-surface water system due to irrigated agriculture, the specific impacts of irrigated parcels depend on their position in the landscape, underlying aquifer properties, and distance to various surface water features. To capture these variables and to investigate the timing of the effects of groundwater withdrawals, we need to look at recharge and pumping differences within a groundwater flow model. As described in the groundwater modeling report (Fienen et al., 2021), the Monte Carlo SWB model results were incorporated as inputs into the numeric groundwater flow model to assess the effects of irrigated agriculture on the three CSLS study lakes. By checking the SWB outputs like evapotranspiration, pumping amounts, and recharge against observed or reported values for the 2011-2018 period, we increase our confidence in using the SWB model to calculate recharge inputs for the "what if" scenarios that we need to create in the groundwater model to answer our central study questions.

Limitations and Assumptions

Recharge remains one of the most difficult components of the water cycle to estimate, and the estimation methods we chose each have advantages and limitations. The simplified annual water balance model includes few parameters, giving it both the advantages and disadvantages of simplicity. Scientific advances in recent years have provided better estimates of the important components of the water cycle used in the water balance calculation: improved precipitation data (e.g., PRISM) and evapotranspiration (e.g. AmeriFlux towers, MODIS). However, this simplified model makes several assumptions about the water cycle; notably it assumes that there is no net change in soil storage over the course of a year. This assumption may or may not be valid. This makes the estimates that we obtain using this method somewhat uncertain.

The SWB model uses a more complex set of inputs and calculations. This allows us to assess shorter time steps and hypothetical scenarios. But, the more complex calculations require their own assumptions, each carrying some uncertainty. We used the Monte Carlo method to capture some of this uncertainty and incorporate it into our results.

In both the simplified annual water balance model and the Soil-Water Balance model, input parameters and recharge estimates are averaged over the area of the model cell. This is a necessary step, given the scale of the data available, but does smooth some of the field-scale variability in recharge that we know exists. Because of this, our recharge estimation results should be applied at a regional rather than a parcel-specific scale, and only reflect estimations of the dominant land use within a cell.

Estimates of recharge, including the timing of recharge throughout the year under different land uses, is an important component of a broader examination of the effects of irrigated agriculture on water resources. However, in order to understand how the recharge differences affect the groundwater-surface water system, additional tools such as groundwater models are needed. These tools can examine the degree to which changes in recharge result in changes to groundwater levels, lake levels, or streamflows. Groundwater models also let us explore how those recharge timing impacts translate through to the broader groundwater system.

Conclusions

Recharge is highly variable spatially, temporally, and by land cover. While difficult to estimate and nearly impossible to measure directly at a regional scale, the process described here and in the groundwater modeling report (Fienen et al. 2021) builds upon past scientific efforts for estimating recharge. The results are validated against independent measurements and estimates, such as Water Use reporting and MODIS evapotranspiration estimates. The results of these water-balance approaches for recharge estimation tell us:

- In the long run, precipitation is the biggest driver of the system. Recharge estimates track most closely with precipitation, regardless of land use. Irrigation has some influence on recharge, but irrigation is not necessarily the primary controller of groundwater levels.

- There is significant amount of spatial variability in recharge patterns, regardless of land use type. Differences in precipitation and evapotranspiration patterns, crop dynamics, soils, and many other factors can lead to different recharge rates for two fields growing the same crop in different parts of the Central Sands (or even differences between nearby fields).
- The simplified annual water balance model is too coarse a tool at this scale to calculate differences between recharge for irrigated crops and non-agricultural land uses. The spatial variability, plus the simplifying assumptions needed to make these estimations, produce too much uncertainty to identify any differences that may exist.
- The SWB model is more precise than the simplified annual water balance model, but still has some uncertainty. To account for this uncertainty, the SWB model was run with 349 combinations of parameters to produce a range of recharge estimates. The groundwater flow model uses this entire suite of recharge estimations as inputs. This method provides bounds on the range of possible lake drawdown outcomes. See the Modeling Documentation Technical Report (Fienen et al., 2021) and the Lake Ecosystem Characterization and Response Technical Report (Voter et al., 2021) for further discussion.
- Long-term differences between irrigated agricultural effective recharge and non-agricultural recharge are comparatively small. Larger differences are seen in years with dry summers, when more water is pumped for irrigated agriculture.

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