M.L. 2016 Project Abstract
For the Period Ending July 1, 2020

PROJECT TITLE: Assessment Tool for Understanding Vegetation Growth Impacts on Groundwater Recharge
PROJECT MANAGER: Gene-Hua Crystal Ng
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WEBSITE: https://www.esci.umn.edu/groups/Hydro/Minnesota-Ecohydrology-and-Groundwater
CODE: https://github.com/harshanurag/Ecohydrology_MN
DATA REPOSITORY: https://z.umn.edu/5nfp

FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2016, Chp. 186, Sec. 2, Subd. 03f

APPROPRIATION AMOUNT: $212,000
AMOUNT SPENT: $202,294
AMOUNT REMAINING: $9,706

Sound bite of Project Outcomes and Results
Year-to-year variations in vegetation can impact recharge over short periods (annual, seasonal, or monthly). Accounting for this will be especially important for predicting future recharge as vegetation responds to increasing and more variable temperatures. Groundwater recharge in the water-limited western part of Minnesota is most sensitive to the impacts of changing temperature and vegetation.

Overall Project Outcome and Results
This project investigated the impact of varying plant growth on groundwater recharge using an ecohydrological computer model, the Community Land Model (CLM). With the model, we simulated recharge for two different vegetation conditions – one in which actual, year-to-year varying vegetation conditions were included, and the other (the standard approach) in which the average 16-year vegetation conditions were included. The study was carried out for 2000-2015 at a resolution of 25km for the entire state of Minnesota. The overall statewide average recharge for the 16-year period was 2.9 inches per year with varying vegetation and 2.8 inches per year with repeated, 16-year average vegetation. Although the difference between these results is very small, it is more variable on an annual and local scale and can differ up to 28% for certain times and locations. The impact on recharge due to the vegetation also varies by ecoregions. Recharge in the North Central Hardwood Forests (NCHF) is the most sensitive to varying vegetation, and the North Lake and Forests (NLF) in northeastern Minnesota (consisting primarily of coniferous forests) is the least sensitive. Across the state, we also found that most year-to-year variations in vegetation occur mostly due to temperature rather than precipitation, with the greatest temperature sensitivities in the Great Plains (GP) in the western Minnesota. With overall increasing and more variable temperatures projected for the future, accounting for dynamic responses in vegetation becomes even more important for accurately predicting changes in recharge, especially in sensitive areas of the state like western and central Minnesota. Through our study, we also found that southeastern and northeastern Minnesota suffer from sparser and lower quality groundwater level data compared to other parts of the state, serving as a major limitation in accurate recharge assessments there. Expanding groundwater monitoring in these areas will be important for managing and preparing for future impacts of climate and plant variability on recharge in these areas.

Project Results Use and Dissemination

The methodology and main results will be documented on the project website. Poster and oral presentations were made in multiple national and regional conferences, workshops, and seminars including: American Geophysical Union Fall Meeting (2017, 2018 and 2019), Community Earth System Model workshop, Colorado (2019), Earth and Environmental Sciences Student Research Symposium, Minnesota (2018), and Water Resource Symposium, Minnesota (2017).

Source code modifications for the ecohydrological CLM model and the Ensemble Kalman Filter (EnKF) calibration code have been publicly shared online via a GitHub code repository. An error in the source code of the ecohydrological CLM model – a model used by a large number of users globally - was discovered and fixed. We will be submitting the fix officially for the public review so that it can be included in future versions of the model. We filtered and removed erroneous observations for multiple wells in the Cooperative Groundwater Management (CGM) Database. We have communicated these issues to MN-DNR in order to help them improve this public dataset. Additionally, we are preparing a scientific journal article to share our findings with the academic community.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2016 Work Plan Final Report

Date of Report: July 1, 2020

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: June 30, 2020

Does this submission include an amendment request? _No_

PROJECT TITLE: Assessment Tool for Understanding Vegetation Growth Impacts on Groundwater Recharge

Project Manager: Gene-Hua Crystal Ng

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Location: Statewide

Total ENRTF Project Budget:

ENRTF Appropriation:	**$212,000**
Amount Spent:	**$202,294**
Balance:	**$9,706**

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 03f

Appropriation Language:

$212,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to develop a statewide assessment tool to help understand the relationship between vegetation growth and impacts on groundwater recharge under changing land use and climate. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Assessment Tool for Understanding Vegetation Growth Impacts on Groundwater Recharge

II. PROJECT STATEMENT:

Vegetation growth depends on climate and land-use conditions; this directly affects groundwater recharge, because plants compete with shallow aquifers for water through evapotranspiration. New statewide groundwater recharge maps are valuable for current water management, but they assume plants to be static and neglect the timing of water table impacts. A biophysical model planned for Minnesota will provide vegetation details but omits data connecting these to groundwater systems. Thus, we lack the ability to predict groundwater recharge when vegetation growing conditions change. **Our proposed project addresses this gap by providing:**

1. Statewide time-lapse maps of plant growth and groundwater recharge estimates
Evaluations of how plant and groundwater impacts are linked under climate and land-use change
Reliability maps indicating where additional data are needed for improving recharge estimates

Our **statewide assessment will cover Minnesota's diverse eco-regions, natural and managed systems, hydrogeological provinces, and sharp precipitation gradient**. It will address questions such as: how much could above-normal spring temperatures trigger early green-ups that diminish recharge; how much will roots deplete deep soil moisture when summer rains are scarce; and how does this depend on plant and soil type? Answers are most urgent for areas such as: (1) the drier west, where low recharge rates are highly susceptible to climate and vegetation perturbations, (2) the north-central lakes region, where conversion from deep-rooted forests to cropland strongly alters recharge, and (3) northern mixed forests, which will likely shift from conifers to more broadleaf species as temperatures warm. Throughout the state, our maps will benefit ecological and water resources managers in their long-term preparations as land-cover and climate boundaries move.

The challenge in accurately quantifying groundwater recharge is insufficient data. To generate our maps, **we will develop an assessment tool that (1) incorporates multiple datasets spanning the land-surface all the way down to the water table and (2) represents the physical mechanisms of plant growth and water flow to bridge data gaps.** This project will be primarily carried out by a graduate student researcher over three years under the guidance of Project Manager Ng.

The proposed assessment tool will be implemented using the "Community Land Model", a computer model that represents the physical and biochemical processes of water transport through soil, vegetation, and the atmosphere. Statewide application of such a complex model requires significant computational resources. We will develop and execute the assessment tool using high-performance computing resources of the Minnesota Super-computing Institute (MSI). Model results will be processed and interpreted into formats easily distributable and accessible to both technical resource managers and the general public.

The assessment tool development will rely heavily on leveraging widely available weather, soil, and vegetation maps. We will compile observations from national climate and soils databases, and we will work with the Minnesota Geological Survey to incorporate surface and subsurface geologic maps from the County Geologic Atlas series and the state-wide groundwater well network. Vegetation change data will be collected from newly available land-cover maps and repeat satellite imagery of vegetation density. A major component of the work will entail the rigorous calibration of the assessment tool using the diverse datasets. By connecting the climate-vegetation domain and groundwater systems, our project will help enable critical coordination between ecological and groundwater management in Minnesota by state agencies and private stakeholders concerned about water and land resources.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 1, 2017:

For Activity 1, we have completed the data compilation for inputs needed for to the CLM model; these include meteorology, near-surface soil texture, subsurface lithology, and vegetation. Data covering the state have been extracted. We are now processing the data to a standardized spatial resolution and file format for the model. We are also selecting a subset of groundwater wells with extensive subsurface and water level data that are installed in water table aquifers – these are most directly responsive to vegetation change. These wells will serve as the basis for developing the model implementation before extending it statewide.

For Activity 2, our graduate student has completed coursework needed to carry out the vegetation and groundwater modeling and its calibration. He has begun preliminary generic tests with the model software before customizing it for Minnesota. Work has not yet begun for Activities 3 and 4.

Amendment request (January 1, 2017):
This amendment request is to reallocate funding originally budgeted for PI Ng's summer salary and for the undergraduate researcher in Year 1 (for Activity 1) and Year 2 (for Activity 2) to be applied to a computer programmer in year three (for Activity 2). Funds originally budgeted for PI Ng and the undergraduate research assistant are no longer needed the first two years, because a computer programmer has recently joined PI Ng's research group and will be able to provide assistance with developing the assessment tool in Activity 2. Other funding is available for her the first two years, but she will require funding the third year.

Amendment Approved by LCCMR 1/05/2017

Project Status as of July 1, 2017:
(Not required – see cumulative status report below)

Project Status as of January 1, 2018:

Data compilation in Activity 1 is nearly complete for the inputs needed to calculate recharge across the state. Before publishing the data compilation, we are carrying out preliminary model runs to finalize the necessary data for the project. A project website (https://www.esci.umn.edu/groups/Hydro/Minnesota-Ecohydrology-and-Groundwater) has been developed to post the data and other project results when ready.

Substantial progress has been made in Activity 2. Our graduate student has implemented both single point model simulations to test the model with data compiled in Activity 1, as well as statewide simulations to evaluate the sensitivity of recharge predictions to dynamic vegetation growth. Although the model has yet to be fully calibrated, results thus far demonstrate that representing dynamic vegetation growth has a strong impact on water table depth and recharge predictions across the state and must be taken into account for accurate groundwater assessments. The model set-up for statewide implementation has been completed. Our graduate student has also written and tested the initial computer code for calibrating the model using state-of-the-art statistical methods.

We presented a poster at the 2017 American Geophysical Union meeting in December (no LCCMR funds were used for attending the conference) showing preliminary results for the statewide model sensitivity test and the model calibration framework. At the conference – the most widely attended in the geosciences field – we showcased that state-of-the-art tools and methods are being used to evaluate recharge throughout the distinct ecoregions of Minnesota. We have made public these findings to-date by posting the poster on our project website (url provided above).

Project Status as of July 1, 2018:

As part of the final stage of Activity 1, we made progress on formatting the input data for the model. The meteorological and satellite vegetation data that we previously compiled are now in the standardized gridding and NetCDF file format for the project. The remaining soil data will be similarly formatted as we incorporate them into the model.

