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

Date of Report: December 4, 2015

Date of Next Status Update Report: January 1, 2017

Date of Work Plan Approval:

Project Completion Date: June 30, 2019

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:	**$0**
	Balance:	**$212,000**

Legal Citation: M.L. 2016, Chp. xx, Sec. xx, Subd. xx

Appropriation Language:

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**
2. **Evaluations of how plant and groundwater impacts are linked under climate and land-use change**
3. **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:

Project Status as of July 1, 2017:

Project Status as of January 1, 2018:

Project Status as of July 1, 2018:

Project Status as of January 1, 2019:

Overall Project Outcomes and Results:

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: $ 66,001
Amount Spent: $ 0
Balance: $ 66,001

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:

Activity Status as of July 1, 2017:

Activity Status as of January 1, 2018:

Activity Status as of July 1, 2018:

Activity Status as of January 1, 2019:

Final Report Summary:

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.

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: $ 120,335
Amount Spent: $ 0
Balance: $ 120,335

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:

Activity Status as of July 1, 2017:

Activity Status as of January 1, 2018:

Activity Status as of July 1, 2018:

Activity Status as of January 1, 2019:

Final Report Summary:

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: $ 12,832
Amount Spent: $ 0
Balance: $ 12,832

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:

Activity Status as of July 1, 2017:

Activity Status as of January 1, 2018:

Activity Status as of July 1, 2018:

Activity Status as of January 1, 2019:

Final Report Summary:

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: $ 12,832
Amount Spent: $ 0
Balance: $ 12,832

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:

Activity Status as of July 1, 2017:

Activity Status as of January 1, 2018:

Activity Status as of July 1, 2018:

Activity Status as of January 1, 2019:

Final Report Summary:

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:

Status as of July 1, 2017:

Status as of January 1, 2018:

Status as of July 1, 2018:

Status as of January 1, 2019:

Final Report Summary:

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$ 207,976	Project manager Ng ($40,868; 9.6% FTE for 3 years) will supervise the project. Project partner Tipping ($24,987; 8.3% FTE in Yr1 and Yr3, 12.5% FTE in Yr2) will lead data compilation from statewide databases and generation of GIS data files. A graduate student researcher ($126,938; 50% FTE for 3 years) will work under the Ng and perform most of the project activities. An undergraduate researcher ($15,184) will assist with data compilation and organization and maintenance of data and model files.
Professional/Technical/Service Contracts:	$0	
Equipment/Tools/Supplies:	$2,024	3 external hard drives will store data, model results, and map files ($324). Software licenses (Matlab: $500 and Intel compilers: $1200) are needed to implement the assessment tool and create the map products.
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:	$0	
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 $24,966 of the ENRTF appropriation for 3.5 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): See attached figure.

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, and January 1, 2019. A final report and associated products will be submitted between June 30 and August 15, 2019.

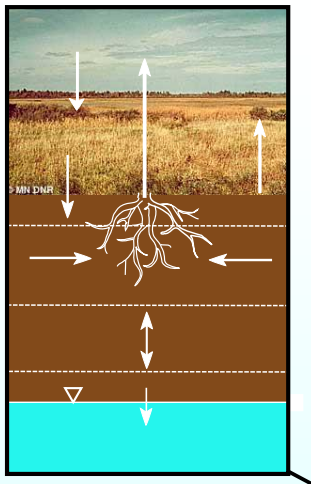
Environment and Natural Resources Trust Fund
M.L. 2016 Project Budget

Project Title: Assessment Tool for Understanding Vegetation Growth Impacts on Groundwater Recharge
Legal Citation:
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
Date of Report: 12/4/15

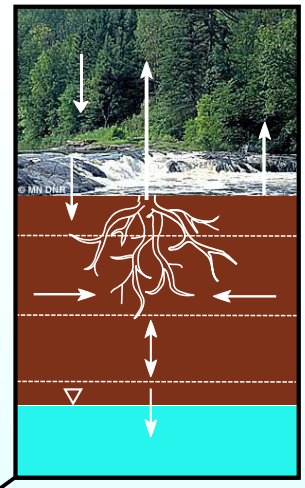
ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	Activity 4 Budget	Amount Spent	Activity 4 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM	Compile and 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)	$63,977	$0	$63,977	$120,335	$0	$120,335	$11,832	$0	$11,832	$11,832	$0	$11,832	$207,976	$207,976
Crystal Ng, Project Manager: $40,868 (75% salary, 25% benefits), 9.6% FTE in each year														
Bob Tipping, Hydrogeologist: $24,987 (79% salary, 21% benefits), 8.3% FTE in Yr1 and Yr3, 12.5% FTE in Yr2														
1 Graduate Research Assistant: $126,938 (55% salary, 45% benefits – includes tuition), 50% FTE in each year														
1 Undergraduate Research Assistant: $15,184 (100% salary), 21.9% FTE in each year														
Professional/Technical/Service Contracts														
Equipment/Tools/Supplies														
3 external hard-drives	$324	$0	$324										$324	$324
Computer software and licenses for model development (Intel compilers, Matlab)	$1,700	$0	$1,700										$1,700	$1,700
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: N/A														
Other														
COLUMN TOTAL	**$66,001**	**$0**	**$66,001**	**$120,335**	**$0**	**$120,335**	**$12,832**	**$0**	**$12,832**	**$12,832**	**$0**	**$12,832**	$212,000	$212,000

