Lower Poplar River Watershed Sediment Source Assessment

John L. Nieber

Caleb Arika

Bradley Hansen

Department of Bioproducts and Biosystems Engineering

University of Minnesota

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Karen Evens and Greg Johnson, Project Managers

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Introduction

In 2004 the reach of the Lower Poplar River (Figure 1) at Lutsen Minnesota was placed on the MPCA's impaired waters list for excessive turbidity. Monitoring of the Lower Poplar River for flow and turbidity was conducted from 2002 through 2006. Both upstream and downstream monitoring was conducted in an attempt to narrow down the source of the turbidity impairment. The monitoring data showed that the turbidity standards for aquatic life were exceeded at the lower monitoring station near the mouth of the Poplar River as it enters Lake Superior, but the standard was not exceeded at the upper station. This result indicates that the source(s) of the excessive sediment is (are) within the Lower Poplar River watershed.

In response to the turbidity impairment a study reported in RTI (RTI, 2008) was conducted to attempt to quantify the source(s) of the sediment producing the impairment. That report provided estimates of the amount of sediment generated from various sources within the Lower Poplar River watershed. Prior to the RTI study, there was also a study by North American Wetland Engineering (NAWE, 2005) which was intended to study the possible impacts of further proposed developments within the Lower Poplar River watershed, in particular the Ullr Mountain Planned Unit Development. The NAWE report also provided some estimates of sediment sources within the Lower Poplar River watershed. A third study was undertaken by the University of Minnesota (UofM) starting in 2009 to provide a better characterization of the runoff processes occurring in the watershed using additional field data and observations and more detailed applications of the WEPP model. A report by Hansen et al. (2010) reported on the results of the detailed field reconnaissance and analysis of archived field data and historical information. This report presents the results of the assessment of sediment sources using the findings of the first report and the additional WEPP modeling.

In the Lower Poplar River watershed sediment is generated from the following sources: sheet erosion from the land surface; erosion of streambanks and channel bottom; erosion of exposed slump surfaces; and erosion from downcutting in ravines. The sediment generated from the land surface by the sheet erosion process is associated with various land uses within the Lower Poplar River watershed, including forest (predominantly deciduous), ski slopes, golf course, developed areas (housing and commercial establishments), and roads. This report summarizes the results of an analysis to quantify the annual sediment load in the Lower Poplar River associated with each of these sources. A combination of methods was used to arrive at these estimates and the background for these methods along with estimated results will be presented in the following sections.

Analysis of sediment generated from sheet erosion

Modeling background

Erosion from upland areas is in the form of sheet and rill erosion, and gully erosion. The prediction of sheet and rill erosion has advanced significantly since the days of the Universal Soil Loss Equation (Wischmeier and Smith, 1960), an empirical equation for prediction of edge-of-field erosion. Today we have models such as the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) which is a physically-based model that provides estimates of pointwise erosion in the field and also predicts the amount of eroded soil that actually is delivered to the point of interest/concern. The WEPP model, version 2010, was applied in the current project to estimate the local erosion in the Lower Poplar River watershed and to estimate the delivery of eroded soil to the outlet of the watershed.

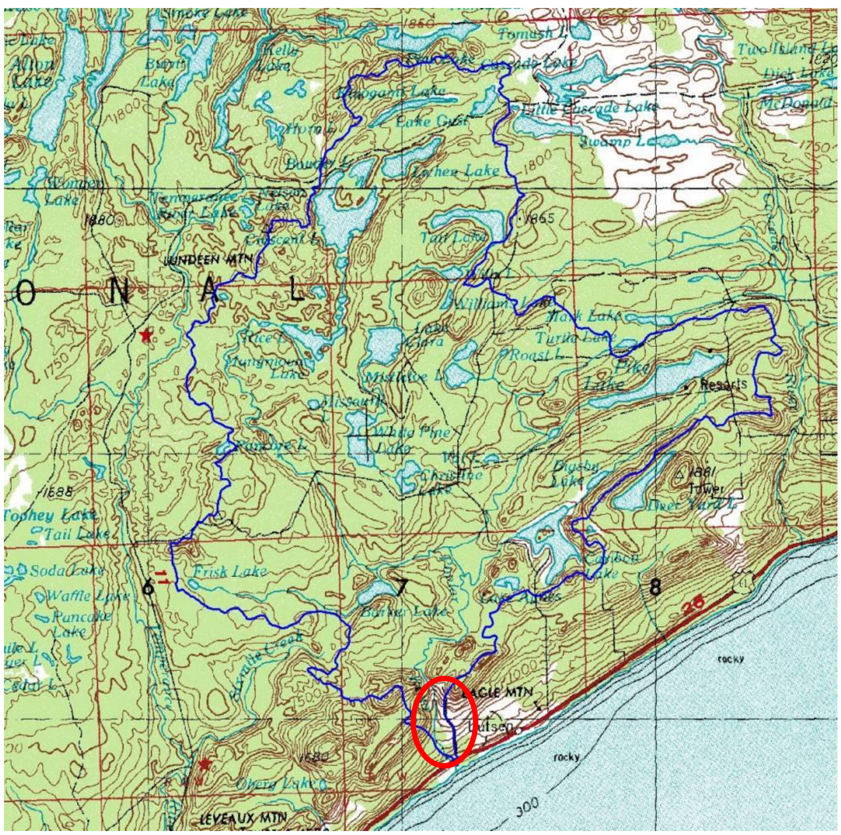

Figure 1. Topographic map with the outline of the Poplar River located along the north shore of Lake Superior. The red oval outlines the area of interest with regard to the turbidity impairment, that is, the Lower Poplar River watershed.

The WEPP model was developed to simulate the runoff hydrology of a landscape on the basis of individual hillslope units (see Figure 2a). It simulates the runoff generated on a hillslope in response to individual or series of rainfall/snowmelt events, and erosion associated with the runoff events is simulated simultaneously. Sediment generated at locations on the hillslope is transported by runoff water to downslope locations on the hillslope. The transported sediment can be deposited on lower portions of the hillslope, or else it is transported off the toe of the hillslope into an established stream channel.

Important properties of a hillslope that influence runoff generation, soil erosion, and sediment transport on a hillslope are the type of soil (soil thickness, texture, hydraulic conductivity), soil cover (vegetative type and vegetative density), surface slope, and soil erosivity. The WEPP model uses these properties as inputs to a system of physically-based equations for calculating surface runoff generation, evapotranspiration, soil particle detachment, and suspended sediment transport.

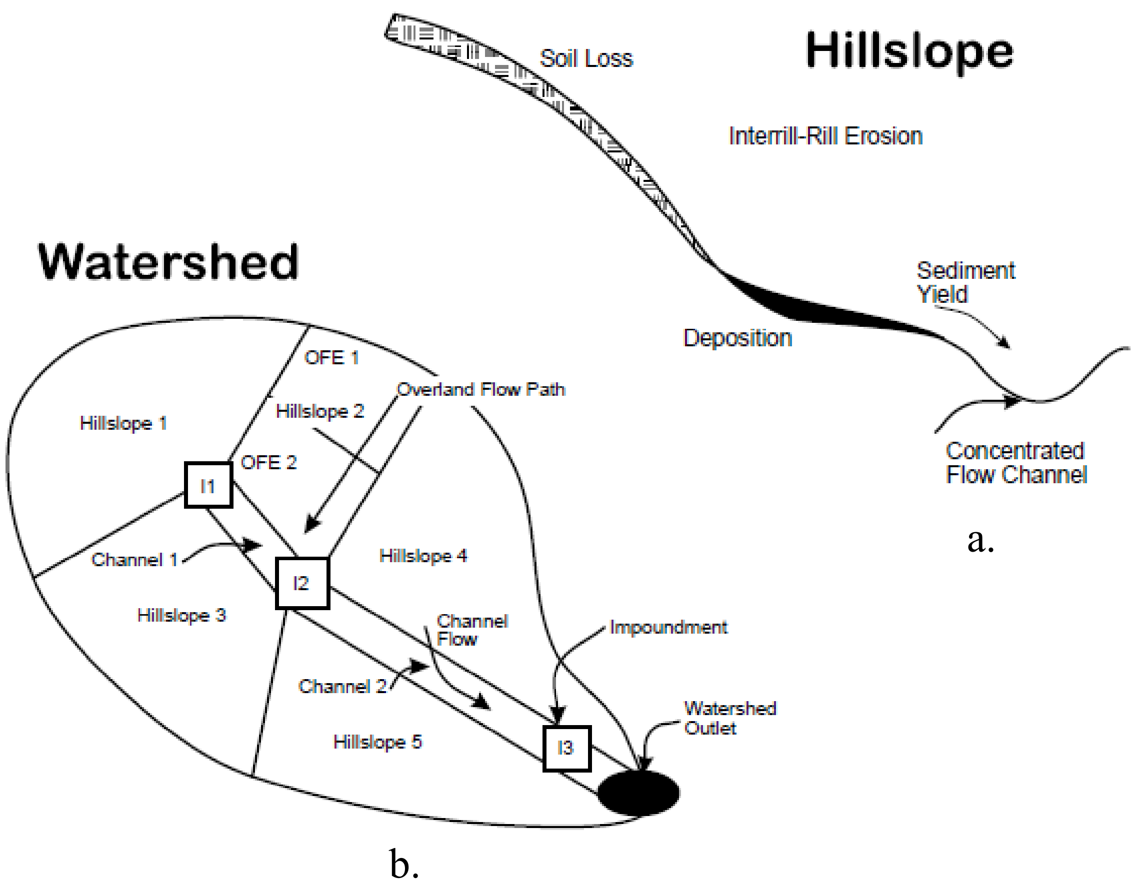

Figure 2. Illustration of the conceptual framework of the watershed version of the WEPP model. (a) The framework for the individual hillslope component and (b) the framework for the watershed. All hillslopes have a channel at the toe of the hillslope.

While the WEPP model can be applied to individual hillslopes, the watershed version of the model allows one to subdivide a watershed into a number of hillslope segments as shown in Figure 2b. The hydrology and sediment transport is then calculated for each of the segments, and the results are then combined through runoff routing and sediment transport routing to provide estimates of sediment delivery to the watershed outlet. The outlet of the watershed is the location where the sediment is monitored, and that is therefore the point of interest for the calculation of the sediment load by the WEPP model and matching with observed sediment load. However, since the WEPP model simulates the erosion and sediment transport on individual hillslopes, the resulting simulations also provide details of where the sediment is originating.

A useful tool for setting up (preprocessing) a WEPP model for a watershed is the GeoWEPP model (2008). This model serves as an ArcGIS interface between GIS data layers that are readily available for landscapes in the U.S., and the WEPP model. The GeoWEPP model was applied in the current project to prepare the input data for the WEPP model simulations. While the preparation of this input data would seem to be rather automatic using the GeoWEPP model, it will be mentioned later that a significant amount of modification of the prepared input data is necessary because of the changes in GIS databases over time, and due to the fact that manual interaction with the data is necessary to provide the most accurate representation of land surface conditions.

Water balance calculations in WEPP

The WEPP model conducts calculations of all of the significant water balance components associated with the terrestrial phase of the hydrologic cycle. It uses as input climatic/weather data either synthesized with stochastic methods or developed from direct observations. This input is then partitioned into the components of vegetation interception, infiltration, surface runoff, shallow subsurface flow, deep percolation, soil evaporation and plant transpiration. A schematic of the processes involved in the water balance for a single hillslope is presented in Figure 3. The fate of deep percolated water is not taken into account in the WEPP model; the percolated water is assumed to be lost from the watershed system. Some recent developments in the WEPP model point to the fact that a new version of WEPP will include baseflow from groundwater recharged by the percolated water.

Runoff generation processes

Possible processes of runoff generation in the landscape include surface runoff, shallow subsurface storm flow (SSSF), and groundwater discharge (Kirkby, 1978). While there are contributions to runoff from SSSF and groundwater discharge in the Lower Poplar River, those contributions are quite small in comparison to direct runoff from the land surface as a result of rainfall and snowmelt events. The SSSF and groundwater discharge components are small in this area because of shallow soil conditions (reduces the SSSF contribution), and the predominance of bedrock in the area leading to low availability of groundwater with regard to storm flows. We did not consider the contributions of SSSF or groundwater discharge to the generation of soil erosion within the Lower Poplar River, and instead focused on the direct surface runoff mechanism.

It is generally recognized that direct surface runoff can be generated by two mechanisms, the Hortonian mechanism which involves the exceedance of infiltration capacity of the soil at the soil surface, and the Dunne mechanism, also called saturated overland flow resulting from saturation of the soil profile due to downslope migration of soil moisture. The Hortonian mechanism generally occurs in the case where the vegetation is sparse and the surface of the soil is drastically disturbed, and thereby the surface hydraulic conductivity is significantly small, while the Dunne mechanism dominates when the soil has very high hydraulic conductivity at the surface and downward percolation of water is restricted by low conductivity layers of soil or bedrock.

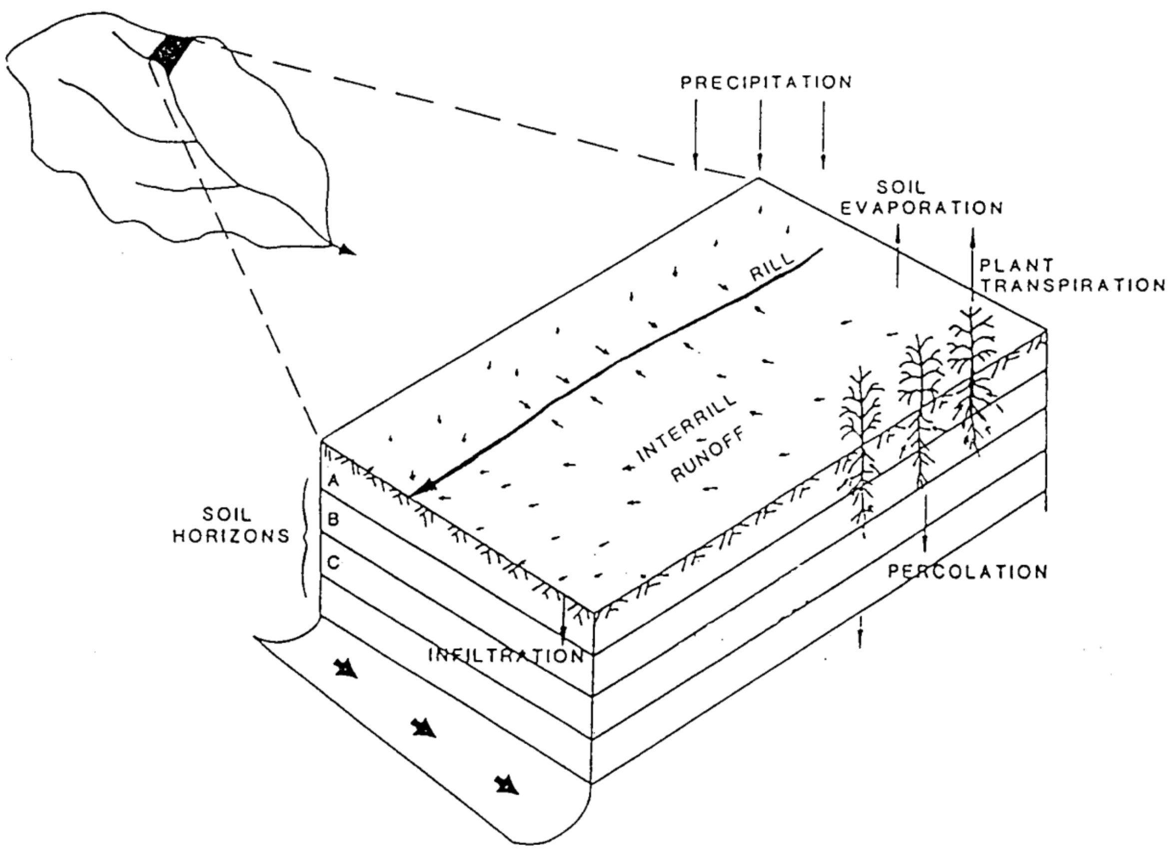

Figure 3. Illustration of the water balance components handled in the WEPP model hydrologic calculations. Vegetation interception and shallow subsurface flow are not shown here but they are included in the model calculations.