Our graduate student moved forward Activity 2 – the major component of the project – which entails developing the model to estimate recharge. He has begun to customize the statewide model using detailed state-specific data – in particular, finer spatial scale meteorological and time-varying vegetation variables. Work to incorporate the time-varying vegetation is still in-progress; it requires developing a new approach for executing the model, which is central to incorporating vegetation dynamics to evaluate its influence on groundwater recharge. Since the last update, we have also further developed the calibration software so that it can be used to estimate soil parameters that control both water uptake by plants as well as infiltration to the water table. This step has required calculating statistical metrics to link soil properties to water table depths. At this development stage of the study, calibration tests are being carried out at specific test points within the state. This Activity will accelerate after our new computer programmer begins her funded work on the project in Year 3.

Graduate student Harsh Anurag presented his work at our department's Soft Rock Seminar series in March 2018 (Department of Earth Sciences, University of Minnesota – Twin Cities).

Amendment Request (July 1, 2018):

The amendment request is for two changes. First is a request to reallocate personnel budget to different individuals. Due to scheduling issues, co-PI Tipping was unable spend the planned time on the project this past year on Activity 2. Also, the Department of Earth Sciences at University of Minnesota covered our graduate student's first summer to provide more time for training. We would like to move most of this unspent budget to fund research hydrogeologist Scott Alexander (University of Minnesota – Twin Cities) and to increase the time of computer programmer Kathy Tokos, both in Year 3. Alexander has the technical skills for carrying out tasks intended for co-PI Tipping: identifying, processing, and interpreting the hydrogeologic and groundwater data needed to calibrate the model. Alexander will also be carrying out fieldwork to deploy instruments for collecting validation data, described next. Tokos will provide valuable computer expertise to help finish the model development.

The second request is to use the small remainder of the unspent personnel budget for some fieldwork. We would like to purchase field instruments and supplies to collect model validation data at the Cedar Creek Long-Term Ecological Research station; model validation will be an important final step for developing the model in Activity 2. Working at this site will allow us to leverage decades of data and ecological understanding accumulated at the site, which has previously received LCCMR funds ("Biofuel Production and Wildlife Conservation in Working Prairies"). Also, the site contains a variety of vegetation types, making it an efficient location to evaluate our model under different ecological conditions.

Project Status as of January 1, 2019:

In finalizing Activity 1, we encountered some complications but were able to overcome them with new datasets. All model input data, including meteorological, soil, and vegetation data, have now been fully processed, regridded and formatted for use with the model. The processing of raw vegetation data from MODIS satellite revealed some shortcomings including temporal data gaps, especially during winter. We have replaced it with an improved and temporally more continuous vegetation dataset called GLASS. We also replaced the SSURGO soil dataset with a new soil dataset named POLARIS. POLARIS is an improvement over SSURGO – it provides more consistent and spatially continuous soil information across Minnesota. The processing and formatting of both GLASS and POLARIS dataset have been completed.

Substantial progress was made in Activity 2. We are in the final stages of testing our calibration framework. Our method improves the model estimate of recharge by constraining both the model states and parameters using water table depth observations. Preliminary tests at a test location were performed to assess the calibration method; these showed good performance of our algorithm in estimating soil parameters. However, computer run-times have been longer than anticipated, even on the Minnesota Super-computing Institute's system. To address this, we are making additional software changes that will allow for more efficient model simulations.

We also made progress in Activity 3. We have completed the development of our new approach to directly incorporate satellite vegetation data into the model. This allows us to evaluate the impact that time-varying vegetation has on recharge. As a first step, state-wide model runs with default soil and vegetation model parameters using both fixed and dynamic vegetation inputs were performed for 2000-2015 to assess the sensitivity of simulated recharge to dynamic vegetation. Results show notable (up to 65%) difference in recharge between the two vegetation conditions demonstrating the importance of dynamic vegetation. The results also suggest that vegetation can disproportionately affect groundwater recharge and thus small changes in vegetation can lead to substantial changes in recharge.

We also began work on Activity 4; uncertainty estimates for recharge have been made at our test location. This will be extended statewide as we conclude the project.

Amendment Request (January 1, 2019):

We request to extend the final report submission to 1/1/2020.

Amendment Approved by LCCMR 1/16/2019.

Project Status as of July 1, 2019:

A few of the input datasets compiled as part of Activity 1 were modified. We are now using the organic matter content in the soil from the POLARIS dataset. This is an improvement over the coarse, default organic matter information included in the older dataset. The new data had to regridded and reformatted before it could be incorporated into the model's subsurface input file. We have also included the geologic data compiled by the Minnesota Geological Survey (MGS) in our input dataset. POLARIS soil data is available up to a depth of 2m and MGS data is used to extend the soil profile to 3.8 m as required by the model. The observation records collected earlier has also been substantially modified, because the parent database (CGM well records) is under active maintenance. The entire input dataset including climate, subsurface, and observation data has been reformatted and is ready to be made available to the public.

Substantial progress was made in Activity 2. We tested our calibration code for several observation wells (total of 12) distributed across the state. This was necessary to ensure that our algorithm is working correctly in different ecological and hydrogeological conditions throughout the state. Significant improvement in model simulations was observed in all 12 test locations after we used our code to calibrate the model. As the next step, we have extended our calibration method to process observations from multiple wells (instead of observations from just one well) to cover the entire state simultaneously. This last step in the model calibration process is in its last stages. The final work on Activity 3 and 4 will proceed once the state-wide calibrated model results are available.

Amendment Request (November 4, 2019):

We request to extend the final report submission to 7/1/2020.

Summary from correspondence with MV: Due to finding a bug in the computer model code in a model created by the National Center of Atmospheric Research, the Ng Lab must now redo a large number of computationally expensive model simulations with the corrected model code. There is considerable wait and compute time on the Minnesota Super Computing Institute's cluster; consequently, the delay to July would allow for more testing and higher accuracy in the final products.

Amendment Approved by LCCMR 11/4/2019.

Project Status as of January 1, 2020:

Compilation and reformatting of input datasets including climate, vegetation, and land-surface data are complete and ready to be used in the model. We will soon be publishing these datasets online. The MNDNR's database containing groundwater level records was found to contain several wells with major measurement errors. These faulty observations were hampering our calibration process. We have now reviewed the entire database and removed several wells from our dataset that had physically infeasible groundwater level fluctuations (indicating measurement error).

Progress on Activity 2 was slowed due to a bug that we found in the model software during our final tests. The bug resulted in the faulty calculation of water table depth and groundwater recharge by the model.

This took several rounds of testing and analysis before we were able to identify and remove the bug from the code. Swift progress was made after this, and we have completed all our initial tests first for single columns and then extending it to regional settings (multiple columns). These test runs were carried out in varied locations in the state to test the robustness of our calibration code across a combination of climate, vegetation, and hydrogeology. The results are very encouraging and show that our method is successfully able to integrate groundwater level observations in our simulations and significantly improve our model outputs in all the test regions. We are in the final stages of extending our method across the full state and completing the final set of simulations. We will be able to proceed with Activity 3 and 4 soon when the state-wide simulations are finished.

Overall Project Outcomes and Results:

Abstract: This project investigated the impact of varying plant growth on groundwater recharge using an ecohydrological computer model, the Community Land Model (CLM). With the model, we simulated recharge for two different vegetation conditions – one in which actual, year-to-year varying vegetation conditions were included, and the other (the standard approach) in which the average 16-year vegetation conditions were included. The study was carried out for 2000-2015 at a resolution of 25km for the entire state of Minnesota. The overall statewide average recharge for the 16-year period was 2.9 in/yr (Figure 1 in Section IX) with varying vegetation and 2.8 in/yr with repeated, 16-year average vegetation. Although the difference between these results is very small, it is more variable on an annual and local scale and can differ up to 28% for certain times and locations. The impact on recharge due to the vegetation also varies by ecoregions. Recharge in the North Central Hardwood Forests (NCHF) is the most sensitive to varying vegetation, and the North Lake and Forests (NLF) in northeastern Minnesota (consisting primarily of coniferous forests) is the least sensitive. Across the state, we also found that most year-to-year variations in vegetation occur mostly due to temperature rather than precipitation, with the greatest temperature sensitivities in the Great Plains (GP) in the western Minnesota. With overall increasing and more variable temperatures projected for the future, accounting for dynamic responses in vegetation becomes even more important for accurately predicting changes in recharge, especially in sensitive areas of the state like western and central Minnesota. Through our study, we also found that southeastern and northeastern Minnesota suffer from sparser and lower quality groundwater level data compared to other parts of the state (Figure 2 in Section IX), serving as a major limitation in accurate recharge assessments there. Expanding groundwater monitoring in these areas will be important for managing and preparing for future impacts of climate and plant variability on recharge in these areas.

Overall Project Outcome and Results:

Previous recharge studies in Minnesota either did not consider the impact of vegetation dynamics or oversimplified its representation by assuming the same vegetation conditions each year. Our study incorporated dynamic, satellite-derived vegetation and investigated the impact of the year-to-year vegetation changes on recharge. We used the Community Land Model (CLM) as our assessment tool. The model couples dynamic vegetation with land-surface and sub-surface hydrological processes and is thus capable of capturing the impact of changing vegetation on recharge. We performed the model simulations for 2000-2015 at a resolution of 25km for the entire state of Minnesota. The computational cost of the model prevented us from carrying out simulations at the originally planned 1-km resolution.

The statewide average recharge estimate accounting for dynamic vegetation is 2.9 in/yr (Figure 1 in Section IX). The default, average vegetation resulted in a recharge estimate of 2.8 in/yr. The 25th and 75th percentile uncertainty of the recharge estimate are 0.13 in/yr and 5.69 in/yr respectively (Figure 3 in Section IX). The large uncertainty range is primarily due to the limited availability of good quality statewide groundwater level observations. Out of the 879 groundwater wells in the state, we were able to use only 330, as others lacked reliable measurement records between 2000-2015. The data is especially scarce in the northeastern and southeastern parts of the state (Figure 2 in Section IX). It should be noted that the recharge estimate uncertainty is significantly lower for the regions of the state where we have dense observations.

Although the 16-year average statewide recharge estimate under dynamic versus average vegetation is almost the same, the annual recharge differences can be as much as as 28% for certain locations between 2000-2015 (Figure 4 in Section IX). Different ecoregions across the state exhibit varying sensitivity of recharge to vegetation. Minnesota has primarily 3 ecoregions – i) Great Plains (GP) in the west, which is largely used for agriculture, ii) the North Central Hardwood Forests (NCHF) in central Minnesota, and iii) the Northern Lakes and Forests (NLF) in northeast Minnesota. NCHF followed by GP shows the highest recharge difference for dynamic versus average vegetation. This difference is the least in NLF. The annual variability of the recharge difference is the highest in GP. This indicates that recharge in the NCHF and water-limited GP area are the most sensitive to changing vegetation growth.