Assessing Vegetation's Control on Minnesota's Groundwater

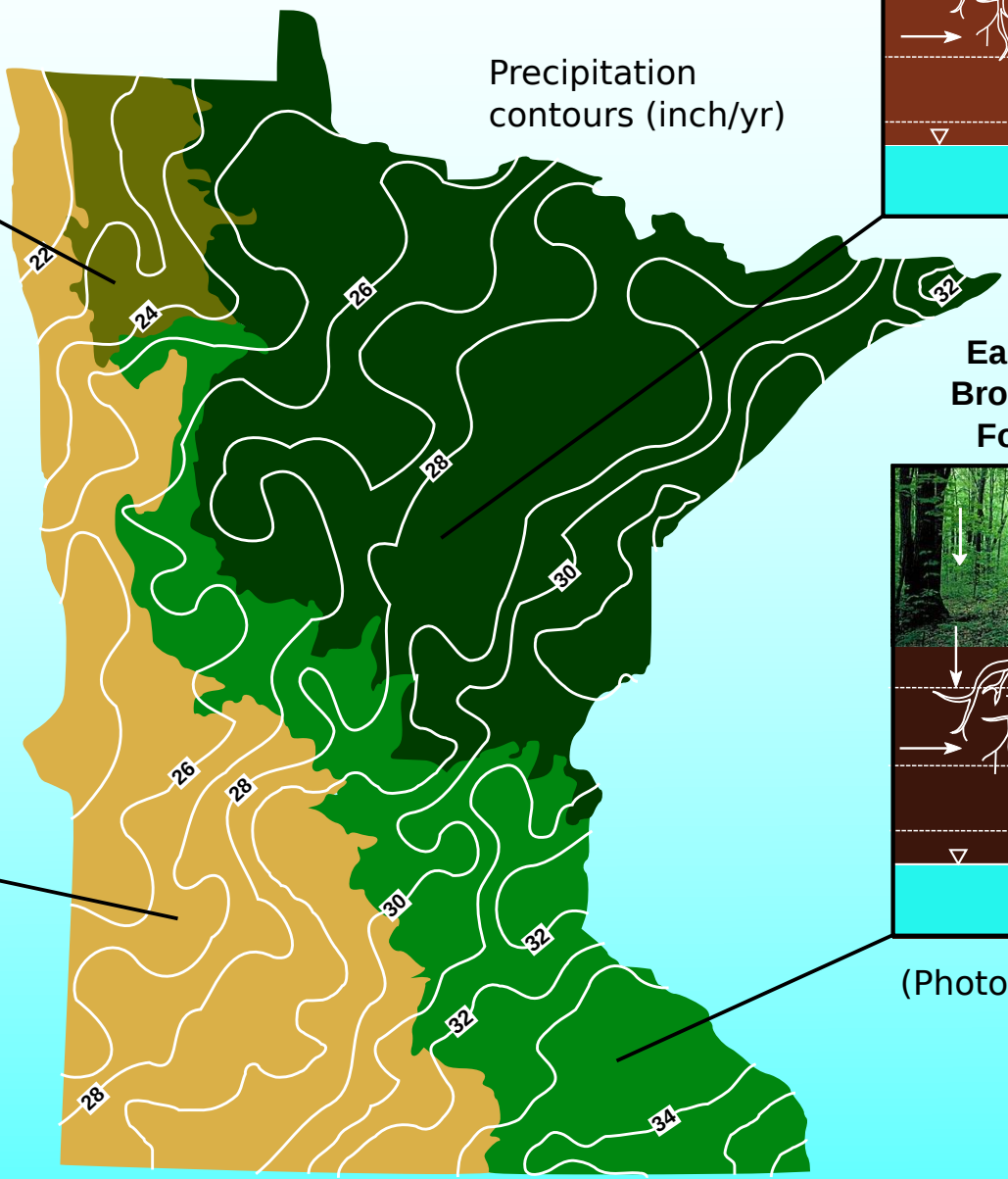
Tallgrass Aspen Parkland



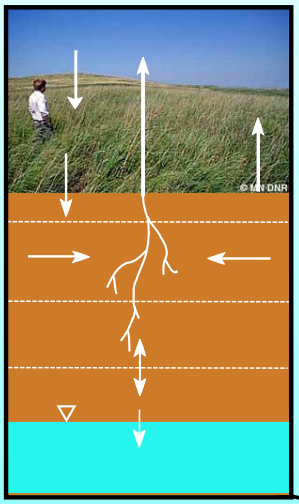
Laurentian Mixed Forest



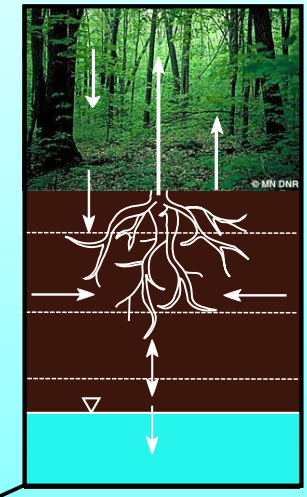
Precipitation contours (inch/yr)



Prairie Parkland

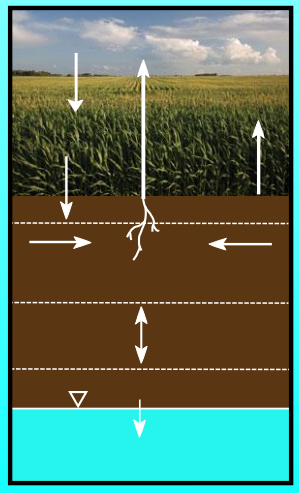


Eastern Broadleaf Forest



(Photos by DNR)

Farmland



Vegetation controls groundwater recharge across Minnesota's diverse eco-regions, hydrogeological provinces, and sharp precipitation gradient.

Our proposed assessment tool will provide statewide maps of plant growth and groundwater recharge estimates to help prepare for impacts when climate and land-cover change.