Measurements of saturated hydraulic conductivity in the forested areas of the Lower Poplar were determined to be upwards of 40 inches/hour, while on the ski slopes the conductivities were generally greater than 2 inches per hour. With hydraulic conductivities of this magnitude it requires an infrequent rainfall event of high intensity and long duration to produce surface runoff by the Hortonian mechanism. Runoff in these areas during the non-frozen period of the year then can only occur if the profile is susceptible to saturation as a result of a subsurface layer that restricts downward flow. Such restrictive layers do exist on many or all of the slopes since bedrock is shallow over most of the watershed (see discussion to follow with map analysis of bedrock depth), and even when bedrock is deeper the soils generally have denser soil layers at fairly shallow depth and these layers restrict downward percolation of water.

The condition where the Hortonian mechanism will be significant is during the winter and spring snowmelt period when the soil surface is frozen. Under the frozen condition the soil hydraulic conductivity is reduced drastically because water freezes in the soil pores, thereby blocking the pathways for water supplied by snowmelt and rain-on-snow at the soil surface. The degree of severity of this effect depends on how frozen the soil becomes over the winter, and the amount of moisture residing in the soil profile in the late fall just before freezing begins to occur. A wet profile will lead to very frozen soil and soil with very low surface hydraulic conductivity, and the surface will in effect not allow much water to infiltrate, while a dry soil will not have frozen water at all and the infiltration will then be high. Having a dry soil going into fall is very uncommon, and even during the winter some moisture can infiltrate into the soil during mid-winter thaw periods and then freeze to the point where hydraulic conductivity is drastically reduced. The amount of moisture present in the profile will be greatly affected by the fall rainfall amount, and also by the type of vegetation present on the surface. Healthy vegetation will tend to reduce the moisture in the profile going into the freezing period.

The WEPP model is able to simulate both the processes of Hortonian overland flow runoff generation and saturated overland flow generation. It does this by using mechanistically-based equations describing the two mechanisms. Hortonian overland flow is calculated by the well-known Green-Ampt methods (1911), while the saturated overland flow mechanism is calculated by using the Sloan and Moore (1984) approach to determining the zone of soil profile saturation.

The WEPP model accounts for the effect of freezing on the soil hydraulic conductivity as the model simulates the thermal energy balance of the soil profile and takes into effect the insulating properties of snow cover. The depth of freezing of the soil profile is calculated using the daily thermal energy balance at the soil surface (snow surface if snow is present) and the hydraulic conductivity of the soil is calculated to decrease exponentially with any increase in ice content of the soil. Experience with the model shows that hydraulic conductivity of a soil can be readily reduced by two orders of magnitude (e.g., 4 inches/hour for unfrozen conditions to 0.01 inches/hour for frozen soil conditions). This has a tremendous impact on the process of generation of runoff from snowmelt as well as rainfall on frozen ground following snow disappearance, and will partially explain why much of the runoff in the Lower Poplar is generated during the snowmelt period.

Setting soil hydrologic and erosion parameters

In setting the parameters for the soils within the Lower Poplar watershed the soil horizon properties provided by the WEPP soil database were used without modification since the study of Hansen et el. (2010) did not measure soil horizon properties in the field. Parameters that were assigned, other than the default values provided, were the effective saturated hydraulic conductivity K_e, the critical shear stress τ_c, and the soil erodibility coefficient k_r. Measured values of K_e were reported by Hansen et al. for forested areas, golf course areas and for ski slopes (graded and non-graded). As mentioned above, the lower values of K_e were about 4 inch/hour (100 mm/hour), so that value was used for all soils within the watershed except for pavement in developed/commercial areas, and for roads/trails. Values of τ_c were assigned based on the measurements reported by Hansen et al., and these values were all in the range of 2-3 N/m^2. Data for determining values of k_r was derived in the study by Hansen et al.; however values were not determined from the data. Additional work will need to be done to make this determination. Instead, the values of k_r were determined from regression equations given in the WEPP model documentation. Depending on soil classification, resident root density, and soil bulk density the value of k_r ranged from 0.0002 to 0.0008 s/m.

The WEPP model default condition for deep drainage from the soil profile is to assume free drainage out of the bottom of the profile at a potential rate equal to the saturated hydraulic conductivity of the soil. If deep drainage is truly free to occur the loss of water from the soil profile can constitute a significant effect on the water balance of the soil profile. In general it is fast enough in every case to bring the soil profile back to field capacity following any significant infiltration event and thereby provide plenty of storage capacity in the soil to prevent surface runoff in subsequent rainfall or snowmelt events. However, the situation in the Lower Poplar watershed is that the soils are generally underlain by shallow bedrock, generally less than 0-2 feet below the soil surface. A map showing the distribution of depth to bedrock is shown in Figure 4. One does see some places in the landscape where the depth to bedrock is quite large, 60-70 feet; however, in most instances the depth is quite small. The locations where bedrock depth is large might be locations of large fractures in the bedrock. Maps showing the bedrock geology and the locations of available well logs in the area are included in Appendix A.

The WEPP model facilitates the accounting of the effect of a restricting layer at the base of the soil profile on the soil profile water balance by allowing one to specify whether such a layer exists, and then also allows one to specify the depth of the layer and the saturated hydraulic conductivity of the layer. The resulting water balance is very sensitive to the assignment of the restricting layer saturated hydraulic conductivity value. If that value is sufficiently small, the resulting lack of downward percolation will allow for water buildup in the soil profile, leading then to saturated soil conditions and consequently to surface runoff generation by the Dunne mechanism. Since the soils in the area were determined to have very high saturated hydraulic conductivities for the soil surface, it is unlikely that surface runoff will be generated by the Horton mechanism for any but the most intense storm events in summer periods.

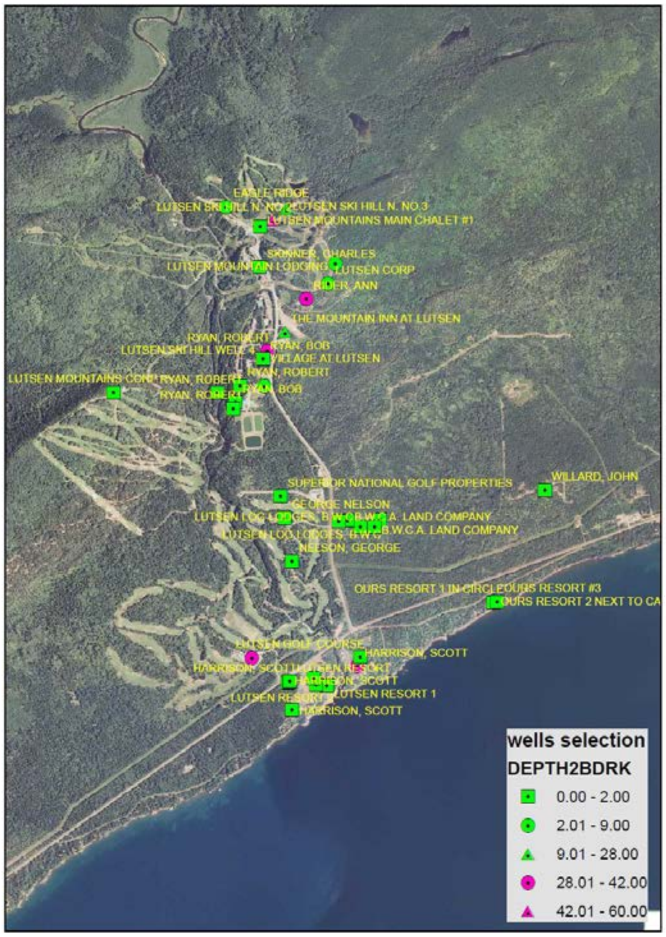

Figure 4. Map showing the depth to bedrock as indicated from the well logs for the locations shown.

The effect of this restricting layer on the soil profile water balance is illustrated in Figure 5. The illustration shows the temporal variation in stored soil moisture for a soil, with one plot representing the variation when the profile drainage is not restricting, and the other plot when the profile is restricted by a layer having a saturated hydraulic conductivity of zero. We can see that with free drainage the moisture profile remains well below the 118.6 mm, but with the restrictive layer the profile reaches the 118.6 mm limit frequently for the case of the short prairie grass. With the perennial forest this is not the case; the moisture profile is drawn down significantly due to evapotranspiration from the forest. This plot was using results generated by the WEPP model, and shows that the soil water storage responds to precipitation, evapotranspiration, and deep drainage. For the case with deep drainage equal to zero the graph shows that at times the profile becomes saturated. At those times, if rainfall or snowmelt occurs the incident rainfall/snowmelt will not infiltrate but will contribute to runoff, streamflow, and possibly to soil erosion.

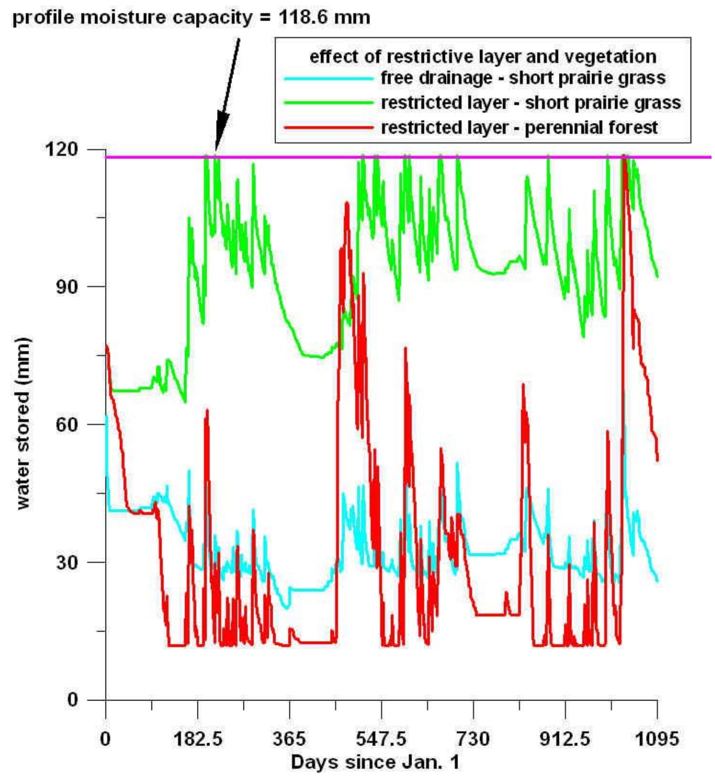

Figure 5. Illustration of the effect of the restrictive layer on the water balance of the hillslope. When the soil water stored reaches 118.6 mm, any rainfall will run off. This is for the Quetico - Barto soil (13 inches thick) over unweathered bedrock.

Influence of soil freezing on runoff generation

As mentioned above, the freezing of the soil fills some or all soil pores with ice, and these pores are then not available to transmit water. The effect of freezing drastically reduces the saturated hydraulic conductivity of a soil. So, even if a soil has a very large saturated hydraulic conductivity, when freezing occurs the actual hydraulic conductivity can decrease by orders of magnitude and even be reduced to zero in the case where all soil pores become filled with ice. Besides the calculation of the balance of liquid water in the soil profile, the WEPP model also conducts calculations on the thermal energy balance of the soil profile and determines the fraction of soil pores filled with ice during freezing periods (late fall, winter, and early spring).

An illustration of the effect of soil freezing on soil hydraulic conductivity is illustrated in Figure 6. The time scale begins with January 1 of the year at which time the soil is frozen and the effective hydraulic conductivity is zero. The soil then thaws around the end of April and the effective hydraulic conductivity increases to near the saturated hydraulic conductivity value. The soil freezes once around the first week of December, sufficiently so that the effective hydraulic conductivity of the soil drops to zero once again and this cycle moves into the next winter season and snowmelt season.

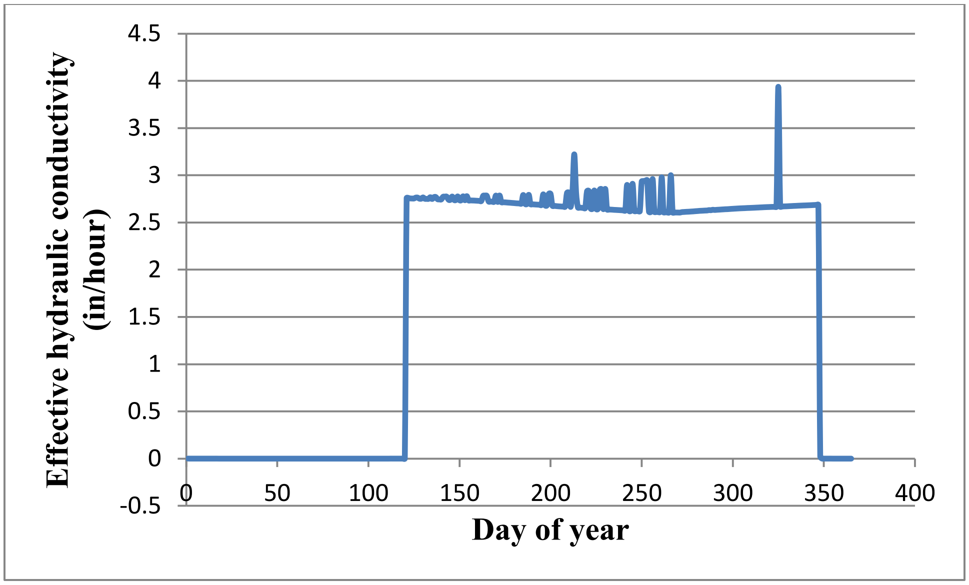

Figure 6. Illustration of the effect of soil freezing on the hydraulic conductivity of the soil. Shown is a plot of the hydraulic conductivity versus time for the period during the winter season, the time of soil freezing.

Naturally, if the soil hydraulic conductivity is decreased as a result of freezing, then rainfall or snowmelt incident on the soil will result in the generation of surface runoff if the rainfall rate or snowmelt rate exceeds the hydraulic conductivity of the frozen soil. The greater the degree of freezing, the lower will be the hydraulic conductivity and therefore the greater the rate of surface runoff generation, and also the greater the potential for generation of soil erosion. Hydrologic records for the Poplar River show that runoff generation is greatest during spring snowmelt periods, indicating partially the effect of the large amount of water made available due to the stored snowpack, but also the effect of reduced soil infiltration capacity due to soil freezing.

The effect of soil insulation by snow and by vegetative cover/organic residue on the soil freezing process is dramatic. Denser vegetation and higher surface residue delays the date of first freezing and also decreases the intensity of freezing. The snow pack that develops during winter also helps to reduce soil freezing, with greater amounts of insulation being provided by deeper snowpacks. The 'fluffier' the snow in the pack the greater the insulation benefit. Packing by snow aging (metamorphosis), or by machine grooming/skiing/snowboarding decreases this insulating effect.

Modeling variation of vegetative cover

The WEPP model simulates the temporal variation in vegetative cover and root biomass for a given plant species. The details for the plant growth model are given in Arnold et al. (1995), chapter 8 of the WEPP model documentation. That documentation explains that the plant growth model in WEPP is based on empirical equations that use air temperature and incident solar radiation to simulate daily plant biomass growth. The model does not directly account for nutrient cycling, nor deficit or excess soil moisture conditions. The model also simulates the accumulation of biomass residue on the soil surface, the temporal degradation of the residue, and the temporal degradation of below-ground biomass. The below-ground biomass is limited to root mass only since for the hillslopes in the Lower Poplar River watershed there is no tillage and therefore no burial of surface biomass.

Biomass cover, both live and dead standing biomass and flattened dead biomass provide protection of the soil from erosion caused by raindrop impact and overland flow. The plant growth component of the WEPP model simulates the growth and decay of vegetative biomass. The amount of surface coverage provided by plant materials (live or dead) has been correlated to biomass accumulation based on field observations in a number of studies (e.g., Weltz et al., 1992 and these relations are used by WEPP to predict soil surface protection by vegetation.