We also studied the role climatic conditions (temperature and precipitation) play in determining the year-to-year vegetation variations that impact recharge. Although the absolute amount of recharge across the state in each ecoregion is determined primarily by the precipitation it receives, temperature most strongly drives the variations in vegetation that influence recharge. Specifically, dynamic vegetation driven changes in recharge has a stronger correlation with temperature than with precipitation. This correlation with temperature is strongest for GP and weakest for NCHF in central Minnesota.

Overall, this study demonstrates that for long-term recharge studies, dynamic vegetation can be simplified with average vegetation conditions. However, year-to-year vegetation dynamics become an important factor to incorporate in studies looking at recharge at shorter time periods (annual, seasonal, or monthly). Further, for future recharge predictions, we expect temperatures to increase and vary even more due to climate change, triggering even greater changes in vegetation conditions in the future. Thus it becomes all the more important to consider dynamic vegetation for reliable recharge calculations under future climate change. Special attention to monitoring vegetation and water-resources should be given in the sensitive areas in the state, which includes central and western Minnesota.

Funding remained at the end of the project. In reviewing final accounts, it was found that the actual balance of $9,706 was slightly different than the previously reported balance of $8,439, because it included an incorrect salary encumbrance amount. The attached budget spreadsheet has been corrected to show the adjusted balance.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Compile and analyze data connecting climate and vegetation to groundwater systems

Description:

In this activity, we will compile data needed for the vegetation and recharge assessment. This includes daily data on precipitation, temperature, humidity, and solar radiation, which we we will obtain from the Daymet database. This is a gridded climate data product that is generated using weather station observations published by the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC). Surface soil data include texture class, which strongly influences how much water infiltrates surface soils. We will collect surface soil data from the USDA NRCS's (National Resources Conservation Service) Soil Survey Geographic (SSURGO) database and the State Soil Geographic (STATSGO) database. These national climate and soil databases have been previously utilized for the the USGS/MPCA's 1-km resolution statewide recharge map.

Vegetation data for this work will include national and state-specific databases. We will leverage new 30-m statewide land cover maps currently produced by the LCCMR-funded project "Update Statewide Land Cover Use Map" led Joe Knight. To be completed and disseminated by June 2016, these maps will provide 2013-2014 land cover information. Differences between the previous 2000 and new 2013-2014 land-cover map will provide key information about ecological changes for our assessment on how recharge responds to vegetation.

Within major shifts vegetation-type cover, we will also evaluate how interannual and seasonal plant growth controls recharge. To do this, we will use MODIS satellite data on plant density, which is available on a 1-km spatial and 8-day temporal resolution starting in 2000.

Water that infiltrates the surface soil and percolates through root zone must flow through the soil column before recharging the water table. An advancement in our new recharge assessment tool compared to previous recharge mapping work in the state will be the incorporation of deeper subsurface information, which importantly controls the timing and rate at which water flows from surface soils to recharge the water table. Physical hydraulic properties will be inferred by combining information from geologic maps from the County Geologic Atlas series and statewide groundwater well databases. The County Well Index includes approximately 450,000 entries throughout the state and provides well drilling logs that characterize subsurface properties in the vertical direction. These data will be supplemented horizontally using surface and subsurface geological maps.

In addition to physical borehole data from well drilling logs, statewide well databases will provide us with water level observations that will serve as calibration points for our assessment tool. The observation well network in the Cooperative Groundwater Monitoring program is a subset of the County Well Index that provides water levels over time for approximately 1800 wells throughout the state.

Activity 1 will comprise the most comprehensive state-wide dataset to date for information related to groundwater recharge. Data will be standardized to a 1-km resolution grid covering the state and will be processed into different file formats. All data will be entered into an efficient netCDF format required by our assessment tool, in GIS format for technical resource managers, and in graphical maps for general-public stakeholders.

Project manager C. Ng will guide a graduate student researcher in carrying out this activity. An undergraduate student researcher will help in retrieving and organizing datasets. Project partner Tipping will assist with accessing statewide databases and creating data files in the GIS format.

Summary Budget Information for Activity 1: **ENRTF Budget: $ 47,801**
Amount Spent: $ 45,868
Balance: $ 1,432

Outcome	Completion Date
1. Comprehensive dataset over the entire state for evaluating groundwater recharge	1/31/17
2. Publicly available information in easy-to-use formats for resource managers	6/30/17

Activity Status as of January 1, 2017:

We have completed the comprehensive data compilation that will serve as inputs to the CLM model in Activity 2, and we have begun processing the data to standardize the spatial resolution and file format. Progress has also been made on compiling calibration data for the model, including groundwater levels.

Model input data has been collected for 4 categories: meteorology, near-surface soil texture, subsurface lithology, and vegetation. For meteorological data, we obtained daily data from 1980 to 2015 on 4 variables – precipitation, humidity, solar radiation, and temperature from the Daymet dataset. Daymet is archived and distributed by Oakridge National Laboratory at 1km x 1km resolution; data for Minnesota has been extracted from the full dataset. For surface soil information, the SSURGO and STATSGO2 datasets for Minnesota were obtained from USDA NRCS. SSURGO has information collected at scales ranging from 1:12000 to 1:63360. STATSGO2 is a coarser dataset with information at the scale of 1:250000. For the sub-surface data, we have identified the geographically verified groundwater wells from the County Well Index (CWI) database (this includes 323760 of the total 510777 wells), for which we extracted data on: well depth and location, stratigraphic interpretation (including depth to bedrock), and static water level measurements.

The data from Joe Knight's Minnesota Land Cover Classification and Impervious Surface Area by Landsat and Lidar project (MLCC) was obtained for vegetation information. The National Land Cover Dataset (NLCD) was also downloaded for comparison; MLCC utilizes more detailed, state-specific remote sensing products and classifications and will thus be more relevant for this project compared to NLCD. We also obtained MODIS leaf-area-index (a leaf density measure) satellite data to provide constraints on interannual and seasonal plant growth.

Table 1 below lists the original dataset resolutions and file formats. We are in the process of implementing QGIS software to execute spatial re-gridding to the planned 1km x 1km model domain; all data will be reformatted to the netCDF file format needed for the CLM model.

Table 1: Compiled data with their original spatial and temporal information and file formats.

Data	Dataset	Temporal Resolution and Availability	Spatial Resolution (available over MN)	File Format
Meteorology	Daymet	Daily (1980 - 2015)	1km x 1km	netCDF
Soil texture	SSURGO	Version 2.2 (October 2005)	Vector data (1:12000 scale)	Tabular and Spatial (GIS Compatible)
	STATSGO2	2006 release	Vector data (1- by 2- degree)	GIS Compatible
Vegetation cover	MLCC	Based on Landsat and lidar data over 2008-2013	15m	TIFF
	NLCD	2011 release, amended 2014 (updated every 5 years)	30m	.img/.ige
Leaf-area-index	MODIS (MCD15A3H)	4 day (2002/07/04 – 2016/10/23)	1km x 1km	.HDF
Sub-Surface Data	County Well Index(CWI)	Various	N/A	Access Database
Groundwater level data and lithology	Cooperative Groundwater Management (CGM)	Various	N/A	Excel files

Subsurface data is essential for connecting the surface and groundwater in the model, yet subsurface information is diverse in its forms and typically does not relate directly to soil hydraulic properties needed for the model. In addition to cross-referencing new hydrogeologic county maps, we will use groundwater level data from the Cooperative Groundwater Management (CGM) as our main model calibration data. Before attempting an exhaustive state-wide calibration with disparate subsurface measurements, we are selecting a small subset of wells on the basis of hydrological setting and groundwater data availability to serve as preliminary test cases for developing the model. Out of the 1830 wells in the CGM program, we identified 776 wells installed in water table aquifers, which are most responsive to vegetation changes. We are in the process of shortlisting 10-15 wells depending on the most complete record of the data. These wells will then be used for our pilot model implementations.

Activity Status as of July 1, 2017:
(Not required – see cumulative status report below)

Activity Status as of January 1, 2018:
We obtained additional data from NCEP's North American Regional Reanalysis (NARR) for some of the necessary climate inputs for the CLM model (used to calculate recharge) that is not available in the Daymet

dataset (atmospheric pressure and wind). The data from the two datasets (Daymet and NARR) were combined and processed into a compatible format that is readable by the CLM model. This included downscaling the daily Daymet into hourly data and spatially re-projecting the NARR dataset to match the Daymet dataset. The compiled data was also standardized into a 1 km x 1 km grid covering the entire state of Minnesota and converted to the NetCDF file format.

Before fully formatting and publicly releasing the all the statewide datasets for the recharge calculations, we determined it be necessary to first test the CLM model at several representative locations and carry out preliminary model runs (see Activity 2) before we are able to finalize the input datasets and formats needed for this project. However, in preparation for the public release of the data, we have developed a project website where this information will be disseminated: https://www.esci.umn.edu/groups/Hydro/Minnesota-Ecohydrology-and-Groundwater.

Activity Status as of July 1, 2018:

Updates and corrections were made to the previously processed meteorological data. Upon testing in the model, we found that the data from the two different sources (DayMet and NARR) were not at compatible map projections, and this required re-gridding. After completing this, we fully processed and tested the data for the entire 1980-2015 time period covered by the Daymet dataset.

Progress was also made on converting remotely sensed dynamic vegetation data (from MODIS) into the format used by the model. The default model is set up use only static vegetation inputs, and so we are developing software for cycling through a changing set of vegetation inputs based on the satellite data. This requires extracting the remote sensing data from its original file format and recasting it into the NetCDF data format required by the model for a series of files for each year.

Activity Status as of January 1, 2019:

The meteorological dataset, which includes data from Daymet and NARR database, has been fully processed, regridded, and formatted for Minnesota. We are preparing for the final upload of the data on our project website, where it will be easily accessible to the public. For the surface soil information, we are using a recently published probabilistic soil series database called POLARIS instead of the originally planned SSURGO dataset. POLARIS was derived using a combination of the legacy SSURGO dataset, high-resolution geospatial environmental data, and a state-of-the-art machine learning algorithm. It remaps SSURGO and overcomes several of its weaknesses, including variable data quality and incomplete spatial coverage. POLARIS dataset has been regridded and incorporated in the model.