As an example of the dynamics of soil surface protection for two vegetative cover conditions the fraction of cover provided by standing vegetative biomass is illustrated in Figure 7, while the variation of residue cover is provided in Figure 8. The two cases shown in these figures are both for plants in the category of short prairie grass, with a maximum stand height of 15 inches. In one case the leaf area index of the plant was assigned a maximum seasonal value of 0.5, while in the other case the maximum value was set to 4.0. The leaf area index (LAI) is defined as the ratio of total area of leaves (one side of each leaf) to the area of the soil directly beneath the vegetative canopy. For an LAI of 0.5 it means that if all the leaves on the canopy were picked off the plant and laid on the soil underlying the canopy the leaves would cover only one-half of the soil area. In contrast, with an LAI of 4.0, the leaves would be able to cover a soil area that is four times the area of the soil underlying the canopy.

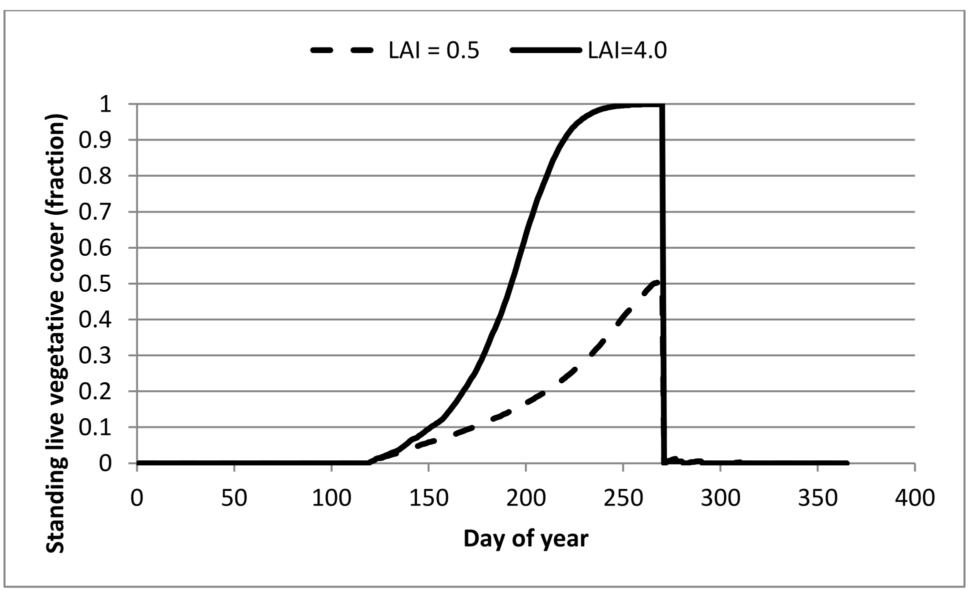

Figure 7. Variation of surface cover provided by standing vegetation for two cases of maximum leaf area index, 0.5 and 4.0.

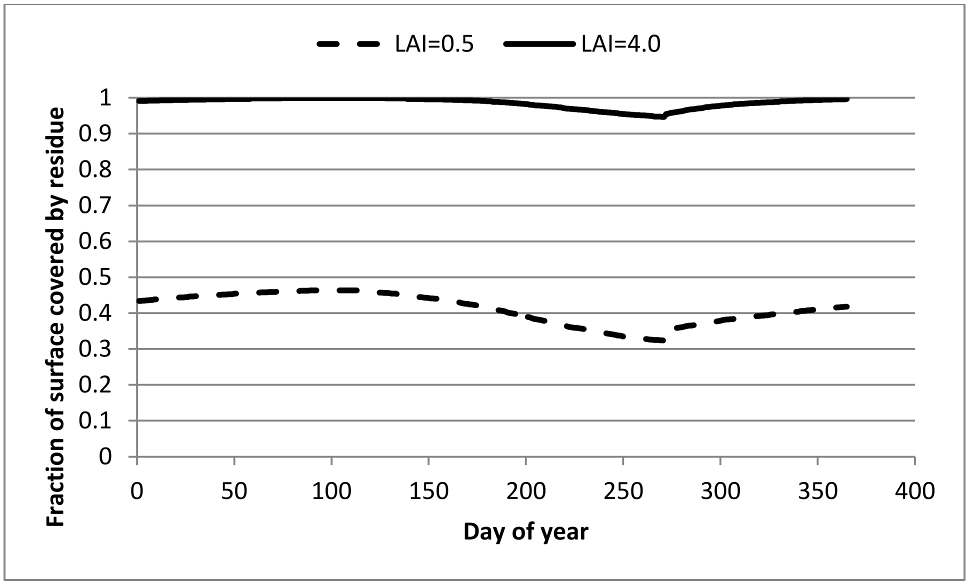

Figure 8. Variation of surface cover provided by plant residue for two cases of maximum leaf area index, 0.5 and 4.0. Both of these cases are for short grass prairie.

WEPP application to Lower Poplar River watershed

The GIS data layers available for the Lower Poplar River watershed were the 30-m DEM, the 2006 NLCD layer for land use (MnDNR Data Deli), and the soils data layer using either STATSGO format (NRCS U.S. General Soils Map) or for the more refined soil data (Coastal Zone Management Area soils data). The land use data layer provided a description of the type of land cover and therefore characterized the vegetation present on the landscape.

Delineation of watershed boundary and designation of hillslopes/stream channel

The ArcHydro tool was used in ArcView to construct the boundary of the Lower Poplar River Watershed. The resulting delineation for the UofM effort is shown in Figure 9 along with the delineation produced by the RTI study (RTI, 2008). The differences in the boundaries extents are clear, especially at the northern part of the watershed. Since both studies applied the same input data (30 m resolution DEM, Minnesota Department of Natural Resources data deli) to delineate the watershed for the study area, the differences in watershed area and shape are unexpected. It is conceivable that, the two studies having been conducted at different times (2007 and 2010), some of the input data, especially the DEM data, could have been modified or even upgraded. In their delineation of watershed and sub-catchments, the RTI study located the outlet point more southerly compared to the UofM study; this is evident in the more downstream extension (towards Lake Superior) of the watershed in the RTI study, adding more area to the watershed compared to that by the UofM study. These factors might explain the difference (200 acres) in the areas of the delineated watershed as evaluated in the two studies.

The GeoWEPP preprocessor was applied to the DEM data to delineate the individual hillslopes in the watershed. Naturally, the preprocessor model examines the topographic features contained in the DEM data and determines the length and width of each hillslope. This process produced the map shown in Figure 10. The land use and land cover features were assigned to these individual hillslope segments.

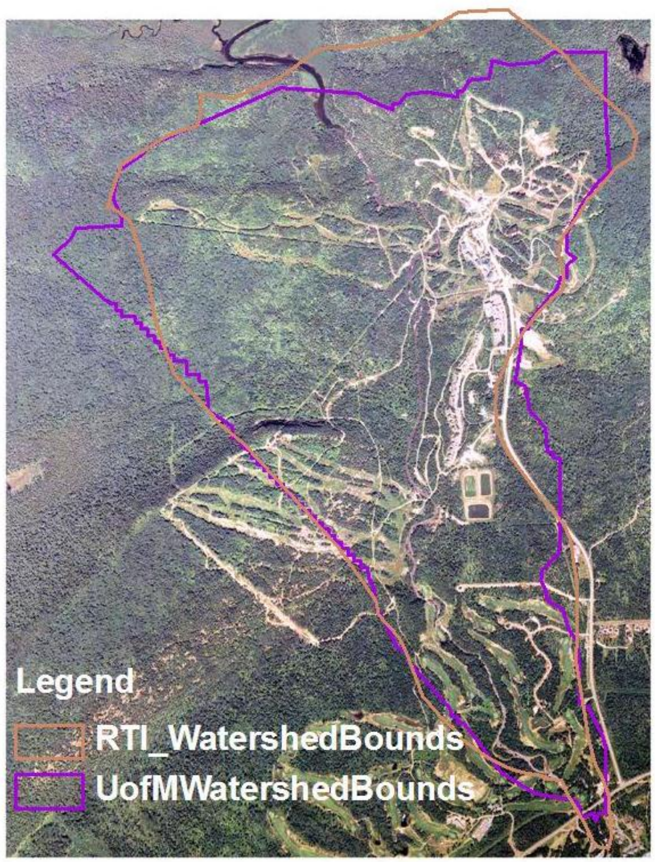

Figure 9. Watershed delineations for the Lower Poplar River watershed. One delineation is for the current effort (UofM) while the other one is for the RTI study (RTI, 2008).

Assignment of soil type

The soil type GIS layer downloaded in the more detailed Coastal Zone Management Area (CZMA) format was opened into GeoWEPP to assign the soil type properties to the hillslope elements generated in GeoWEPP. The CZMA data base showed eight distinct soil types within the Lower Poplar River watershed, while the STATSGO database (map not shown) had only three soil types within the watershed boundary. The soil parameters contained in the CZMA database include the soil thickness, field capacity, wilting point, hydraulic conductivity, soil erodibility, and soil critical shear strength. A map of the soil map with the overlay of the delineated hillslope elements is presented in Figure 11. A detailed description of these soils is presented in Appendix C.

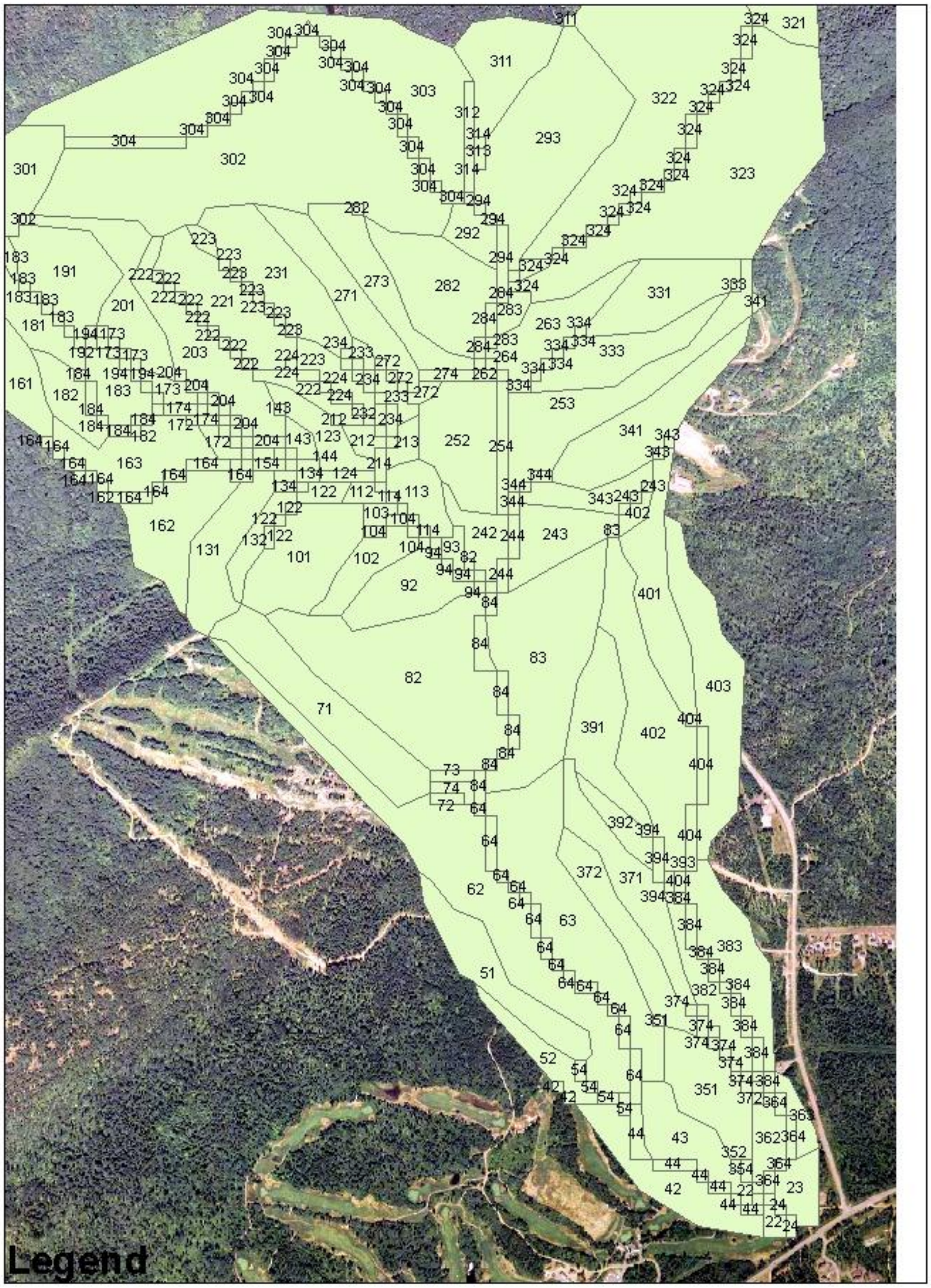

Figure 10. Delineated hillslopes and stream elements of the Lower Poplar River watershed. Individual hillslopes are assigned a unique number. The stream elements are identified by a linear sequence of elements that have the same number. Different stream segments are distinguished by the assigned numbers.

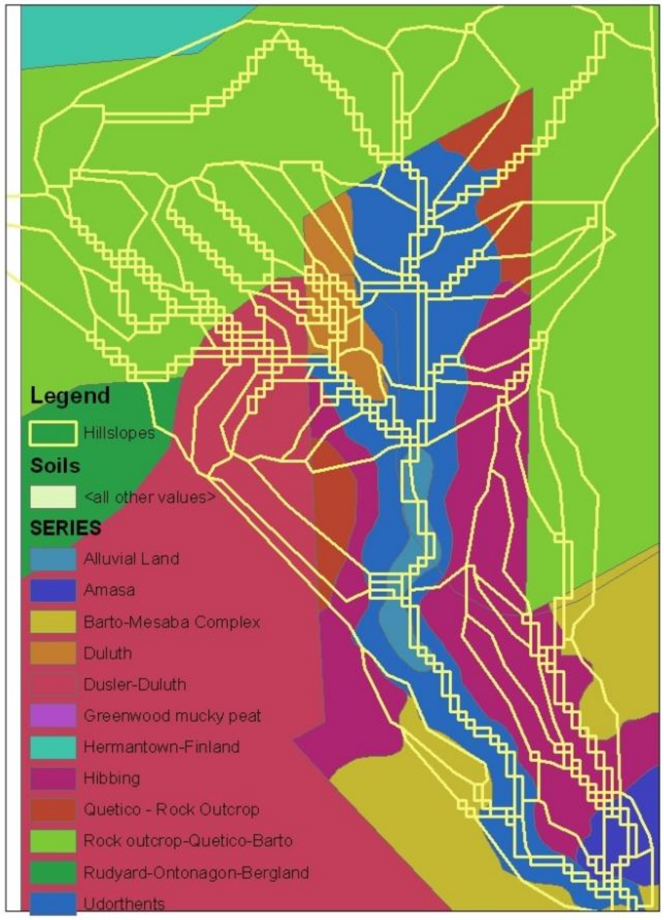

Figure 11. Distribution of soil types with the Lower Poplar River watershed using the Coast Zone Management Area soil database.

Assignment of land use and cover type

Land cover type affects the parameterization in WEPP related to the protection of the soil surface from direct shear by water flowing over the surface. In effect, the presence of plants on the surface serves two purposes with respect to soil protection. First, the plants reduce the direct impact of raindrops on the soil surface, and second, the shear stress exerted by water flowing over a surface is partitioned between the soil particles, and any plant stems/surface residue present. The presence of vegetation is also important with respect to the soil water balance because plants enhance the removal of water from the soil profile by transpiration processes, and this then reduces the potential for surface runoff during subsequent rainfall events.