The processing of raw MODIS satellite data also revealed some problems with that dataset. Cloud cover and occasional failure of satellite's data processing algorithm decreased the quality of the final product and caused several data gaps during the period of 2000-2015. Thus, MODIS satellite data, which we originally planned to use for vegetation information, is now being substituted by another vegetation dataset named GLASS. This dataset has less uncertainty and is temporally more continuous than MODIS's raw data. It is available at 8-day temporal resolution and 0.05° spatial resolution. GLASS has been fully formatted and is also ready to be used as an input.

Activity Status as of July 1, 2019:

The new soil dataset POLARIS is being used, because it includes estimates of soil properties not available in the previous dataset, namely organic matter (OM) content in the soil. A better estimate of OM has the potential to improve groundwater recharge model simulations. OM and other POLARIS soil data has now been reformatted and incorporated into our sub-surface input dataset.

We also obtained the surficial geologic texture database from Minnesota Geological Survey (MGS). This database contains soil parent material data. POLARIS describes the first 2m of soil texture. The MGS data is being used to extend the POLARIS soil profile to 3.8m depth as required by the model. The entire subsurface dataset with updated soil and organic matter properties has been fully formatted, regridded and is ready to be used as an input in the model.

The CGM well database is undergoing active maintenance. As part of this activity, several improvements have been introduced in the database, including updates to several well observation records. We had to directly contact the CGM database manager at MNDNR to obtain the raw updated observation dataset. This dataset had to be further edited and reformatted before it could be used for model calibration tests. The observation dataset upgrade has been completed, and the fully formatted groundwater observation record for more than 600 wells across the state is ready for use for our final calibration.

Activity Status as of January 1, 2020:

The input dataset including vegetation, atmospheric, and land-surface data have been formatted and is ready to be used in our model simulations. As mentioned in the previous update, we had about 600 well records in the updated CGM database. However, we found out that several of these wells did not pass our quality control checks. Some groundwater records appear to include random fluctuations that are not physically feasible, and we attributed these to measurement noise. This required us to review the entire observation database and remove several wells that had noisy observations. The observation dataset has now been cleaned up and is ready to be used in our simulations. All our datasets, including input data and observation records, have undergone all the formatting and are ready to be shared publicly. We are planning to upload these databases in online repositories soon.

Final Report Summary:

Activity 1 comprised a comprehensive compilation of state-wide data related to groundwater recharge estimation as needed by our assessment tool. This included collecting data in 4 main categories: meteorology, near-surface soil texture, vegetation, and groundwater level observations. The data came from multiple sources with widely varying spatial and temporal resolutions that required extensive processing, regridding, and formatting to prepare it for use in the model. Because of the availability of better or newer data sources, we modified our original dataset list.

The table below lists the information about the final set of data sources used for model implementation. All data has been reformatted to either the netCDF file format (needed for the CLM model) or easy-to-use GIS compatible format. These final data files can be downloaded from the "Input" folder at https://z.umn.edu/5nfp.

Data	Dataset	Temporal Resolution and Availability	Spatial Resolution (available over MN)	File Format
Meteorology	Daymet	Daily (2000- 2015)	1km x 1km	netCDF
	NCEP NARR	3-hourly (2000- 2015)	32km x 32km	
Soil Texture	POLARIS	2018 release	1km x 1km	TIFF and netCDF
Vegetation	GLASS	8-day (2000-2015)	1km x 1km	netCDF
Groundwater Level (Observation dataset)	Cooperative Groundwater Management (CGM)	Various	N/A	Excel, TIFF

ACTIVITY 2: Develop and calibrate an assessment tool for computing plant growth and recharge throughout Minnesota

Description:

The "Community Land Model" (CLM), a computer model developed by the National Center for Atmospheric Research (NCAR) for evaluating water transport through soil, vegetation, and the atmosphere, will serve as our vegetation and recharge assessment tool. The initial model set-up will be tailored to Minnesota-specific conditions using the extensive data from Activity 1. Model input files will be generated from the climate time series data, surface and subsurface soil and geological maps, vegetation type maps from 2000 and 2013-

2014, and vegetation density change time series. Climate data can be directly implemented with the model. Raw geological and vegetation data will be converted to specific parameter forms for CLM, such as percent sand and clay and plant photosynthesis properties. We will rely on more intensively instrumented sites to develop techniques for inferring appropriate model parameters from generally available raw data.

The development of this assessment tool requires technological facilities not readily available to resource managers or even most state agency scientists. The project team will utilize the University of Minnesota's Super-computing Institute (MSI) system to create the assessment tool and make accessible its results. Implementing CLM on MSI will require software customization and optimization.

After the initial set-up of CLM, model calibration and validation will be an essential component of this work. This step will address uncertainty in data inputs (e.g., measurement errors) and in the conversion step from raw data to model parameters (e.g., geological map unit to hydraulic conductivity). Calibration is a computationally intensive and difficult process for complex models such as CLM, which requires many grid cells and parameter variables. We will employ a statistical calibration and estimation method, the ensemble Kalman filter (EnKF), which rigorously treats uncertainties in both the model and data. Model parameters and simulation results will be calibrated to water-level observations in wells.

Implementation of the EnKF calibration method will entail a number of steps. First, the algorithm requires observation error quantification, which we will calculate based on variability among measurements and other reported information from field sources. Next, we will carry out model sensitivity assessments to determine which model parameters should be calibrated. We will then conduct the calibration through a multi-tiered approach. We will first implement the calibration procedure for locations with densest availability of calibration data, including counties with completed county geological maps and greatest clusters of observation well data. Implementation of the EnKF method requires tuning of certain algorithm parameters and optimized usage on MSI. Starting with the most favorable locations for model calibration will facilitate the algorithm-tuning. The calibration will then be extended to grid cells in the state with progressively fewer data. Important calibration parameters will likely include hydraulic properties controlling water flow through the soil column and root uptake properties controlling the rate at which plants remove water from the soil.

To establish confidence in the model implementation and calibration method, we will validate the results using detailed water table data collected below a variety of vegetation types at the Cedar Creek Long-Term Ecological Research station. At the site, we will be able to leverage decades of ecological data and understanding, which we will further augment by measuring water table changes over Year 3 of the project using automated water level sensors (pressure transducers). We have identified candidate locations with monitoring wells already installed below grassland, deciduous forest, and mixed forest plots. These wells have not previously been instrumented with automated sensors, which can more easily measure changes over rain events and seasons than when relying on manual measurements. The advantage of utilizing data from this site is that both the ecologic and hydrogeologic conditions are much better constrained than for the extensive statewide observation well network. Proximity to the University of Minnesota – Twin Cities (35 miles) keeps travel costs and logistics to a very manageable level.

After the initial set-up and calibration, CLM model simulations will be carried out for the entire state at a 1-km, daily resolution from 2000 to 2014. Project manager Ng will guide the graduate student researcher in implementing the model on MSI. The undergraduate student research will continue to help maintain the datasets and new model files. The project team will work together to document the model implementation, calibration, and execution procedure. This document will be important for end-users to understand the features and assumptions in the assessment tool.

Summary Budget Information for Activity 2:

ENRTF Budget: $ 140,257
Amount Spent: $ 140,133
Balance: $ 625

Outcome	Completion Date
1. Assessment tool development using University of Minnesota's computational facilities	10/31/18

2. Execution of assessment tool to estimate vegetation growth and recharge for the entire state	1/31/19
3. Documentation of assessment tool for use by state agencies and technical managers.	2/28/19

Activity Status as of January 1, 2017:

In Fall 2016, graduate student Harsh Anurag completed coursework in “Biometeorology” and “Probability and Stochastic Processes” in preparation for implementing and calibrating the ecohydrological model. He has ported the CLM model on MSI (University of Minnesota's high-performance computing system) and has carried out preliminary simulations to familiarize himself with the model.

Activity Status as of July 1, 2017:

(Not required – see cumulative status report below)

Activity Status as of January 1, 2018:

After completing the CLM model set-up on MSI (University of Minnesota's high-performance computing system), graduate student Harsh Anurag carried out single point simulations using coarse-scale climate data for two locations in Minnesota as a preliminary analysis of the effect of vegetation dynamics on groundwater recharge. He then carried out separate simulations for the sites using fine-scale meteorological data to test out the incorporation of data compiled in Activity 1 into the model. From the two single point simulations, we found that recharge predictions differ notably depending on whether dynamic vegetation growth is taken into consideration, supporting the the need for our proposed new recharge assessment tool.

To evaluate the impact of vegetation beyond the two preliminary test sites, we next set up the model for statewide implementation. To determine an optimal spatial scale that strikes a balance between computational efficiency and adequate representation of ecological and hydrological heterogeneity, Anurag performed a series of model runs at different resolutions (1km, 10km, 25km) and found 25 km resolution to be most suitable for the current model development stage. Anurag has implemented two statewide simulations at 25 km resolution simulations for the of period 2000 – 2010 – one that incorporates dynamic vegetation growth and the other that follows the standard approach of static vegetation. The two simulations revealed clear differences in water table and recharge predictions across the state, and it showed the greatest sensitive to dynamic vegetation growth to occur in the western drier region of Minnesota. We also compared model results against satellite observations (MODIS leaf-area-index) and further verified that vegetation across Minnesota can vary significantly season-to-season and year-to-year, which we have now determined needs to be incorporated into model prediction of recharge.

The single-point and statewide simulations carried out thus far have been with preliminary soil and vegetation parameters and require further calibration to observed water table levels and satellite vegetation data. Anurag has begun to set up the calibration framework by writing the computer code for the state-of-the-art Ensemble Kalman Filter (EnKF) method. EnKF will be used to reduce uncertainty in our model by integrating the field and satellite observations into our simulations and estimating the model parameters in a probabilistically rigorous way. We have carried out initial tests with the newly written computer code to evaluate the necessary data that will be required for calibrating the model.

We have presented our preliminary statewide simulations and model calibration framework at the 2017 American Geophysical Union (AGU) Fall Meeting in New Orleans in December (no LCCMR funds were used for the conference expenses), which is the largest meeting in the geosciences and is attended by over 24,000 participants. We were able to show that we are using state-of-the-art tools and methods for calculating recharge over the diverse ecoregions of Minnesota. The poster is available for the public through our project website: https://www.esci.umn.edu/groups/Hydro/Minnesota-Ecohydrology-and-Groundwater.

Activity Status as of July 1, 2018:

The previously set-up statewide model (using the CLM computer code) has been further developed and tested using customized data for Minnesota, including high-resolution meteorological data and dynamic remote sensing vegetation data (data-compilation and processing described in the above Activity 1 report). We found that model results using higher quality data inputs differ notably from model results using the default coarse-scale global inputs that are distributed with the model, demonstrating the importance of having state-specific information for accurately predicting hydrological conditions in Minnesota. Development and testing of the model implementation with the dynamic vegetation inputs is in-progress. Because the default mode of CLM is for time-static vegetation inputs, we are writing a new computer program that cycles through multiple model executions with the different vegetation input files, in order to simulate recharge under changing vegetation conditions.

Previous initial set-up of the calibration method (the state-of-the-art Ensemble Kalman Filter, EnKF) for CLM has also been moved forward. For the last report, our graduate student wrote the code for the most basic version of the method, which only included estimate of model "states." He has now coded the more advanced version of EnKF that includes estimation of model "parameters," which importantly allows for the calibration of soil parameters that control water uptake by plants and infiltration to the water table. This included making changes to the CLM model source code to make it possible to tune soil hydraulic parameters. Our graduate student is in the process of testing this parameter estimation procedure, which requires the calculation of statistical metrics for the link between soil parameters and water table depth.

Our student presented his work to-date at our department's Soft Rock Seminar in March 2018. Progress on this Activity will accelerate in the final year with the on-boarding of a new computer programmer.

Activity Status as of January 1, 2019:

The development of the model calibration framework (the "Ensemble Kalman Filter" method, or "EnKF") is in its final stage. We have finished setting up the calibration computer program which is designed to estimate the model variables based on the available groundwater level measurements. We have successfully tested the performance of our calibration method through several tests. The algorithm shows good performance in estimating the correct model parameters based on the observations. In addition to this, we also performed some sensitivity tests to identify the most important set of subsurface model parameters that need to be calibrated to improve the recharge prediction of the model.

Since the last project update, we have also completed the set-up of our scheme to incorporate dynamic vegetation as a direct input to the model. The model was originally hard-coded to use fixed vegetation data as the input and so extensive changes to the source code had to be carried out to incorporate time-varying vegetation in the model. Because of the long computer run times, even on the Minnesota Super-computing Institute system, we are making software modifications to speed up simulation times.

As the final step in testing our calibration method, we have implemented the calibrated model with dynamic vegetation at a test location in Minnesota. The newly developed calibration procedure was used to calibrate the model using the observation data from the CGM's groundwater level database. EnKF was able to successfully constrain the model parameters. The calibrated model was run using both the default, fixed vegetation and the satellite-based, dynamic vegetation for the period 2000-2015. The results showed substantial differences in recharge predictions for the two vegetation scenarios. It was also found that more vegetation generally leads to lower recharge and that even small differences in vegetation have the potential to cause substantial variability in groundwater recharge. Initial analysis of the results also indicates that climate, ecoregion and soil properties affect the response of recharge to dynamic vegetation.

Activity Status as of July 1, 2019:

We performed the single-column calibration tests using the EnKF algorithm at multiple locations across the state in varied ecological and hydrogeological regions. A total of 12 observation wells distributed across the state were chosen for these calibration tests. These extended tests were necessary for multiple reasons: (1) to check that the calibration method is working correctly in the different conditions found in Minnesota, (2) for identifying bugs in the code, and (3) analysis of multiple test results allows us to introduce several statistical tweaks in our code to improve its performance. The results showed substantial improvement in the model simulations in all the 12 test locations.

Progress has been made in the final stages of the calibration set-up. This includes extending our single column tests to multiple locations – the goal is to simultaneously assimilate all the observation information available across the state at a particular time step. We have chosen a small sub-region in the state to perform tests for this spatially distributed implementation of EnKF. The initial tests were successful and we are now in the final stages of completing our calibration computer code.

Activity Status as of January 1, 2020:

On extending our single-column calibration tests to the regional areas (multiple columns), we found that our model simulated groundwater level and recharge were looking strange. Looking deeper into the model source code, we found a bug in the software that was resulting in an error in the recharge calculation for specific cases when the simulated groundwater level was at a certain threshold depth. We had to perform multiple iterations of testing and analysis to fix this bug. This also meant that we had to repeat several of our single column and regional test simulations. We have made good and fast progress with this and have completed all of our calibration tests. Results from both single column and regional simulations are promising and indicate that our code is successfully able to constrain our model and significantly improve the simulations. We are now in the final stages of finalizing our calibration code and testing it out for the entire state. We also plan to soon make our calibration code and model modifications public via GitHub so that other users can access it.

Final Report Summary:

Activity 2 consisted of two main parts: (1) Development of the model (CLM), and (2) Writing computer code for the model calibration framework.

We chose the complex assessment tool CLM because it couples hydrological processes with vegetation and climate, allowing us to investigate the interconnected plant-soil-groundwater continuum. Because of its complexity, several time-intensive steps were required to set it up for simulations. The model code is machine-specific and thus had to be customized before execution on the computing infrastructure of the University of Minnesota (Minnesota Supercomputing Institute). Additionally, the default configuration of the model is to read fixed vegetation inputs, and so extensive changes to the model code were necessary for incorporating year-to-year dynamic, satellite-derived vegetation data. In addition to this, several tweaks in the model's code were required for setting it up to communicate with the Ensemble Kalman filter, our calibration algorithm. The model development activity also led us to discover and fix an error in the CLM computer code, which had led to faulty calculations of recharge under certain climatic conditions.

We used the state-of-the-art statistical calibration framework, Ensemble Kalman Filter (EnKF) to constrain our model estimates on water table observations. Several rounds of code development and testing were done to identify a suitable set of hydrologic parameters in the model to calibrate. The calibration code was designed to incorporate the highly irregular - in both in space and time - dataset available through the Cooperative Groundwater Management database. The final calibration results showed that EnKF was successfully able to tune model parameters based on the water table observations, which led to a substantial improvement of model simulations of water table depths. Because water table depth is closely tied to groundwater recharge, we can infer that improved water table simulations correspond to improved estimates of groundwater recharge. The calibration effort reduced the model mean error in water table by almost 53% indicating state-wide improvement of CLM's groundwater level and recharge outputs.

CLM is developed and maintained by the National Center for Atmospheric Research. The original source code of the model is openly available for anyone to download and use. We have made our modifications to the CLM source code and our calibration code available to the public via the code-sharing repository GitHub (https://github.com/harshanurag/Ecohydrology_MN). The repository will also contain a document with details on setting up and running CLM on the UMN computing cluster. The EnKF code has detailed comments to help the user understand the process of setting it up for CLM and using groundwater level observations in the Cooperative Groundwater Management database.

ACTIVITY 3: Produce and disseminate statewide time-lapse maps of vegetation growth and groundwater recharge estimates.

Description:

In this activity, we will process raw model outputs (generated in file formats requiring specialized software) into readily accessible forms for resource managers and the general public. Daily 1-km model results of recharge over 2000-2014 will be scaled up to weekly, monthly, and annual estimates to reduce the data volume and aid interpretations. The final maps will be side-by-side presentations of climate conditions, vegetation cover density, and groundwater recharge. This presentation layout will facilitate analyses of how climate and vegetation growth conditions control groundwater recharge rates. Final climate, vegetation, and recharge maps over time will be made available in multiple file formats, similar to the data files in Activity 1. We will develop maps in GIS formats consistent with the Minnesota Geospatial Commons website for ready plug-in into resource planning tools. A PDF file (readable with e.g., Adobe Reader) containing graphical images of the recharge maps will also be produced for easy referencing.

The climate, vegetation density, and recharge maps over time will be directly produced from the model outputs. In addition, we will also provide analysis of the recharge estimates. Specifically, because travel time through the soil column will often delay the recharge response to changes in weather and vegetation, correlations between these elements may not be obvious through quick inspection of the maps. We will conduct sensitivity and statistical analyses to identify salient connections, which we will describe in an info-sheet accompanying the maps. We will also create interpreted maps indicating locations and historical times when recharges appear most susceptible to climate variability, land-cover change, and vegetation growth. For sensitive regions such as drier western prairies and recently converted cropland regions, we will also use the assessment tool to identify weather thresholds and critical vegetation types for recharge, which will also be included in the info-sheet.

The final map generation and interpretations will be led by project manager Ng and the graduate student researcher. Project partner Tipping will participate in the production of GIS files to ensure that they conform to Minnesota Geospatial Commons standards. Tipping will also facilitate distribution through the Minnesota Geological Survey and to other state agencies. The undergraduate student researcher will assist with the map presentation and file organization.

Summary Budget Information for Activity 3: **ENRTF Budget: $ 11,971**
Amount Spent: $ 9,971
Balance: $ 2,000

Outcome	**Completion Date**
1. GIS and graphical files with statewide maps of plant-growth and recharge estimates	3/31/19
2. Risk assessment maps indicating locations where plant growth and recharge are most vulnerable	4/30/19
3. Reports of weather thresholds and critical vegetation types causing significant recharge changes	4/30/19

Activity Status as of January 1, 2017:

Work on Activity 3 has not yet begun.

Activity Status as of July 1, 2017:

(Not required – see cumulative status report below)

Activity Status as of January 1, 2018:

Work on Activity 3 has not yet begun.

Activity Status as of July 1, 2018:

Work on Activity 3 has not yet begun.

Activity Status as of January 1, 2019:

As a step towards the final statewide recharge assessment, we executed preliminary statewide simulations of recharge using default model parameters. Model runs were carried out using both fixed vegetation and satellite measured dynamic vegetation. The results show a substantial difference (up to 65%) in the simulated recharge under the two vegetation inputs. The differences in recharge due to dynamic vegetation are most prominent in the drier, western prairie region and in the north-eastern mixed forest ecoregion, demonstrating that the combination of climate, geology and vegetation type makes groundwater recharge in some regions of the state more sensitive to changes in vegetation. It should be noted that these are preliminary statewide results with the default model parameters. Work on the state-level calibration of the model is still in progress. However, these preliminary results demonstrate the potential influence that dynamic vegetation may have on recharge.

Activity Status as of July 1, 2019:

We have updated our preliminary statewide recharge maps with the new soil inputs from Activity 1. The maps will be finalized once the full model calibration is complete in Activity 2.

Activity Status as of January 1, 2020:

Work on Activity 3 will be started as soon as we have the state-wide results at the conclusion of Activity 2.

Final Report Summary:

We used the Community Land Model (CLM) to calculate monthly mean groundwater recharge estimates for Minnesota for a period from 2000 to 2015. The simulations were performed at 25km resolution to avoid the significantly higher computational cost of running the model at the originally planned 1km scale.