The land use and land cover data downloaded from the Minnesota Department of Natural Resources (DNR) website Data Deli accepted in GeoWEPP was used to assign land use/cover classes to the hillslope elements delineated within the watershed. The data is a vegetative cover map with a one acre resolution generated from two season pairs of satellite imagery. Model parameters related to vegetative cover, runoff, surface erosion, and infiltration, were estimated using this land use data. These parameters were applied in combination with the land use data to generate suitable format land, which was then incorporated in the erosion simulation by the WEPP models. The areas identified by the GeoWEPP delineation of land uses and cover types in the watershed are presented in Table 1. The areas reported in the RTI (2008) report are also presented. Some differences in areas exist between the two studies; however, the differences are not too large considering the difference (200 acres) in overall areas of the watersheds for the two studies. One potential source of error generated during assignment of land use/cover types in the WEPP model is due to aggregations of land use/land cover types for each hillslope. While the WEPP model does allow for changes in land use/land cover along the slope axis of a hillslope, small deviations can occur in the direction parallel to the slope and this can lead to some misrepresentation of the conditions. A description of each land use and cover type is presented in the following paragraphs.

Forest cover type in the Lower Poplar River watershed comprises lowland conifer forest, lowland deciduous forest, upland conifer forest, and upland deciduous forest (RTI, 2008). According to the same report by RTI, these forested areas are historically known to have been logged between 1890 and 1930. For the purposes of this modeling effort (UofM), the land use type is assumed to be mature forest with an average age of “20-years or greater”.

Golf Course cover type areas have been represented as “short grass or lawn-grass with 100% cover”.

Ski Runs were identified from land cover data as those areas designated in the land cover data as shrub and grasslands. The areas contained roads and trails, but these roads and trails were not separated out from the land cover type since erosion from those features were modeled using a different method (Rosgen, 2007) to be described later. This cover type was represented in WEPP/GeoWEPP simulation as either “tall grass prairie” or “short grass prairie” with initial residue cover of 40%. The description of these two grass types is described in the manual for the Disturbed WEPP Model (http://forest.moscowfsl.wsu.edu/fswepp/docs/distweppdoc.html). Descriptions are copied below directly from Table 3 of that online source.

“**Tall Grass Prairie** – Areas covered by tall bunch grasses, with gaps between bunches. Plants are about 0.6 m tall and 0.3 m average spacing. The percent cover entered is an indication of the percent of the canopy or ground covered by the vegetation. This vegetation treatment would best describe blue-stem or similar range communities in the west, or ryegrass, brome, or orchard grass pastures in the east. It may also describe post-fire conditions where wheat or oats have germinated to provide post-fire erosion mitigation. This treatment may also be a reasonable estimate of a harvested forest 2 years after a prescribed burn, or 3 years after a wild fire.
Short grass prairie - Areas covered by short sod-forming grasses. Plants are about 0.4 m tall and with an average spacing of 0.2 m. The percent cover entered is an indication of the percent canopy or ground covered by the vegetation. This vegetation treatment would best describe

buffalo grass or similar sodding grasses in the west, or Kentucky bluegrass in the east. It may also best describe sparsely-covered reclaimed mine lands. This treatment may best describe forest conditions 1 year after a prescribed fire or two years after a wild fire."

With the disturbance caused by snow being compacted on top of the grass each ski season it would seem that the grass would not come back each growing season to the tall grass type. The loss of vegetative diversity is described in Rixen et al. (2003). They show that the snow and snowmaking/grooming process and the skiing itself can lead to stands of less species diversity for grasses. Generally higher diversity provides for more resilience to disturbance. There is also a decrease in species diversity on ski slopes that have been graded with machinery as reported by Pohl et al. (2012).

One aspect of snowmaking that Rixen et al. (2003) pointed out that may be beneficial to ski slope plant populations is that the added water may help with reducing the severity in events of drought and this can then lead to more vigorous vegetative growth. A second aspect is that constituents (nutrients in particular) added to the snowmaking water will also help to fertilize the soil and thereby improve plant growth conditions.

Vegetative residue from the prairie grass does decay over time with decay being slower during the snow season. To initiate simulations it was assumed that the initial residue cover was 40%. Thereafter the model accounts for accumulation and decay of the residue cover. The amount of cover that develops during a given growing season depends on plant growth conditions (temperature, solar radiation, moisture, soil conditions, and nutrients). In general it was found that the maximum residue cover developed to a maximum of about 55% toward the end of each growing season.

Developed areas were identified from the DNR Land coverage data, verified with FSA (2003) digital orthophoto quad data for the area. These areas were represented in the model as well maintained resort areas with low infiltration capacity and very low erodibility. This land use type was represented in GeoWEPP as Pavement, and also assigned soil type as pavement ("pavement.rot").

S**lumps, roads, and ravines** were all mapped through the field investigations reported by Hansen et al. (2010) and not using the GIS database. Overland flow erosion from slumps was modeled using the WEPP model, while the estimated erosion from roads and ravines was derived by other methods to be discussed in separate sections. For the slumps the field measurements were used to determine the slope and the surface area by a procedure described by Hansen et al. Erosion simulation for the slump areas assumed bare soil surface condition with some minimal (10%) vegetation cover. The slump units were not included directly in the WEPP watershed model, but instead the simulation of slump surface erosion was conducted using the WEPP hillslope model. Slumps were presented in this simulation as "fallow" cover type, with minimal cover. The location of the slumps examined in this study is presented in Figure 12.

Table 1. Areas (acres) of the Lower Poplar River watershed occupied by various land use and cover types. Areas reported by the RTI (2008) study are also listed for comparison.

Sediment source	RTI (acres)	UofM (acres)
Developed	32	30
Forest	878	734
Golf	61	85
Ski	164	146
Total of surface features	1,135	1,005
Slumps	2.6	4.6
Roads	8.8	18
Ravines	No area given	2.05

The land use and land cover classifications assigned to the hillslope units are illustrated in Figure 13. The polygons representing the individual hillslope units are outlined in this figure. This land surface discretization contains 195 land surface elements representing specific land cover types and soil types. Even with the level of discretization shown in the figure there are polygons that contain more than one land cover type. The small square units that appear to be variously arranged in somewhat linear patterns represent the locations of the first-order and higher-order streams.

The network representation of the hillslope polygons and channel units shown in Figure 13 is illustrated by the screen shot in Figure 14. The polygons are represented as rectangles in the WEPP model calculations and that is how they are shown in Figure 14. The connection of each polygon to a stream channel (ephemeral, intermittent, or perennial stream channel) is shown in the figure. The channel network is more clearly shown in Figure 15 by hiding the hillslope rectangles.

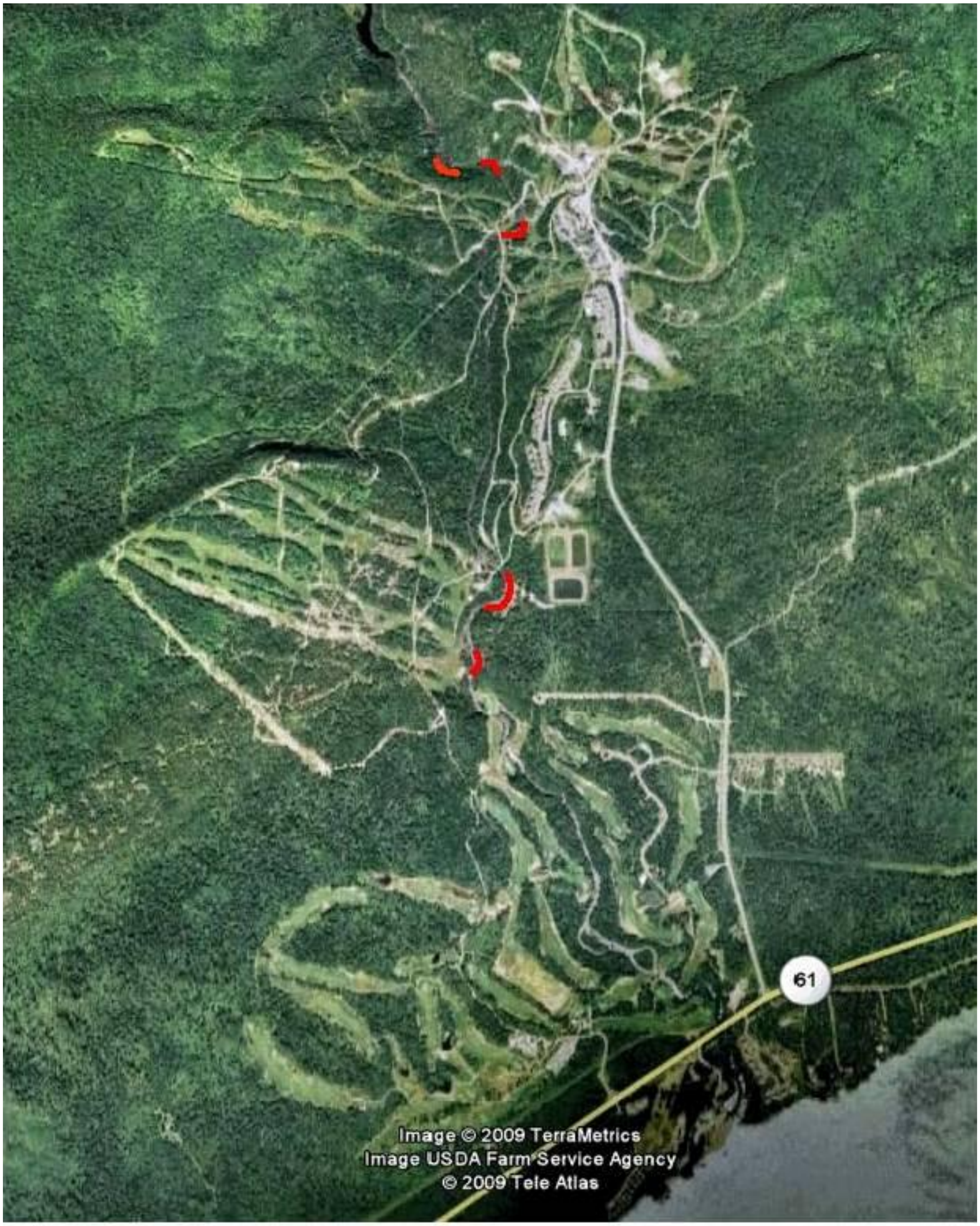

Figure 12. Location of slumps identified in the Lower Poplar River watershed are shown in red.

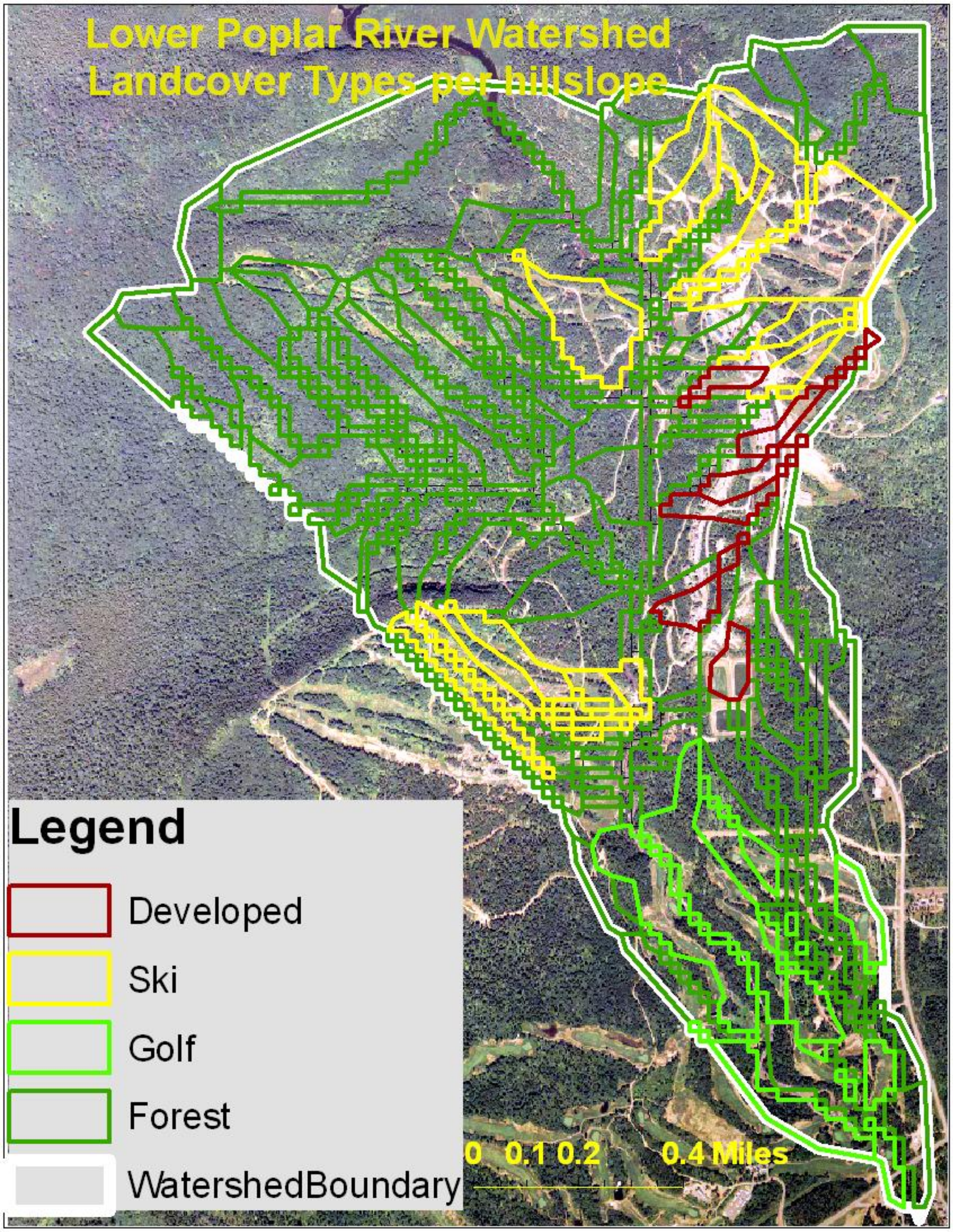

Figure 13. The land use and land cover classifications assigned to the hillslope elements for the WEPP model.

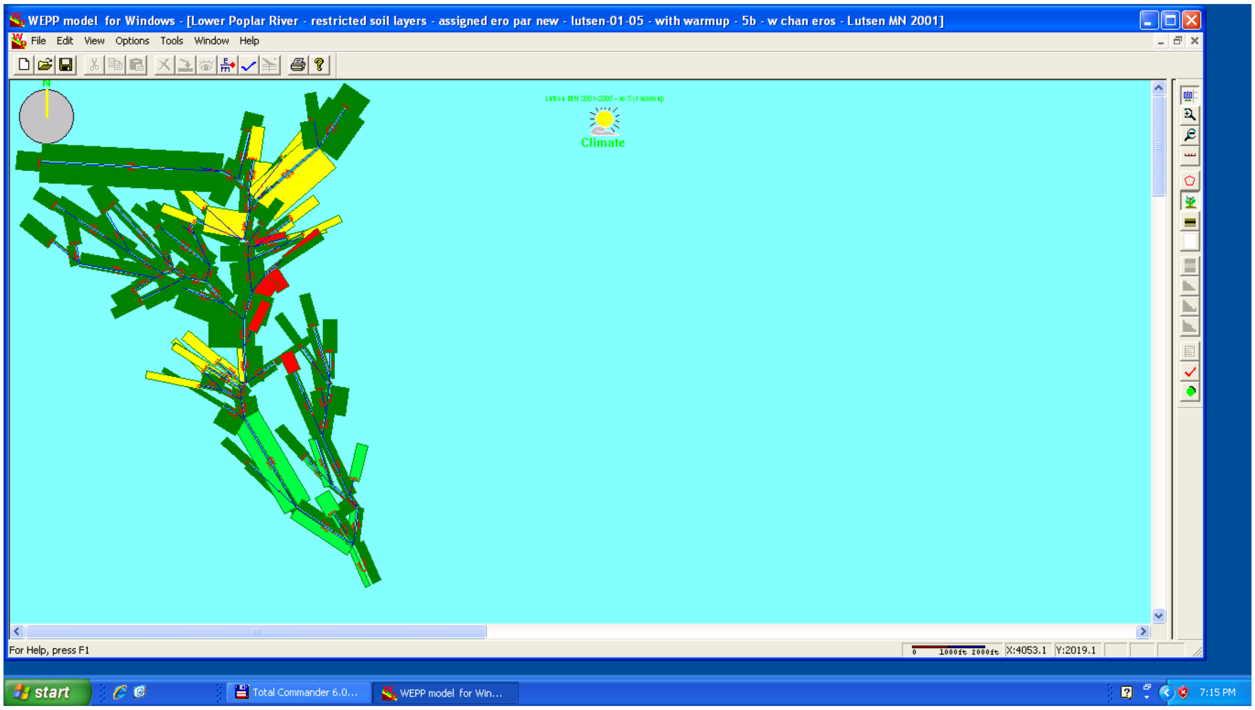

Figure 14. Representation of the hillslope units and the channels for the Lower Poplar River watershed in the WEPP model. Color codes for land uses: Dark green – forested; yellow – ski slopes; red – developed/impervious; light green – golf.