- The statewide mean annual recharge rate (2000-2015) using dynamic vegetation is 2.9 in/year (Figure 1 in Section IX). The recharge for the same period when considering the time-averaged vegetation is 2.8 in/year.
- The 25th and 75th percentile of the recharge estimate are 0.13 in/year and 5.69 in/year (Figure 3 in Section IX)**.** This wide range in uncertainty is mainly due to unavailability of observations for several regions of the state. The model was able to confidently predict recharge with low error for regions where observations were available.
- Lowest average recharge is in northwestern and southwestern Minnesota. Highest average recharge is found in the central Minnesota, including the Anoka Sand Plains region.
- There is a sparsity of good quality, continuous groundwater level observations for a major portion of the state especially in southeastern and northeastern Minnesota
- The difference between the statewide 16-year average recharge estimate using dynamic and average vegetation is very small. However, we see higher annual variability, with the recharge estimates differing by as much as 28% under the dynamic versus average vegetation conditions for certain locations and time (Figure 4 in Section IX). This indicates that considering the impact of dynamic vegetation becomes more important when estimating recharge for short time periods (annual, seasonal or monthly).

Risk assessment

- North Central Hardwood Forests (NCHF) showed the highest 16 year recharge difference when incorporating year-to-year vegetation variations compared to when using average vegetation conditions. The northeastern Northern Lakes and Forests (NLF) showed lowest difference in recharge with dynamic versus average vegetation conditions. However, similar to statewide patterns, annual recharge differences when incorporating vegetation variations were more pronounced for certain years (as much as 28%) in these ecoregions.

- The recharge in the NCHF and water-limited and crop dominated GP in western Minnesota seems to be the most sensitive to changing vegetation. The year-to-year variability in recharge due to vegetation changes is the highest in GP. This sensitivity seems to be lowest for the NLF.

Climatic impact assessment

- As expected the absolute value of recharge is strongly correlated with precipitation. However, the recharge response to dynamic vegetation is strongly correlated with temperature and weakly correlated with precipitation. This correlation of recharge changes with temperature is the strongest in GP. The effect of temperature on recharge via vegetation will become more important in the future when temperature is predicted to increase and vary more due to climate change.

ACTIVITY 4: Produce reliability maps identifying priority monitoring areas for improving recharge estimates.

Description:

We will provide reliability maps for the vegetation growth and recharge estimates, indicating where the assessment tool is more confident and where there is greater uncertainty. Reliability measures are a bonus feature of the statistical calibration method (EnKF) implemented in Activity 3. The EnKF method not only estimates the most likely calibrated model parameters and simulation results based on the data, but it can also calculate error ranges. We will generate maps of these error ranges to accompany the recharge estimation maps. Error ranges will be useful in quantitative assessments by technical resource managers. We will also use these error ranges to generate a map of reliability categories rating areas according to the quality of the recharge estimate. While recharge estimates will be reported statewide, these reliability maps will highlight locations where the assessment tool results should be used cautiously.

To help guide future monitoring efforts and field campaigns to improve statewide recharge maps, we will use the reliability maps to also derive priority maps indicating areas in the state where additional observations are most urgently needed. These areas will be identified through a couple of different approaches. We will identify locations where there is an extensive area of low reliability overlapping “critical” groundwater areas, such as those near high population centers or important agricultural groundwater resources. We will also employ the statistical EnKF algorithm from Activity 2 to quantify where new observations could be most effective in improving the reliability of the recharge estimates.

The model analyses of Activity 4 will be carried out by the graduate student researcher under the guidance of project manager Ng. Project partner Tipping will assist with map generation and dissemination. The undergraduate student researcher will assist with the map presentation and file organization.

Summary Budget Information for Activity 4: **ENRTF Budget: $ 11,971**
Amount Spent: $ 6,322
Balance: $ 5,649

Outcome	**Completion Date**
1. Reliability maps alerting managers where assessment tool results are less certain	6/30/19
2. Recommendations for additional monitoring to improve vegetation and recharge estimates	6/30/19

Activity Status as of January 1, 2017:

Work on Activity 4 has not yet begun.

Activity Status as of July 1, 2017:

(Not required – see cumulative status report below)

Activity Status as of January 1, 2018:

Work on Activity 4 has not yet begun.

Activity Status as of July 1, 2018:

Work on Activity 4 has not yet begun.

Activity Status as of January 1, 2019:

The probabilistic calibration method used to calibrate the model based on water table observations produces both the best estimate of the model parameters and the error ranges associated with the estimates. This error is statistically calculated based on the uncertainty of our model prediction, as well as the error in the measurements (due to, for example, the uncertainty of measuring instruments) that are used to calibrate the model. Thus, we are able to quantify the uncertainty associated with our recharge estimates. The preliminary calibrated model run performed at a test location in Minnesota shows the mean recharge for 2000-2015 at our test location to be 16.9 +/- 5.2 cm/yr. After the state-wide implementation of the calibration method, we will be able to obtain similar recharge estimates with uncertainty bounds for the entire state.

Activity Status as of July 1, 2019:

The probabilistic tests have been extended from a single test case location to 12 locations strategically distributed across the diverse ecological and hydrogeological regions of the state. We are finding reasonable uncertainty estimates that are providing us with the confidence to move forward will a full state-wide implementation. Final uncertainty measures will be produced once the full model calibration is complete in Activity 2.

Activity Status as of January 1, 2020:

Work on Activity 4 will proceed once the state-wide calibrated model results are available upon the conclusion of Activity 2.

Final Report Summary:

One of the main advantages of using a probabilistic method such as EnKF for calibration is that we can quantify the uncertainty associated with the model outputs. Out of the total 879 wells in the Cooperative Groundwater Management Database, we were able to use groundwater well records from 330 wells. The other wells were not useful because of either having a poor quality data or not having measurements within our simulation period (2000-2015). The 330 wells used were unevenly distributed throughout the state with almost all in central, northwestern, and southwestern Minnesota. The northeast and southeast had almost no groundwater level observations that could be used for model calibration. Our statewide recharge uncertainty maps show high uncertainty in the recharge estimate in the following regions (Figure 3 in Section IX):

- Northeastern and southeastern Minnesota, where there is almost no groundwater level data
- Parts of northwestern and southwestern Minnesota
- North-central Minnesota

Groundwater management in the above-mentioned regions of the state would greatly benefit from the installation of more groundwater level monitoring stations. The uncertainty in the northwest and southwest is higher probably because of its combination of high clay in the subsurface, dry climate, and very shallow water table. The model has difficulty in resolving the effect of clayey soils, which results in a shallow water table even when this part of the state receives the lowest rainfall. The southeast is dominated by karst landscape, which adds to the complexity of estimating recharge in the area due to subsurface heterogeneity and flow processes that may not be accurately captured by standard models. Thus, more specialized recharge study might be needed for southeastern Minnesota.

V. DISSEMINATION:
Description:

The files for the maps and accompanying reports developed in Activities 3 and 4 will be made publicly available through a project website. A new project website will be created on project manager Ng's research website: www.esci.umn.edu/groups/hydro; a link to the website will also be listed on Ng's University of Minnesota faculty website: https://www.esci.umn.edu/people/Gene-Hua-Crystal-Ng. Additionally, project manager Ng and project partner Tipping will circulate copies of the info-sheet and announcements about the maps among collaborators and contacts at state agencies including the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency. The project team will also prepare research articles on this work to be submitted to peer-reviewed scientific journals.

Status as of January 1, 2017:

Dissemination of results has not yet begun.

Status as of July 1, 2017:

Status as of January 1, 2018:

We have developed a project website hosted on Ng's research website: https://www.esci.umn.edu/groups/Hydro/Minnesota-Ecohydrology-and-Groundwater. We presented a poster with preliminary results at the 2017 American Geophysical Union Fall Meeting; a copy of the poster is available on our project website. Further results will be posted here as they become available.

Status as of July 1, 2018:

In March 2018, our graduate student Harsh Anurag presented his work at the Soft Rock Seminar in the Department of Earth Sciences, University of Minnesota – Twin Cities.

Status as of January 1, 2019:

The state-wide input datasets have been fully formatted and are ready to be used in the model. We are in the process of uploading these datasets on our project website (https://www.esci.umn.edu/groups/Hydro/Minnesota-Ecohydrology-and-Groundwater), where they will be accessible to the public. We also presented our up-to-date work in the recently concluded American Geophysical Union 2018 Fall meeting in Washington D.C.

Activity Status as of July 1, 2019:

As mentioned earlier, there have been several changes in the input dataset since the last status update. The new and final input datasets have been fully modified, formatted, and are ready to be used in the model. We will upload the updated statewide input data on our project website.

In April 2019, we presented an update of our work at our department’s Soft Rock seminar series. The up-to-date progress of the project was also presented at the University of Minnesota’s Earth and Environmental Sciences Student Research Symposium. The annual symposium had a participation of more than 85 earth scientists, including graduate student and faculty. We also presented a poster of our work at the Community Earth System Model (CESM) Workshop organized by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. This is a 3-day workshop that involves discussion about the development and applications of CESM. CLM, the model being used for the project, is a part of the CESM modeling framework. No LCCMR funds were used in any of the above-mentioned travel.

Activity Status as of January 1, 2020:

We have been performing our final simulation tests for several representative regions in Minnesota before attempting a state-wide simulation. These regions have distinct climate, vegetation and hydrogeology setting, thus allowing us to test the performance of our calibrated model in varied settings. We presented a poster with our preliminary analysis of these regional simulation results at the 2019 American Geophysical Union’s Fall Meeting at San Francisco, California. No LCCMR funds were used for this meeting. We are also working on making the input datasets available through online data repositories and sharing all our computer code via GitHub.

Final Report Summary:

This study has been presented through several posters and oral presentations at various national and regional conferences including:

- American Geophysical Union Fall Meeting (2017, 2018, 2019)
- Community Earth System Model Workshop (2019)
- Earth and Environmental Sciences Student Research Symposium, Minnesota (2018**)**
- Water Resource Symposium, Minnesota (2017**)**

The model outputs a statewide estimate of recharge and other hydrological variables (evapotranspiration, surface runoff, groundwater level) at a resolution of 25km at monthly frequency. All of these outputs are available in the "Output" folder at https://z.umn.edu/5nfp. These results can potentially be used by stakeholders concerned about groundwater recharge on both seasonal and interannual time scales over 2000-2015.

The project website documents the methodology and main results. We will be sharing our modifications to the CLM model's source code and EnKF model calibration code through our GitHub repository. The study has also resulted in the discovery of an error in the CLM model code for recharge calculations. Since this model is widely used in both the USA and outside, we will be officially submitting the error-fix for a review so that it can be subsequently incorporated in the future release of the model's code.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$206,038	Project manager Ng ($24,856; 7.7% FTE in Yr2, 9.6% FTE in Yr3) will supervise the project. Project partner Tipping ($13,093; 8.3% FTE in Yr1 and Yr3) will lead data compilation from statewide databases and generation of GIS data files. A graduate student researcher ($120,037; 50% FTE for 6 semesters and 2 summers) will work under the Ng and perform most of the project activities. A computer programmer ($36,228; 44% FTE in Yr3) will assist with the model implementation. Research hydrogeologist Scott Alexander ($11,824; 15% FTE in Yr3) will assist with compiling/interpreting hydrogeologic and groundwater data for the model, and collecting data at Cedar Creek Long-Term Ecological Research Station for validating the model.
Professional/Technical/Service Contracts:	$0	
Equipment/Tools/Supplies:	$3,809	3 external hard drives will store data, model results, and map files ($324). Software licenses (Intel compilers: $1200) are needed to implement the assessment tool and create the map products. 5 Solinst Leveloggers for

		measuring water table levels at Cedar Creek Long-Term Ecological Research station ($400 each), field supplies – cables, wires, tools ($285).
Capital Expenditures over $5,000:	$0	
Fee Title Acquisition:	$0	
Easement Acquisition:	$0	
Professional Services for Acquisition:	$0	
Printing:	$2000	Printing costs are required for producing info-sheets on the recharge maps and reliability maps.
Travel Expenses in MN:	$153	4 trips to Cedar Creek Ecological Research station (70 miles round-trip from Twin Cities campus, $0.545/mi)
Other:	$0	
TOTAL ENRTF BUDGET:	**$212,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: N/A

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 2.7 FTE's

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: N/A

B. Other Funds: N/A

VII. PROJECT STRATEGY:

A. Project Partners: Project partner Bob Tipping (Minnesota Geological Survey) will help direct the compilation and interpretation of state databases, and he will lead the production of GIS data files and map outputs. Tipping will receive $13,093 of the ENRTF appropriation for 2 summer months of salary over the three years.

B. Project Impact and Long-term Strategy:

The upfront investment in developing the assessment tool will facilitate future evaluations of ecological and groundwater resources. The assessment tool will also be valuable for investigating "what-if" scenarios of climate and land-cover change. Reliability maps will help prioritize future observation campaigns. This can lead to continued coordination between state-wide monitoring programs and the project team for assessing vegetation growth and corresponding groundwater recharge.

C. Funding History: N/A

VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS: N/A

IX. VISUAL COMPONENT or MAP(S):

Below are some of the summary results of our analyses. More detailed figures, maps and analysis will also be shared through our project website.

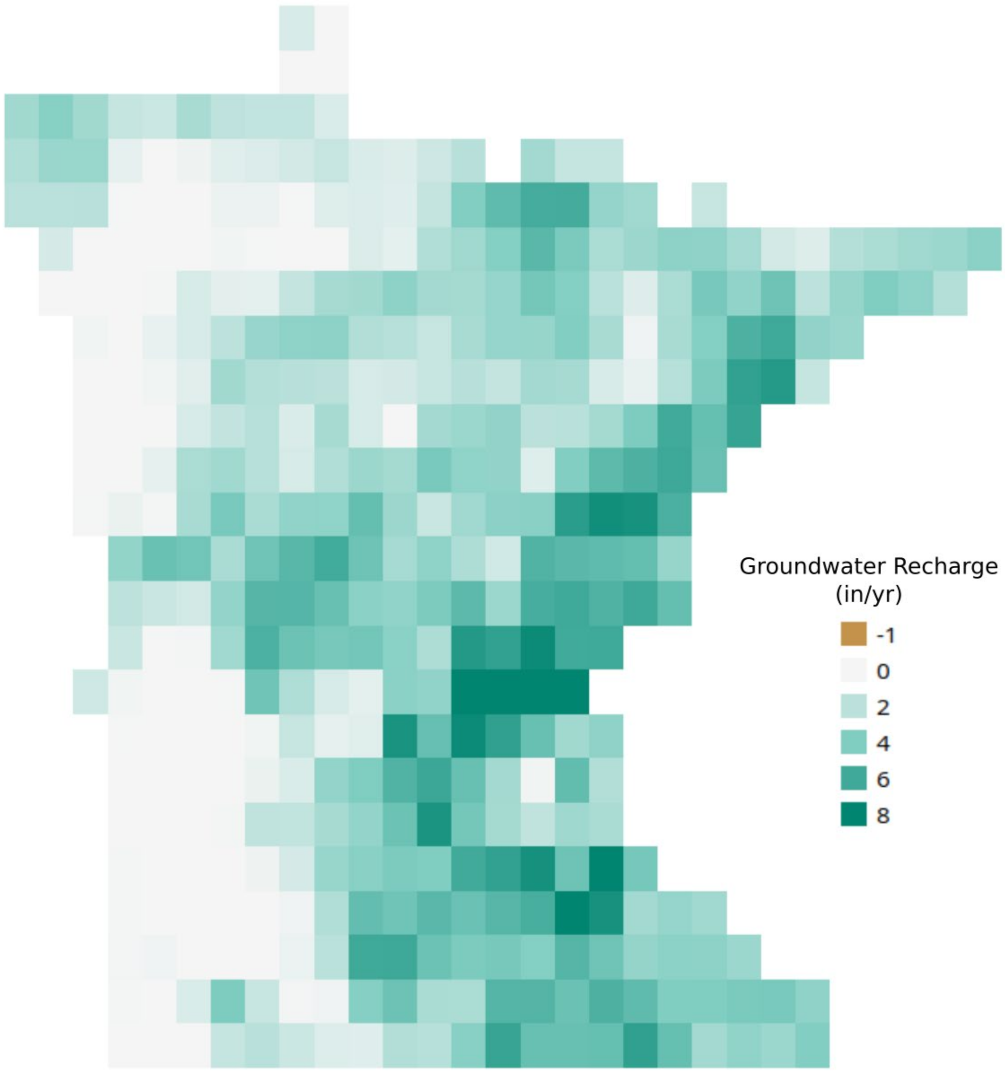

Figure 1: Statewide mean annual groundwater recharge from 2000-2015 estimated with the calibrated model.

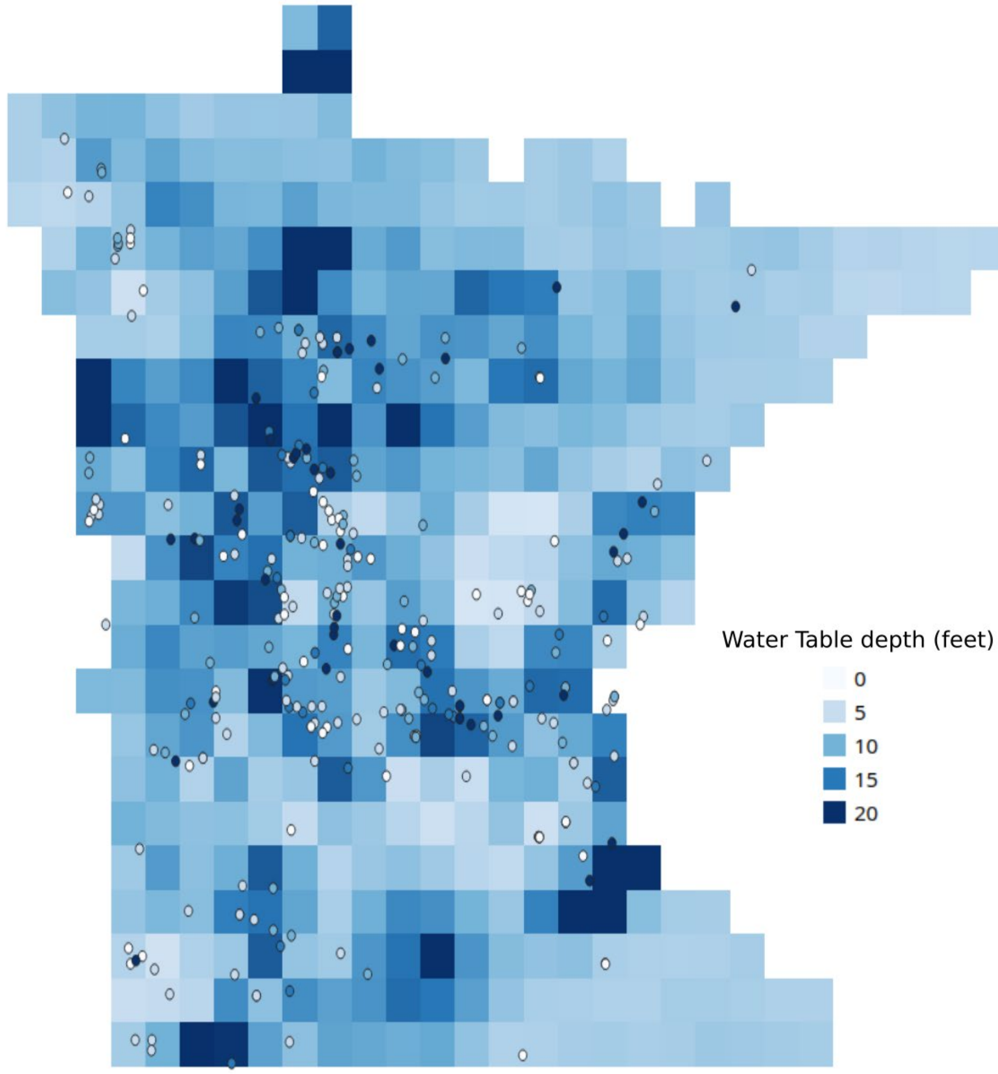

Figure 2: Statewide mean annual water table depth from 2000-2015 estimated with the calibrated model. The dots show the observed average water table depth at the groundwater wells used for model calibration.