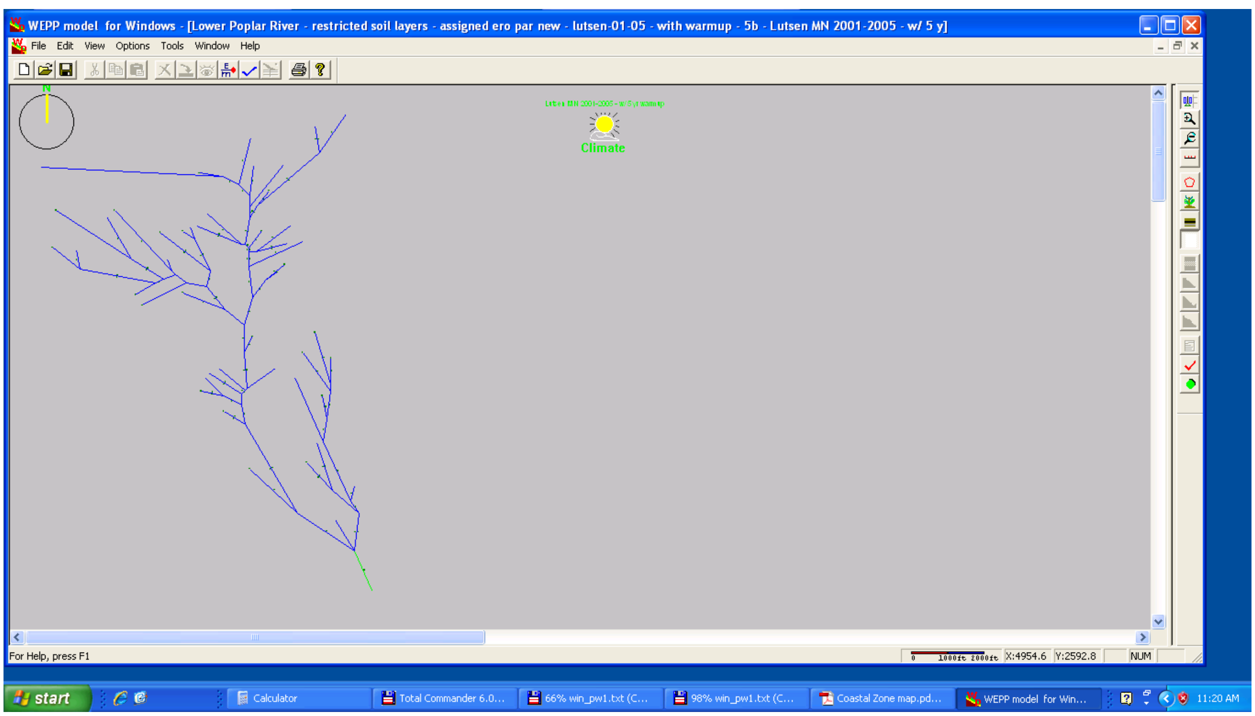

Figure 15. Similar to Figure 14 but with the hillslope units suppressed and without the satellite image.

Climate input data

To assess how well the developed WEPP model fits to the field situation in the Lower Poplar River watershed it was necessary to acquire a climate input data set that corresponds to the period of flow and sediment monitoring at the gaging station near the mouth of the Poplar River. Such an assessment was previously conducted by RTI for the period 2001 to 2005. The RTI analysis produced a climate file for that period of time and the data was made available for the present modeling work. While all of the weather variables were not measured on site, the variables that were measured were the daily precipitation, the storm duration, and the maximum and minimum temperatures. Other variables of interest were the solar radiation, relative humidity and wind speed. The variables were derived by simulation using the CLIGEN model, a model that synthesizes weather data that are serially correlated based on statistics measured at local weather stations in the region. The annual rainfall amounts observed at the Lutsen station for the Minnesota High Density Climate Station network were found to be: 2001 - 42.96 inches; 2002 – 28.79 inches; 2003 – 21.90 inches; 2004 – 34.79 inches; and 2005 – 29.87 inches. These are also illustrated in Figure 16. These values show the high degree of inter-annual variability of the precipitation. The intra-annual variability of precipitation at the Lutsen location is illustrated in Figure 17 which displays the mean precipitation for each month of the year for the period from 2001-2005. The precipitation that falls within each season of the year is also of interest here and this is displayed in Figure 18 for each year 2001 to 2005.

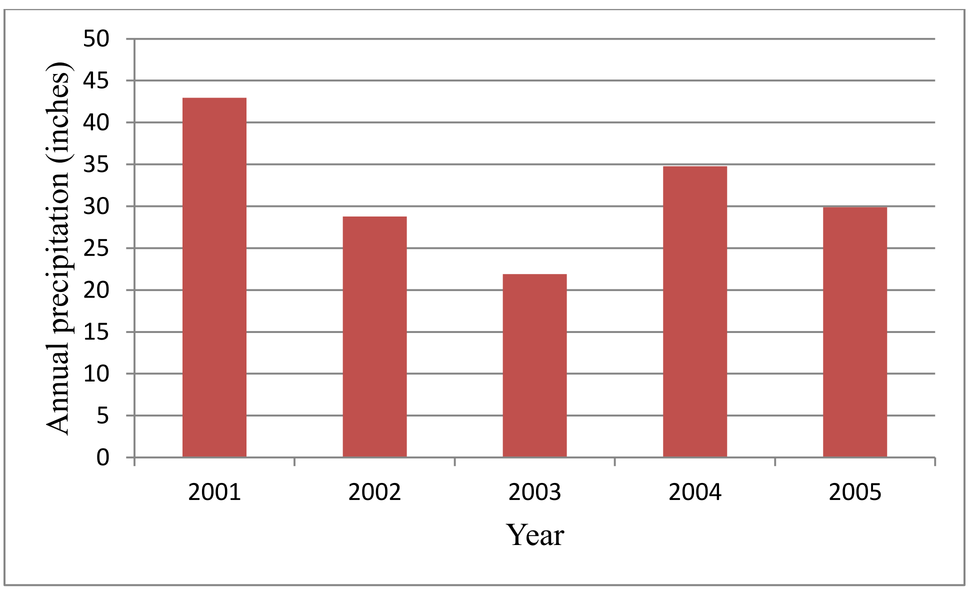

Figure 16. The distribution of inter-annual precipitation at Lutsen as generated through the RTI (2008) study using local and regional precipitation analysis.

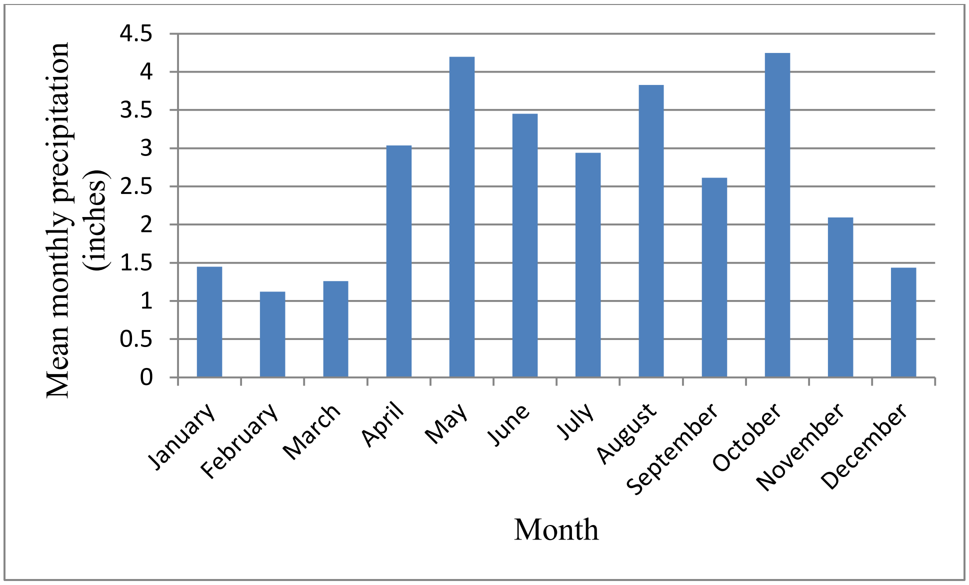

Figure 17. The distribution of inter-annual precipitation at Lutsen as represented by the mean monthly precipitation for the period from 2001 to 2005. The data for this originated from the RTI (2008) study which used local and regional precipitation analysis to derive daily precipitation amounts.

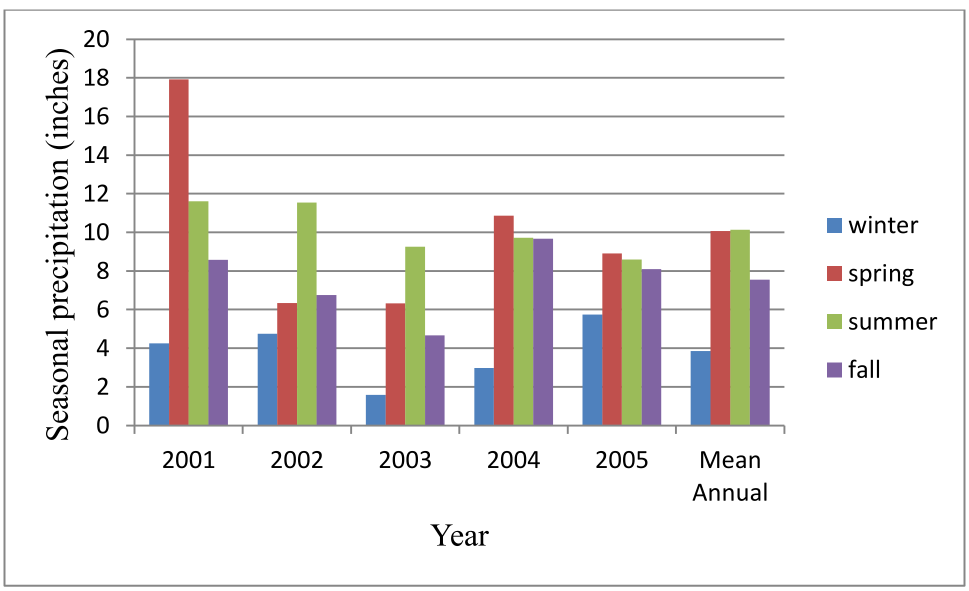

Figure 18. The distribution of precipitation by season at Lutsen for each year 2001 to 2005. The data for this originated from the RTI (2008) study which used local and regional precipitation analysis to derive daily precipitation amounts.

Predicted runoff

After the setup of the watershed WEPP model for the Lower Poplar River watershed using GeoWEPP the weather data prepared for the 2001 – 2005 time period was input to allow for a 5-year simulation of daily runoff, daily erosion, and daily sediment yield. For this simulation a ‘warmup period’ in the simulation was added to the front end of the 5-year simulation to eliminate the effect of imposed initial conditions. The ‘warmup’ period was composed of 5 years of weather input identical to the 5-year simulation period.

The daily values of output variables are available in detailed output files, but they are also compiled internally within the model and erosion and sediment yield can then be summarized by land use and land cover type for various time periods of interest.

The runoff generated in the watershed for each of the years of observation was predicted by the WEPP model and the results for this are illustrated in Figure 19. Although the gauging station is located at the outlet of the Lower Poplar River watershed, it is not possible to know how much of the flow at the outlet is generated from within the Lower Poplar River watershed since the flow at the upper end of the watershed was not measured. This is unfortunate because it would have been valuable to determine the actual runoff generated from the Lower Poplar River watershed as information for the development of the hydrologic and the soil erosion parameters for the WEPP model.

For the flows shown in Figure 20, the period 2002 – 2005 has measured flow for the Poplar River and the simulated result is compared to the measured flows. The simulated flows are the peak flows for different events as output by the WEPP model. Also shown is the WEPP-predicted flow for the year 2001, and the ‘measured’ flow is that which was synthesized by correlation of the Poplar River flow with the record from the Pigeon River. Since the flows in the Poplar River and the Pigeon River are highly correlated the ‘measured’ flow shown should be a good representation of the actual flow. Note the logarithmic scale for the vertical (discharge) axis.

When compared to the flows measured at the gauging station it is seen that the WEPP model predicts higher rates of runoff than that measured at the gauging station for many of the warm season storms as well as for many of the snowmelt month flows.

To arrive at the fairly good comparison between the measured and the WEPP-predicted flows shown in Figure 19 the WEPP parameters associated with runoff generation were adjusted until the somewhat reasonable agreement shown in Figures 19 and Figure 20 was achieved. The parameters adjusted centered around the permeability of the bedrock underlying the soils in the region, and the setting of the parameter for anisotropy of hydraulic conductivity on sloping soils. For the context used here anisotropy is the ratio of the hydraulic conductivity along the slope to the hydraulic conductivity perpendicular to the slope (i.e., down into the soil). The bedrock permeability was set to 0.1 mm/hour, while the anisotropy was set to 25. An increase in either of these parameters decreased the amount of surface runoff generated by either snowmelt or rainstorm events. An increase of the bedrock permeability also decreases the amount of total runoff, which includes both surface runoff and interflow. Water percolating through and below the bedrock recharges groundwater which in the Lower Poplar River watershed does not contribute significantly to streamflow. The value of 0.1 mm/hour is larger than the WEPP associated default value for basalt. That default value is 0.0036 mm/hour. The value of 25 for anisotropy is a reasonable value for undisturbed soils (Brooks et al., 2004).

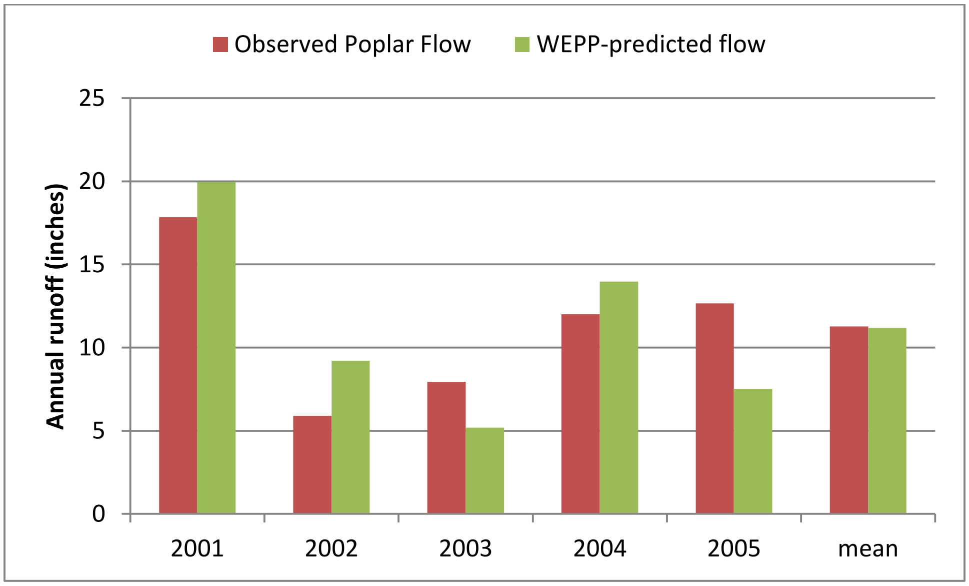

Figure 19. The Poplar River runoff depth derived from the gauging station flows, and the runoff depth predicted by the WEPP model for the Lower Poplar River, for the period 2001 – 2005. The average annual values are given as well. The value for the Poplar River for 2001 is from the synthesized flow data.

Predicted erosion and sediment yield

The total simulated erosion delivered from the upland areas to the watershed outlet is presented in Figure 21. The WEPP model predictions are quite different from the measured values for most of the years, with the differences ranging between -72% (over-prediction) and 133% (under-predicted).

These results are for the case with the vegetative cover on ski slopes being composed of short prairie grasses having a maximum LAI of 0.5 and initial residue cover of 40%. Results for other cases with higher LAI and higher initial residue cover will also be presented in the following.

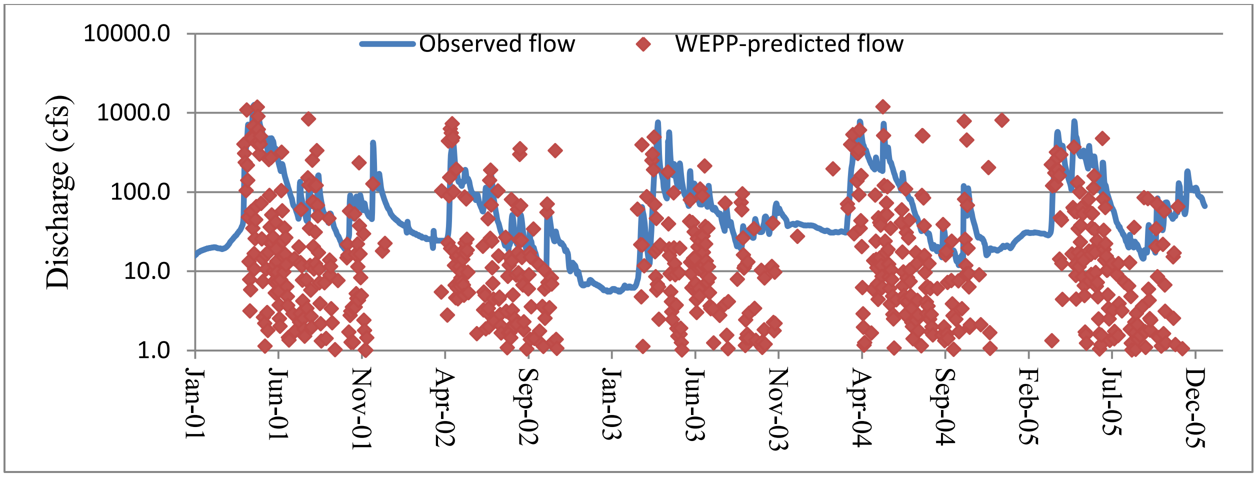

Figure 20. The flows simulated by the WEPP model for the period from 2001 – 2005 compared with the measured flow at the Poplar River gauging station. The first year of observed data and all of the winter periods (December – March) was actually synthesized by correlation with the Pigeon River.

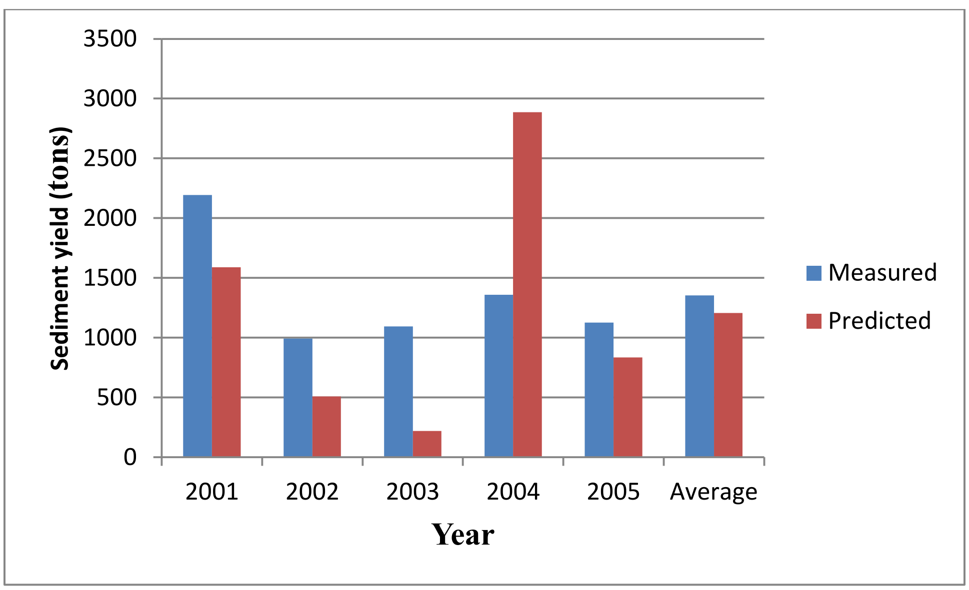

Figure 21. The annual sediment yield estimated from measurements at the outlet of the Lower Poplar River gauging station and the predicted sediment yield from the WEPP model simulations for the years 2001 – 2005. The annual average values are given for both as well. The WEPP model simulation results include contributions from the upland areas with the various land covers, forested, golf, developed and ski, and also the sediment contribution from upland ephemeral channels. These results are for the case with the ski slope vegetation cover being composed of short prairie grasses with a maximum LAI of 0.5.

Sediment yield at the outlet of the Poplar River watershed as simulated by the WEPP model for the period 2001 – 2005 is illustrated in Figure 22. This is compared to the observed turbidity levels for the period 2002 to 2005. While the erosion events in the spring snowmelt period line up quite well with the observed sediment yield, it is seen that there are some simulated sediment yield events that occur during the warmer season that are not found in the observed turbidity record. Those simulated warm season erosion events correspond to simulated runoff events in the warm season that do not have a counterpart in the flow record either. That is, examining Figure 20 one can see that there are discharges predicted by the WEPP model that exceed the discharge observed for the whole Poplar River watershed. It is not reasonable that the Lower Poplar River area would produce a higher discharge than the discharge from the watershed as a whole.

For the simulations of the sediment delivery to the watershed outlet from the 195 modeled hillslopes in the watershed it was initially assumed that the flow channels shown in Figure 15 are all non-eroding channels. This was imposed in the WEPP model by representing the channels as being made up of non-erodible rock material. This was accomplished by assigning a very high critical shear stress for the channel material. This facilitated the separation of channel erosion effects from overland flow erosion on the hillslope elements shown in Figure 14. The sediment delivery at the outlet for the watershed was then partitioned up to identify the delivered sediment sources among the various landuse conditions. For this partitioning of sediment the mean annual sediment delivery at the watershed outlet for the 5-year simulation is summarized in Table 2. The sediment delivery for this is about 45%, that is, of the amount of sediment eroded from watershed hillslopes, about 45% of that sediment reaches the outlet of the Lower Poplar River watershed.

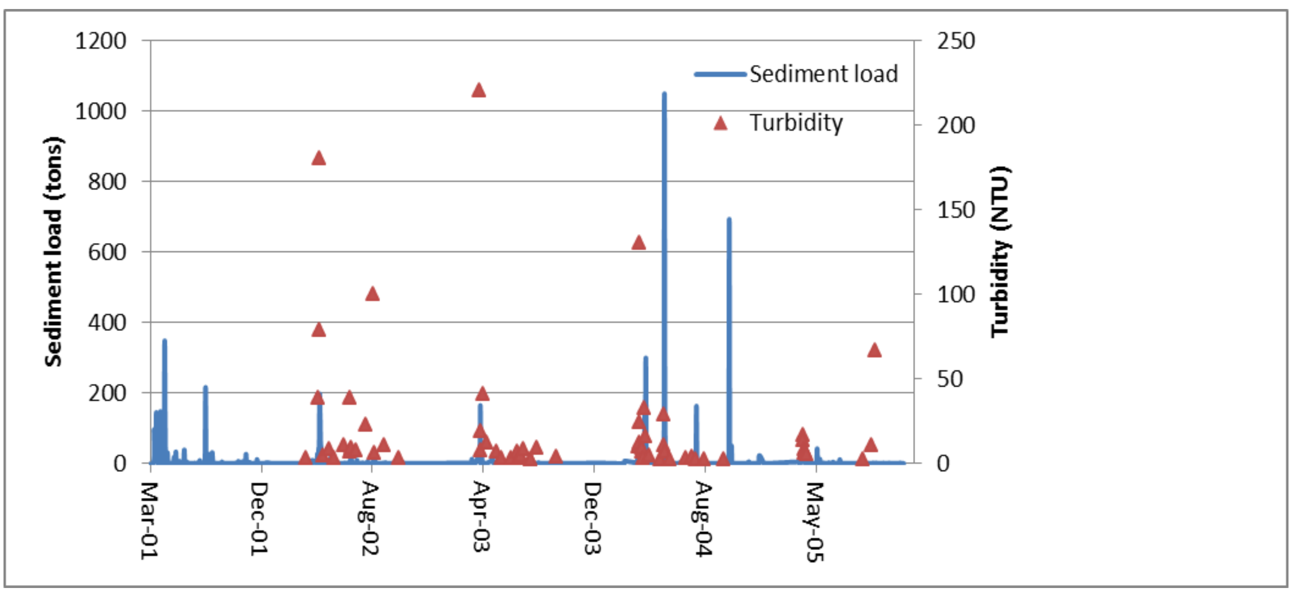

Figure 22. Temporal distribution of sediment yield (tons) at the outlet of the Poplar River watershed as simulated by the WEPP model (for 2001 – 2005) and as observed (2002 – 2005) in terms of turbidity level.

The sediment loss from the developed area shows up as zero. This is the result because the developed area is assumed to be covered with impervious and non-erodible material. This does not mean that the developed area has no effect on watershed erosion. The effect of the developed area on watershed erosion is found in the upland channels that the runoff from the developed areas passes through.

The sediment loss from forested hillslopes as estimated by the WEPP model is significantly different from that predicted in the RTI (2008) report. In that report the sediment yield from the forested hillslopes was estimated with the WEPP 2006.5 model to be 0.32 tons/acre/year, while the present analysis with the WEPP 2010 model shows a value of 0.009 tons/acre/year. The publication by Patric et al. (1984) provides support for the estimate given in the present analysis. In their study Patric et al. examined sediment yield data from 812 forested plots and watersheds from areas around the United States. The majority of the reported sediment yields lie within the range of 0.01 to 1.0 tons/acre/year, with a few exceeding 1.0 tons/acres/year. About one-third of the locations had yields of less than 0.02 tons/acre/year, and three-fourths of all observations had yields less than 0.25 tons/acre/year. All the locations with higher sediment yields are located on the Pacific Coast. In another reference, Brooks et al. (1997), states that erosion from undisturbed forested areas rarely exceed 0.04 tons/ha/year (0.016 tons/acre/year). They state that as long as the soil is not exposed by disturbing/removing natural surface residue the erosion rates will remain low.

The erosion of upland channels can be a significant source of sediment. Runoff from the hillslope areas is concentrated into ephemeral channels and the resulting flows can produce significant erosion. To simulate this, the erosion properties of the upland channels were changed from those for rock to those for the native soil materials present in the area (soil map in Figure 11). The properties were the same properties assigned to those same soils for the hillslopes. Performing simulations with erodible upland channels resulted in a sediment load at the watershed outlet equal to 1,092 tons/year on a mean annual basis for the 5-year period. This result was obtained for the case with the grass cover on the ski slopes being short grass prairie with and LAI equal to 0.5. Comparing this to the value for the case of non-erodible upland channels (780 tons/year) the amount of sediment generated by the upland channels is predicted to be 312 tons/year.

Erodible soil surfaces are sensitive to the density of vegetative cover and to the amount of surface residue accumulated on the soil surface. Of course the higher the residue cover and the higher the LAI the better the vegetative cover will protect the soil from raindrop impact and overland flow shear stress. The model itself calculates the change of vegetative cover during the growing season using these input vegetative parameters. To examine the effect of higher vegetative density and higher accumulated surface residue the input parameters for the short prairie grass land cover condition on the ski slopes was modified. For these the LAI value was varied including values of 0.5, 2.0 and 4.0, and the initial accumulated surface residue was assumed to be 80%.

Table 2. Soil erosion values from WEPP simulation (5-year) for the Lower Poplar River Watershed.

Watershed Method (WEPP) – 5-year results				
Land use	Area Under Cover Type (acres)	Proportion of area under cover	Soil Loss (ton/ac/yr)	Soil Loss Rate (ton/yr)
Developed	30.0	0.030	0.0	0.0
Forest	743.4	0.739	0.006	6
Golf	85.8	0.085	0.07	6
Ski	146.5	0.146	3.92[&&]	575[&&]
Upland channels	--	--	--	312
Total	1005.7	1.000	1.08[&]	1,092

[&]Average rate

[&&]This value is for the case of short grass prairie cover with an LAI equal to 0.5. For tall grass prairie and LAI = 4.0 the erosion rate is 0.9 tons/ac/yr or 143 tons/year

The results of the simulation for these conditions are summarized in Figure 23. It is observed from this figure that the density of vegetative cover and the type of grass has a dramatic effect on erosion from the ski slopes. The resulting sediment contributions range from 575 tons/year for the case of short grass prairie (SGP) with a LAI of 0.5, to 143 tons/year for the case of tall grass prairie (TGP) with a LAI of 4.0. The LAI value directly affects the rate of biomass production and this directly affects the amount of accumulated residue on the soil surface. These results demonstrate the importance of vegetative cover density and accumulated residue on soil surface erosion resistance.

The length of a slope also has a strong impact on the generated sediment. To evaluate this effect the WEPP hillslope model was used to simulate the effect of shortening the effective length of one hillslope in the watershed. The hillslope selected has a slope angle of 35% and a slope length of 680 feet. The soil on the slope is mapped as Quetico, a shallow soil with bedrock close to the surface. The average solum (upper layers of soil profile) thickness is about 5 inches. The saturated hydraulic conductivity of the soil was assumed to be 4 inch/hour consistent with measurements reported by Hansen et al. (2010) for ski slopes. The vegetative cover was assumed to be short prairie grass with 80% initial accumulated residue and LAI of 0.5.

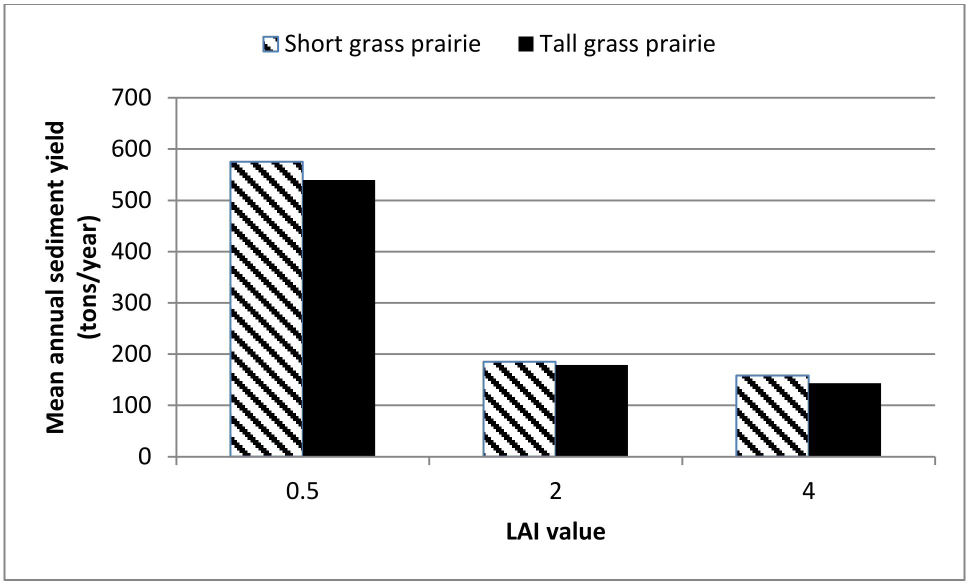

Figure 23. The cumulative mean annual sediment yield from ski slopes within the Lower Poplar River watershed as affected by the biomass growth potential of the plant as reflected by the leaf area index (LAI). Two vegetation classifications are considered, short grass prairie and tall grass prairie. The LAI values include 0.5, 2.0 and 4.0.