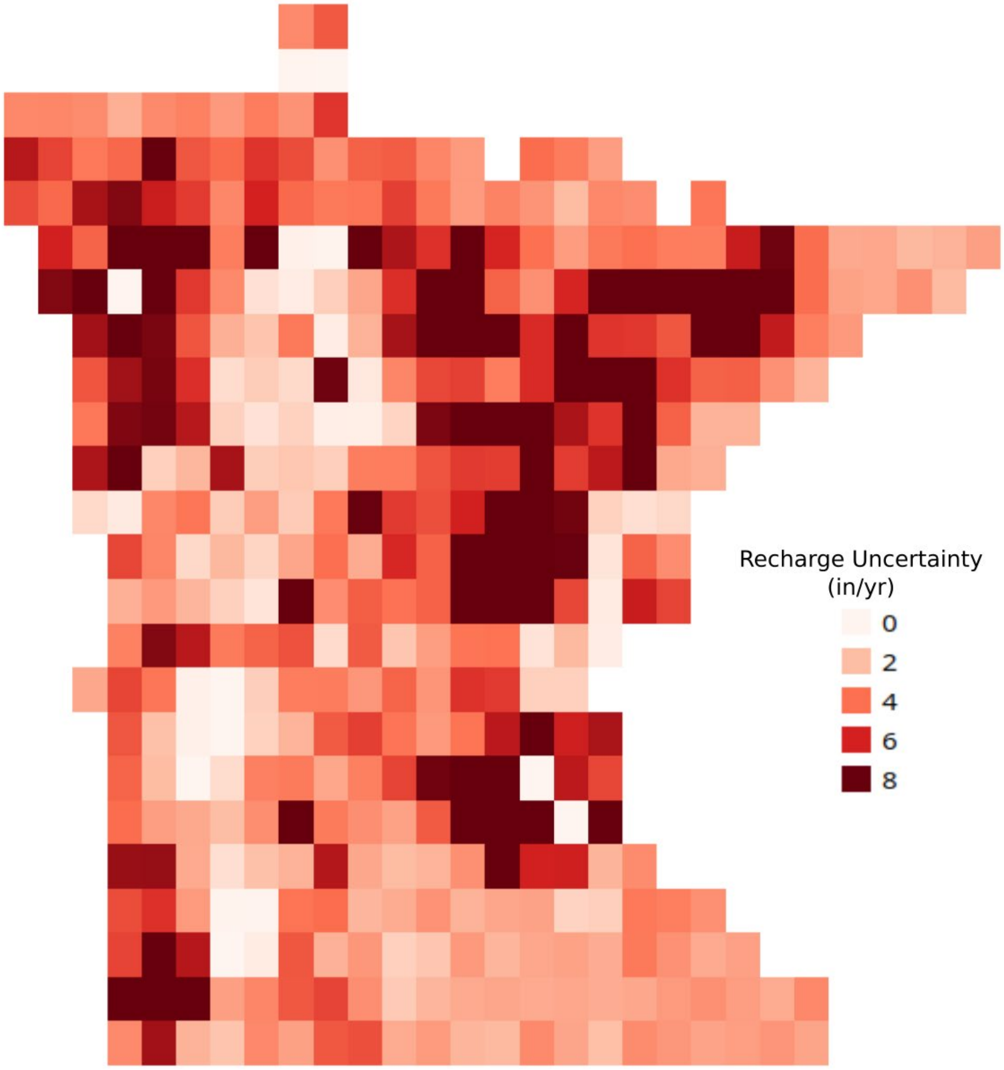

Figure 3: Groundwater recharge estimation reliability map showing uncertainty as measured by the difference between the 75th percentile and 25th percentile recharge estimate. The darker colors show where the model's estimates are more uncertain.

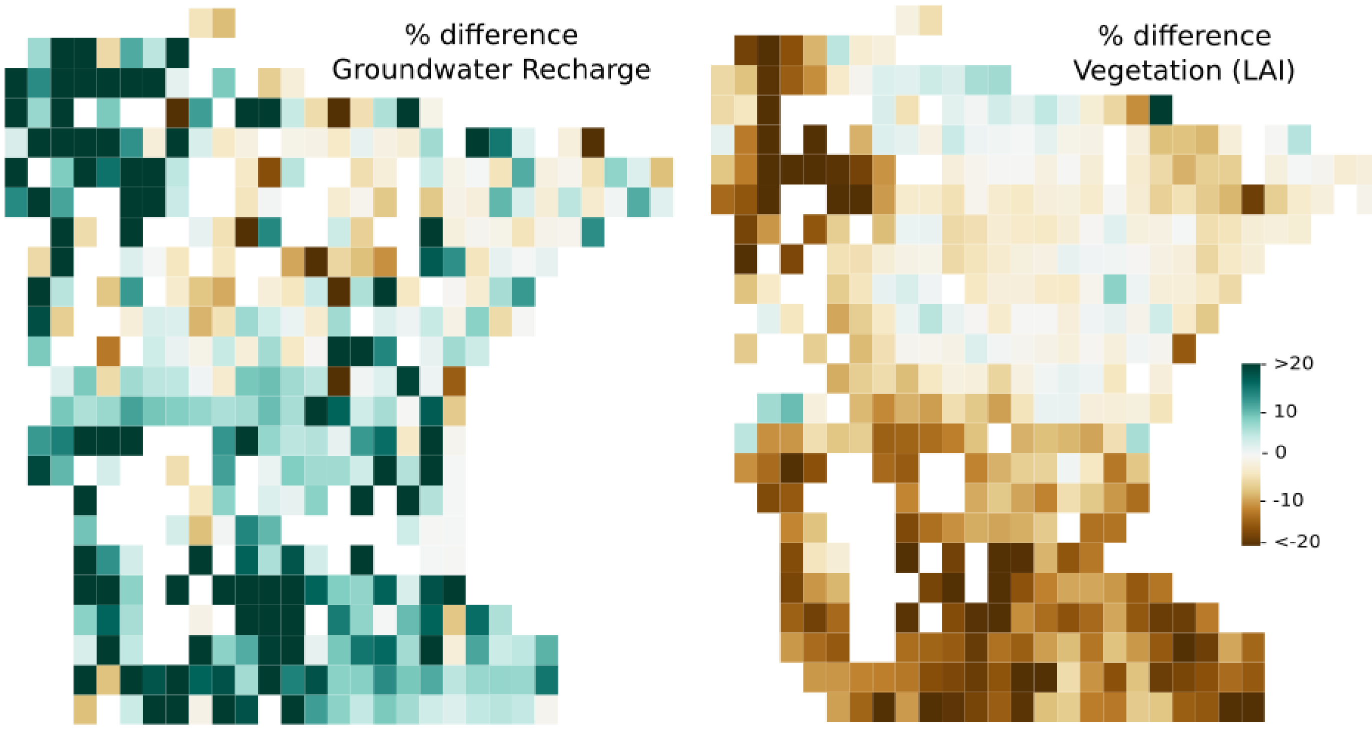

Figure 4: The average recharge estimate difference for the most sensitive year (2013) when the model uses actual year-to-year dynamic vegetation compared to when it uses long-term average vegetation. Positive values indicate that the estimate with year-to-year dynamic vegetation is higher than the estimate with long-term average vegetation. Results shown are for locations with appreciable average recharge amounts (>0.4 in/yr). The right shows the corresponding difference between dynamic green vegetation density (measured by "leaf area index" (LAI)) for 2013 and the long-term average (2000-2015) green vegetation density. Positive values indicate that the year-to-year dynamic green vegetation density is higher than the long-term average green vegetation density.

X. RESEARCH ADDENDUM: N/A

XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than January 1, 2017; July 1, 2017; January 1, 2018; July 1, 2018; January 1, 2019; July 1 2019; January 1, 2020 and July 1, 2020. A final report and associated products will be submitted between June 30 and August 15, 2020.

Environment and Natural Resources Trust Fund
M.L. 2016 Project Budget

Project Title: Assessment Tool for Understanding Vegetation Growth Impacts on Groundwater Recharge
Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 03f
Project Manager: Gene-Hua (Crystal) Ng
Organization: University of Minnesota, Twin Cities
M.L. 2016 ENRTF Appropriation:$212,000
Project Length and Completion Date:3 Years, June 30, 2019; final report due July 1, 2020
Date of Report: July 1, 2020

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	Activity 4 Budget	Amount Spent	Activity 4 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM	Compile and analyze data connecting climate and vegetation to groundwater systems			Develop and calibrate an assessment tool for computing plant growth and recharge throughout Minnesota			Produce and disseminate statewide time-lapse maps of vegetation growth and groundwater recharge estimates.			Produce reliability maps identifying priority monitoring areas for improving recharge estimates				
Personnel (Wages and Benefits)	$45,777	$45,777	$0	$138,319	$138,319	$0	$10,971	$9,971	$1,000	$10,971	$6,322	$4,649	$206,038	$5,649
Crystal Ng, Project Manager: $24,856 (75% salary, 25% benefits), 7.7% FTE in Yr2, 9.6% FTE in Yr3														
Bob Tipping, Hydrogeologist: $13,093 (79% salary, 21% benefits), 8.3% FTE in Yr1 and Yr3														
1 Graduate Research Assistant: $120,037 (55% salary, 45% benefits – includes tuition), 50% FTE for 6 semesters and 2														
1 Computer Programmer: $36,228 (75% salary, 25% benefits), 44% FTE in Yr3														
Scott Alexander, Research Hydrogeologist: $11,824 (79% salary, 21% benefits) 15% FTE in Yr3														
Professional/Technical/Service Contracts														
Equipment/Tools/Supplies														
3 external hard-drives	$324	$92	$232										$324	$232
Computer software and licenses for model development (Intel compilers)	$1,200	$0	$1,200										$1,200	$1,200
5 automated water level sensors (Solinst Leveloggers)				$2,000	$1,814	$187							$2,000	$187
Field supplies for deploying water level sensors				$285	$0	$285							$285	$285
Capital Expenditures Over $5,000:N/A														
Fee Title Acquisition:N/A														
Easement Acquisition:N/A														
Professional Services for Acquisition:N/A														
Printing														
Production of info-sheet on assessment tool							$1,000	$0	$1,000	$1,000	$0	$1,000	$2,000	$2,000
Travel expenses in Minnesota:														
4 trips to Cedar Creek Long-Term Ecological Research station (70 mi round-trip from Twin Cities, $0.545/mi)				$153	$0	$153							$153	$153
Other														
COLUMN TOTAL	**$47,801**	**$45,868**	**$1,432**	**$140,757**	**$140,133**	**$625**	**$11,971**	**$9,971**	**$2,000**	**$11,971**	**$6,322**	**$5,649**	$212,000	$9,706