The mean annual sediment yielded to the base of the hillslope for the original slope length was 4.7 tons/year. Decreasing the slope length to 340 feet reduces this sediment yield to 0.3 tons/year, demonstrating the dramatic effect of slope length on erosion and sediment yield. The ski slopes at Lutsen Mountains ski area use water bars as a best management practice. 'Water bars' act like agricultural field terraces in shortening the effective overland flow length on hillslopes. Detailed information on the number, placement, and specific slope locations of these water bars was not available as input for the WEPP model developed here. However, this result shows the significance of the erosion reducing effect of water bars, assuming that they are functioning properly.

Effect of increased snow

During the period of monitoring there is a record that shows that artificial snow was added to nearly all ski slopes on the Lutsen mountain ski area including those lying outside the boundaries of the Lower Poplar River watershed. The average annual water use to provide this snow was reported by RTI (2008) as being about 70 million gallons. According to reports, this snow was added to about 214 acres of ski slopes, which would include those inside the Lower Poplar River watershed, and those lying outside the Lower Poplar. The equivalent depth of water associated with this volume of applied water is about 12 inches. It is expected that this additional snow will have some effect on the hydrology of the hillslopes; perhaps beneficial, perhaps detrimental. It is of interest to evaluate the effect of added snow on the winter hydrology and the runoff and sediment generated during the spring snowmelt period. The runoff produced from the Lower Poplar River watershed is assumed to be higher during the spring snowmelt period since the runoff from the whole watershed, as reflected at the gauging station, is highest during that period. The effect of snow added to the ski slopes was evaluated using a single hillslope since the current version of the WEPP model does not allow a different amount of precipitation to be added to different hillslope areas.

The hillslope selected has the same parameters as the one used in the previous section to demonstrate the effect of the hillslope effective length. Vegetative cover was varied in the same manner as that in that last section where the LAI value was used to represent the vegetative cover, and accumulated surface residue was varied. Both short grass prairie and tall grass prairie vegetation types were considered in the analysis.

The climate data input to the model was the same as that described in the **Climate input data** section. To account for artificial snow applications the precipitation in the weather input file was augmented with added precipitation on days when the air temperature was below zero degrees thereby producing snow in the model. The amount of water applied to the modeled hillslope in the form of artificial snow on given dates was based on actual monthly water withdrawal records (provided by Randall Doneen, MNDNR) for the five-year period. The amount of water added to the modeled slope was varied, including values of 0 inches, 10.8 inches, 20.9 inches and 31.5 inches, to examine the effect of different amounts of added snow in the model. The amount of 10.8 inches is close to the figure for the amount of water added each year during the past decade (70 million gallons on average), while the other figures are associated with increased proposed allocations (up to 225 million gallons, personal communication Randall Doneen, MNDNR).

One limitation of the WEPP 2010 model is that it assumes that snow formed (natural or artificial) has a 10% water equivalent. Actually artificial snow is closer to a 50% water equivalent value (and natural snow is not always at 10% either). Due to this lower snow density assigned by the model, the artificial snow represented in the model will simulate deeper snowpacks than would actually occur on a managed ski slope, an effect that will insulate the soil more and thereby reduce soil freezing in the model predictions. This will have the effect to predict potentially reduced surface runoff. Thus the sediment yields presented might be underestimated compared to what would actually occur. However, the trend in the effect of vegetative cover and slope length on sediment yield will not be affected by this snow density assumption.

The results of the simulations are summarized in Table 3. In general, the amount of sediment yielded by the hillslope increases as the amount of artificial snow applied increases. It is also observed that in general as the vegetative cover increases the sediment yield decreases.

The reduction of slope length dramatically decreases the sediment yield for all cases of added artificial snow. It is interesting however that the trend for sediment yield for the shorter slope counters that for the longer slope. Examination of the detailed runoff simulated for this case of a shorter hillslope showed that the amount of runoff in non-winter season decreases as the depth of added snow increases. This might be explained by the following two phenomena. First, the deeper snow will reduce soil freezing and thereby offer increased opportunity for deep percolation loss through the slowly permeable bedrock base. Second, the lateral flow that occurs will be greater for the longer hillslope, leading to higher saturation and greater runoff potential at the footslope position. Reducing the slope length reduces the lateral flow and the footslope saturation, thereby reducing runoff potential.

It is clear from these simulated results that it is greatly beneficial to increase the vegetative cover (short grass prairie or tall grass prairie) for a slope, and it is also very beneficial to reduce the slope length.

Table 3. Mean annual sediment (tons/acre/year) delivered to the toe of the hillslope for various conditions of added artificial snow (given as depth of snow water equivalent), vegetative cover, and slope length. The vegetative cover is expressed by type, either short grass prairie (SGP) or tall grass prairie (TGP) and by leaf area index (LAI). The slope length used for nearly all of the calculations was 680 feet.

Vegetative cover; Type, LAI	Snow water equivalent of artificial snow (inches)			
	0	10.8	20.9	31.5
SGP, 0.5	3.0	5.0	12.6	53.8
SGP, 2.0	0.32	0.97	1.3	3.5
SGP, 4.0	0.22	1.3	0.96	2.3
TGP, 0.5	2.7	4.6	11.2	47.3
TGP, 2.0	0.27	0.93	1.0	2.8
TGP, 4.0	0.23	0.86	0.77	1.93
SGP, 0.5 with half slope length (340 feet)	0.96	0.5	0.3	0.08

<u>Surface erosion generated from slumps</u>

To simulate the sediment originating from the slumps the hillslope option for the WEPP model was used. The watershed option was not necessary because the slumps exist next to the main channel and a tributary channel is not needed to deliver eroded sediment to the river.

The total area of the slumps identified in the Lower Poplar River watershed was estimated from field surveys (Hansen et al., 2010). The area was estimated to be 4.6 acres. The average slope of the slumps is approximately 70%. The slumps were treated as having saturated hydraulic conductivities of about 12 mm/hour, and were considered to be bare most of the year. Application of the WEPP model to the slumps yielded a sediment load of 61.7 tons/acre/year or 284 tons per year entering the main stem of the Poplar River.

Sediment contribution from other sources

Besides the obvious sediment sources from the forested areas, the ski slopes, the golf course, and the developed areas there is also the possible sources related to roads, ATV and pedestrian trails, ravines, gullies and mass wasting from slumps. The WEPP model is not able to predict the erosion from these sources, except maybe for roads and ATV trails and pedestrian trails. Instead of using the WEPP model for the roads and trails a method developed by Rosgen (2007) was applied. Estimates of erosion from all of these remaining sources will now be presented.

Sediment contribution by roads

The placement of roads across a landscape can significantly modify the natural flow pathways by concentrating overland flow into rills and ephemeral channels, thereby increasing the erosion potential of runoff events. Roads have this effect by focusing overland flow or subsurface flow from upslope areas into ditches and the ditches then convey this concentrated flow to culverts. This concentration of flow has a way of increasing the drainage density of a watershed, leading to more flashiness of flows and increasing erosion during runoff events. Unpaved roads are also a source of sediment, and the ditches and sideslopes associated with a road (paved or unpaved) are also a source of sediment when the soil is not sufficiently vegetated. In addition, when a road is placed across an existing stream channel, the change in local hydraulics can lead to instability of the channel upstream and/or downstream of the crossing, meaning that the transported sediment will increase. The processes of sediment production from roads are quite complicated due to the unlimited number of different geometric conditions that could be considered. A method that makes the estimation of sediment production from roads is presented by Rosgen (2007). The method is referred to as the Road Impact Index (RII) method. The contribution of roads to sediment yield in the Lower Poplar River was estimated using the RII equations presented by Rosgen. These equations are,

$$SY = 1.7 + 40 * RII \quad ; \quad \text{for road with lower slope position} \qquad (1)$$

$$SY = -0.1595 + 3.0913 * RII \quad ; \quad \text{for roads with mid or upper 1/3 slope position} \qquad (2)$$

where SY is the sediment yield in tons from the road per year per acre of road, and RII is the road impact index. The road impact index is determined based on the following factors:

- Acres of subwatershed containing the road segment of interest;
- Within the subwatershed the acres of surface disturbance of roads including road surface, cut, fill and ditch line;
- Within the watershed the number of stream crossings by the road;
- Position of the road (lower, medium, upper) on the slope relative to stream location;

- Slope of the road;
- Age of the road;
- Mitigation such as road surfacing, ditch lining (e.g., vegetation, paving, armoring, etc.);
- Vegetative cover of cut banks and road fills;
- Presence of unstable terrain associated with mass erosion processes.

Data with parameters from the above list for a particular road are entered into a worksheet (Rosgen, 2007) and the RII value is calculated. Field measurements of roads were conducted in the summer/fall 2009 as reported in Hansen et al. (2010). The total area of road surface, including the ditches and cut banks was estimated to be just less than 18 acres. Most of this area was found to be in middle or upper level positions in the landscape. Data corresponding to the list outlined above was entered and the RII values calculated along with the estimated annual sediment load. The summarized results are presented in Table 4. The total estimated annual sediment load from roads in the Lower Poplar River watershed is 35.3 tons.

Table 4. Road impact index (RII)

Position in watershed	Sub-watershed acres	Acres of roads	Number of crossings	Road Impact Index	Tons/ acre	Annual load Tons
Lower	25	2.27	3	0.27	12.6	28.59
Mid to Upper 1/3	249	15.7	3	0.19	0.42	6.66

<u>River channel/banks</u>

Geomorphic assessment of the condition of the river channel showed that the channel bottom and the channel banks are armored with large rock and cobble materials. While high flows can move large rocks downstream it seems from observations that the river will not downcut at a significant rate. The armoring protects the erodible material composing the channel bottom from direct impact from flowing water and this reduces the potential for detachment of soil particles from the bottom material. While the critical shear stress and the erodibility coefficient for the channel bottom material might be equal to that for the upland soils, the boundary shear stress imposed on the material is drastically reduced due to the armoring of the surface provided by the deposited cobbles and boulders in the channel. The suspended sediment load originating from the river channel and channel banks was therefore considered to be negligible in comparison to other sources.

Mass wasting at slumps

The estimates for erosion and sediment yield due to overland flow on slumps as derived from WEPP modeling were given in the first section along with a map showing the locations of the identified slumps (Figure 12). The issue arises whether sediment production from the slumps might be occurring at the sites along the Lower Poplar River as a result of mass wasting processes. Mass wasting processes along a river will be operative if the river abuts up against the toe of the slumps, thereby removing wasted materials and effectively steepening the slope of the slump. Such a process occurs at slumping bluffs along the Minnesota River and many of its tributaries, e.g., the Blue Earth River (Sekely et al., 2004). For the Lower Poplar River the toes of two of the slumps did abut up against the river bank during the time prior to the repair of the megaslump. These were the megaslump and one other slump upstream of the megaslump near the location of the Brule ravine.

The regression equation developed by Sekely et al. (2002) for estimating mass wasting from slumps is given by

$$SY = 0.23\ A_b \qquad (3)$$

where SY is the sediment yield to the river (tons/year) and A_b is the exposed surface area of the bluff in m^2. The megaslump was estimated to have an exposed surface area of 2.02 acres, or 8178 m^2. Applying this area to equation (3) would give a sediment yield for the megaslump of 1,881 tons/year. This estimate of sediment yield does not seem to be credible since the mean annual sediment load is 1,354 tons/year. In the study reported by Hansen et al. (2010) a hydrologic analysis was conducted to determine estimates of the frequency of occurrence of flood flows in the Lower Poplar River. Then a HEC-RAS model was developed for the entire Lower Poplar River channel starting at the downstream station and ending at the upstream station. Using the hydraulic model to compute water surface profiles in the river for various frequency flows it was possible to relate water surface elevation at selected cross-sections to the discharge and frequency of occurrence of those flows. It was also possible to then determine the elevation required to overtop the rock-protected river banks and potentially access sediment deposited at the toes of slumps.

The flow elevation-flow frequency curves, and present-day channel cross-sections are all presented in the report by Hansen et al. (2010). According to the flow elevation-flow frequency analysis it is clear that the river remains inside the armored channel for all flow less than about the 5-year return period event for most of the channel locations. We would therefore not expect that the toes of slumps near those locations to be affected by out-of-bank flows. However, according to the RTI report (RTI, 2008) prior to the channel repair work completed in 2008 the megaslump and the other slump near the Brule ravine had toes within the near bankfull flow stage, thereby making those slumps susceptible to erosion at the toe. However, the condition is not the same as the slumps associated with the development of the empirical relation given by equation (3). According to the flow records during the monitoring period the daily mean flows never exceeded about 750 cfs in any given year, and those flows occurred only briefly during what appears to be the spring snowmelt period. Unlike the conditions in the Blue Earth River where within the last two decades high flows have been sustained over long periods of time, the high flows in the Poplar River are very short duration. To account for the short duration of the flow it would make sense to reduce the load of 1,881 tons/year to only a fraction of that number. Here we use an amount equal to 10% of the value or 188 tons/year.

The restoration work on the megaslump in 2008 puts the toe of the megaslump well above the elevation of the mean annual flow in the channel. According to the analysis presented in Hansen et al. (2010) the elevation of the toe for the restored system requires a flow of greater than the 100-year event to reach the toe. Based on field surveyed cross-sections reported by Hansen et al. (2010) and RTI (2008), and the record of high flows in the Poplar River it is estimated that to reach the toes of those other slumps requires a flow close to the 5-year flow event. This flow is estimated to be 1,189 cfs (Hansen et al., 2010). Therefore for the present conditions, mass wasting processes should not be a source of sediment from the megaslump area and other slump areas on a mean annual basis.

Ravines

Ravines are defined by Wikipedia (http://en.wikipedia.org/wiki/Ravine) as *"A **ravine** is a landform narrower than a canyon and is often the product of streamcutting erosion. Ravines are typically classified as larger in scale than gullies, although smaller than valleys. A ravine is generally a fluvial slope landform of relatively steep (cross-sectional) sides, on the order of twenty to seventy percent in gradient. Ravines may or may not have active streams flowing along the downslope channel which originally formed them; moreover, often they are characterized by intermittent streams, since their geographic scale may not be sufficiently large to support a perennial watercourse".* Several ravines exist within the Lower Poplar River watershed. The locations and paths of the major ravines identified by Hansen et al. (2010) and by NAWE (2003) and RTI (2008) are shown in Figure 24. Measurements of these ravines by Hansen et al. provided the ravine morphological characteristics summarized in Table 5.

Table 5. Morphological characteristics of major ravines within the Lower Poplar River watershed.

Ravine	Contributing area (acres)	Length (ft)	Mean longitudinal slope (%)	Mean cross-section (ft^2)	Sediment Produced (tons)
Ullr	4.6[&]	380	44	280	5,586
Brule	155[#]	200	47	188	1,974
Moose Mountain	232	3,500	10	44	8,085

[&]Some runoff from Brule had been diverted to this ravine making the effective contributing area about 22 acres.
[#]The installation of a tightline to bypass the ravine has reduced the contributing area to the ravine.

The ravine designated as the Brule ravine previously received runoff from the ski slopes on Eagle Mountain and also from the building/parking complex around the ski lodge and ticketing office. A diversion was constructed in 2006 to divert this runoff and bypass this ravine. The diversion is in the form of a runoff collection structure and a buried pipeline (tightline). Since the construction of this diversion, and the seeding of the ravine itself, the Brule ravine has been revegetating and erosion from the ravine drastically reduced. The contributing area for the Ullr ravine is measured to be about 4.6 acres, but accounting for the effect of the development in the ski complex to the northeast of the ravine the effective contributing area of the ravine is estimated to be about 22 acres. The Ullr ravine is an actively developing ravine and is a source of sediment. It is not clear over what time the Ullr ravine and the Brule ravine developed. These ravines might have existed prior to the development of the Ullr Mountain and the Eagle Mountain ski facilities. It is very clear that the two ravines have been actively growing in the last decade or two, maybe longer. In contrast, the Moose Mountain ravine appears to be a natural feature as it shows up clearly on the survey map for the 1860 survey. The fact that the entire contributing area of the Moose Mountain ravine is forested points to the fact that natural conditions are promoting further ravine development. There might however be some human impacts due to the access road that crosses the ravine contributing area. The estimated amount of sediment produced in the development of each of these ravines is presented in the last column of Table 5. The estimate was determined by first estimating the volume of each of the ravines using the length and mean cross-sectional area, and then applying an assumed dry bulk density of 105 lb/ft^3 for the eroded material. The total amount of sediment for the three ravines is 15,645 tons. For the two ravines assumed to be formed more recently, Ullr and Brule the total amount of sediment is 7,560 tons. If it is assumed that these two ravines formed during the last forty years following the heavier development of the ski slopes on Ullr and Eagle mountains the mean annual load from the ravines is 189/year. It is not clear what rate the sediment might be produced by the Moose Mountain ravine because the fact that is has existed prior to the 1860's. If one considers only the period from 1860 to present, a period of 150 years, the mean sediment production rate for the Moose Mountain ravine would be about 54 tons/year. Combining the estimated sediment production rates for the three ravines the total is 243 tons/year.

Other concentrated flow pathways

The development of ski runs, walking trails, and access roads within the Lower Poplar River watershed has led to the formation of concentrated flow pathways along which erosion potential is significantly increased. During the field reconnaissance surveys reported by Hansen et al. (2010) the location of these pathways was clearly manifested by the presence of gully formation. Unchecked, these concentrated flow pathways could develop into larger sized erosion features like the Ullr and Brule ravines. The major concentrated flow pathways discovered during the field reconnaissance work are identified by location on the map presented in Figure 25. Estimates of erosion from the concentrated flow pathways were not derived in this study. Since those pathways are much like gullies, their sediment production rates might be on the order of those for other Upper Midwest areas, about 12 tons/acre/year. The surface area of the gullies along these flow pathways was not measured so at this time this erosion rate cannot be converted to a total load from that source.

Figure 24. Illustration of the location of major ravines in the Lower Poplar River watershed. (a). Ullr ravine; (b). Brule ravine; (c). Moose Mountain ravine. Image is by courtesy of Google Maps.

Figure 25. Illustration of the location of major pathways of concentrated flow in the landscape of the Lower Poplar River watershed. These flow pathways show evidence of excessive soil erosion in the form of gullies. (a). White Birch pathway; (b). Caribou Highlands pathway; (c). Lower Meadow pathway. Image is by courtesy of Google Maps.

Summary and comparison of estimated sediment loads

The total sediment delivery from the various landscape features in the Lower Poplar River watershed for the NAWE study (NAWE, 2003), the RTI study (RTI, 2008) and the present study are listed in Table 6. The NAWE study considered only the area near the river and this would be one reason for the differences with the other two studies (RTI and UofM). These figures can be compared to the estimate of sediment load derived from the monitoring data. The mean sediment load at the outlet of the Lower Poplar River watershed was estimated from flow records and total suspended solids concentrations to be 1,354 tons/year (+/- 270 tons/year, or a range of 1,084 tons/year to 1,624 tons/year) for the period 2001 to 2005 by RTI (2008). The median estimate of mean annual sediment load given by the RTI study is 1,985 tons/year, with a range of 986 tons/year to 2,983 tons/year. The figure given by the UofM study provides a mean annual sediment yield ranging from 938 tons to 1,370 tons.

Table 6. Summary of sediment deliver estimates for various sediment sources in the Lower Poplar River watershed for three studies.

Sediment Source	NAWE (tons/yr)	RTI (tons/ac/yr)	RTI (tons/yr)	UofM (tons/ac/yr)	UofM (tons/yr)
Developed	179	0.8	25	0[&]	0[&]
Forest		0.32	280	0.006[&]	5[&]
Golf		0.25	15	0.07[&]	6[&]
Ski		4.03	661	0.98 – 3.93[&]	143 - 575[&]
Roads		--	--	0.72[**]	35[**]
Ravines	--	--	225[##]	--	243[##]
Slumps, overland flow erosion		--	48[&&&]	61.7[&&&&]	284[&&&&]
Slumps, mass wasting			726[&&]	27.7[###]	188[###]
Channel incision		--	53	0	0
Upland channels	--	--	--	--	312[&]
Total		N/A	1,985[%]	N/A	938 – 1,370

[&]Estimated with WEPP watershed model (version 2010)
[&&] Estimated using photos and field observations
[&&&]Estimated using WEPP hillslope model (version 2006.5)
[&&&&]Estimated with WEPP hillslope model (version 2010)
[**]Estimated with Rosgen (2007) roads model
[##] Prior to ravine erosion control work.
[###]Estimated from the empirical model of Sekely et al. (2002)
[%]Median estimated total; the range was 986 – 2,983 tons/yr
RTI upland sources estimated with WEPP watershed model (version 2006.5)

The differences between the RTI and UofM numbers are likely the result of various factors. The UofM modeling incorporated the climate data and time period used by RTI to minimize the potential for differences. The RTI modeling was completed without some of the detailed field measurements made by the UofM. The field measurements enabled the UofM to provide a more complete inventory of the ravines and other flow paths for the model, a separate estimate of sediment from roads and upland channels, an improved estimate of the sheet erosion from slumps, and refined model inputs to address runoff processes. The field work helped to validate and/or improve the modeling assumptions made in the previous studies, especially in terms of infiltration and soil critical shear resistance to erosion. The WEPP model produced by the UofM study is more detailed than the model produced in the RTI study. The new modeling also provided the opportunity to examine the influence of the effective length of ski slopes and the effect of vegetation density on estimated sediment yield from ski slopes.

The modeling showed that the use of water bars on a ski slope to divert accumulating runoff from the slope, shortens the effective length of the ski slope with respect to erosion processes, and thereby significantly reduces the amount of erosion. Additional work is needed to map the water bars on the ski slopes to determine the effect of this existing conservation practice on the cumulative load of sediment from the ski slopes within the watershed.

The modeling also showed that by enhancing vegetation stands on the ski slopes, the covering of the soil with live biomass and residue will increase, thereby significantly reducing erosion from the ski slopes. Additional work is needed to better characterize the temporal and spatial distributions of vegetation stands on the ski slope areas. It is important to know how much biomass (live, dormant and dead) is present on the ski slopes at times of the year when snow cover is not present. The modeling showed that when vegetation density and surface residue is consistently high, the erosion rate will be very low.

Neither the RTI or UofM estimates of sediment yield to the Poplar River exactly matched the monitored estimated suspended solids load, but both estimates are reasonably close. For nearly every load source category (forest, ski slopes, golf course, etc.) the UofM estimates of load are less than those given by the RTI study, and the sum total of loads from the UofM estimates is closer to the monitored estimated load than that for the RTI study. This improvement in matching of observations is attributed to the refined model inputs in the UofM modeling allowing a better characterization of the runoff generation, soil erosion, and sediment transport processes occurring in the watershed.

Conclusion

The Poplar River is one of four priority areas designated by the Great Lakes Commission as eligible for their erosion and sediment reduction grants under the Great Lakes Restoration Initiative. The detailed field reconnaissance and data analysis reported by Hansen et al. (2010) and the more detailed WEPP modeling presented in this report provide an in-depth evaluation of the sources and processes of sediment erosion in the lower Poplar River watershed. The work by the University of Minnesota allowed a unique exploration of the hydrology and erosion processes affecting the Poplar River in the development of a turbidity TMDL and ensuing implementation plan for the river. The work was warranted given anticipated future development in the watershed, the significance of the area to the local community and regionally, and the broader impact to Lake Superior.

The WEPP model estimates of sheet and rill erosion, and open channel flow erosion in the upland areas, along with estimates of sediment generated from established ravines, roads, and slumps add up to a value similar to estimates based on monitored stream flow and turbidity during the period 2002 to 2005. The study indicates that the primary sources of sediment in the lower Poplar River watershed include sheet and rill erosion from the ski runs, ephemeral upland channel and ravine erosion, and mass wasting from slumps.

Ski slopes are a potentially significant source of sediment in watersheds due to their high slope angle and large length. One method to reduce erosion from the ski slopes is to reduce the effective length of the slopes. As demonstrated by the simulations with the WEPP 2010 model presented in this report, reducing the effective length of a slope dramatically reduces the soil erosion from the slope. Water bars have been constructed into the ski slopes at Lutsen to cause this effect. Locations of these water bars were not mapped during the field study reported by RTI (2008) or by Hansen et al. (2010). To fully account for the cumulative beneficial effect of these water bars on erosion reduction from the ski slopes it will be necessary to map the locations of the water bars. It is recommended that such a map be produced.

A second method for reducing erosion from ski slopes is to manage the vegetation on the slope to promote high biomass production. Increased live standing vegetation, and high cumulative surface residue, has a dramatic effect on the reduction of sediment production from steep and long slopes, as demonstrated by the simulations with the WEPP 2010 model presented in this report. Detailed measurements of vegetation density were not conducted by RTI (2008) or Hansen et al. (2010) although many photographs of the vegetation were acquired. Those photographs illustrated that there is a wide variation in soil cover provided by the standing vegetation and the cumulated residue. To better characterize the spatial distribution of live standing vegetation and residue cover on the ski slopes surveys should be conducted during at least one complete season. Such a survey would provide quantitative information on how the standing vegetation and residue cover vary from the time of snowmelt until first snowfall.

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Appendix A. Bedrock geology of the Lower Poplar River watershed.

A bedrock map for the Lutsen area is available as a bedrock quadrangle map produced by Boerboom et al. (2007), and is attached here in the next page.

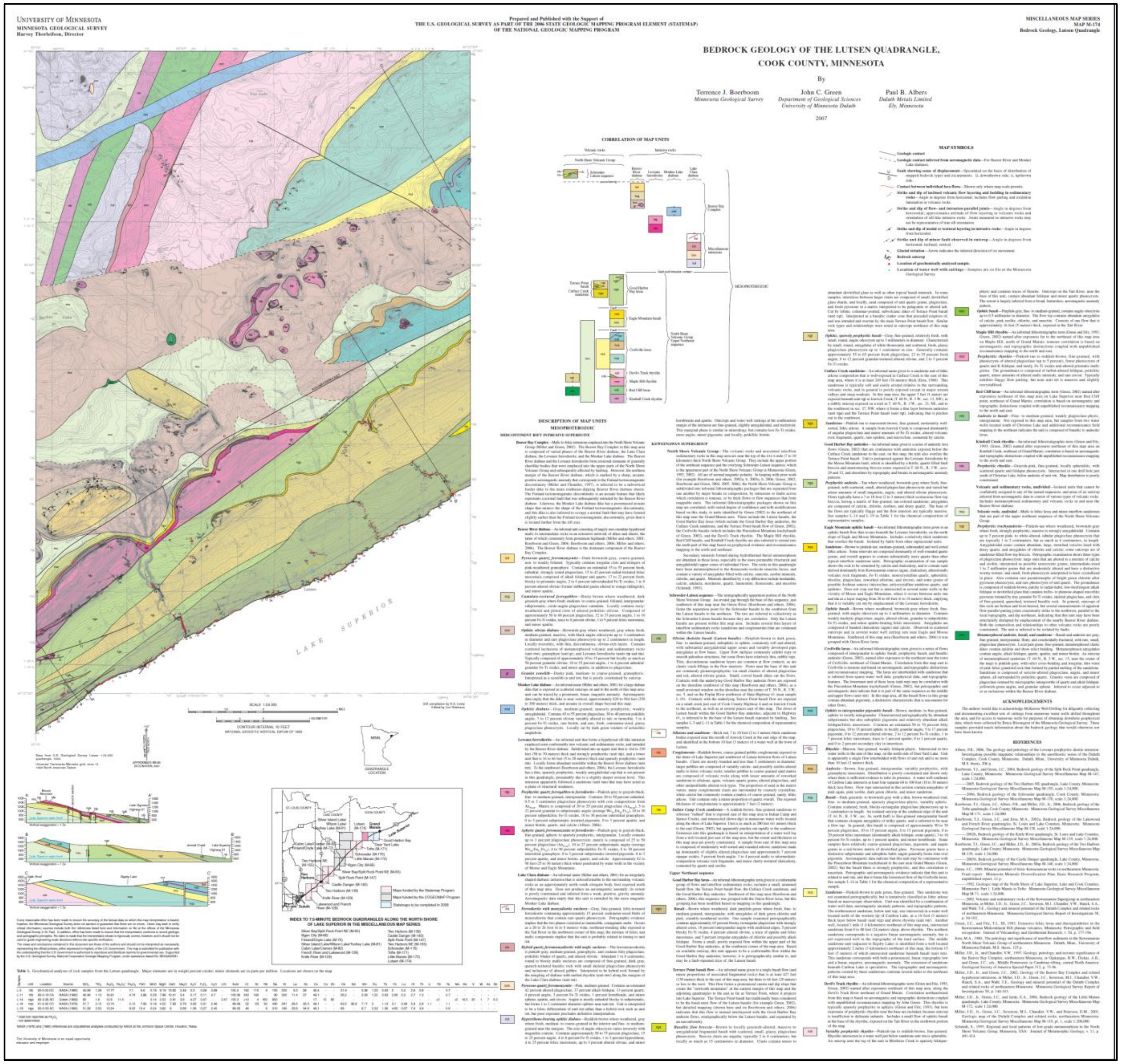


Figure A.1. Bedrock geology map of the Lower Poplar River.

Figure A.2. Map showing location of drilling logs in the Lower Poplar River watershed. These logs are available from the Minnesota Geological Survey.

Appendix B. Vegetative cover inputs

The inputs for the WEPP model for vegetative cover parameters are presented in the form of screen shots for short grass prairie and for tall grass prairie. The input parameters are mainly related to the process of biomass production and to the correlated vegetative cover in the form of live vegetative cover and flat residue. The definitions of these terms are given in Arnold et al. (1995).

For both the short grass prairie and the tall grass prairie, the cases shown are where the initial residue cover is 80% and the maximum leaf area index is 4.0. It should be noted that within the first year of simulation the residue cover condition reaches a quasi-equilibrium condition. For the short grass prairie the quasi-equilibrium value is about 95% cover for the residue cover for the case with LAI equal to 4.0, while it is about 41% for the case with LAI equal to 0.5. The quasi-equilibrium values are slightly higher for both cases for the tall grass prairie. Figure B.1 illustrates the temporal variation in LAI and Figure B.2 provides an illustration of the temporal variation in residue cover.

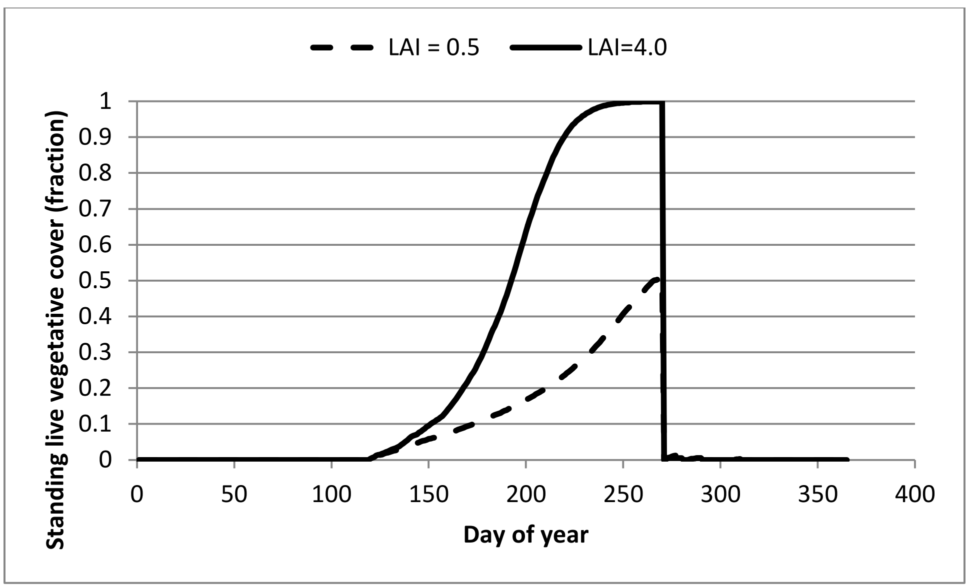


Figure B.1. Variation of surface cover provided by standing vegetation for two cases of maximum leaf area index, 0.5 and 4.0. Both of these cases are for short grass prairie.

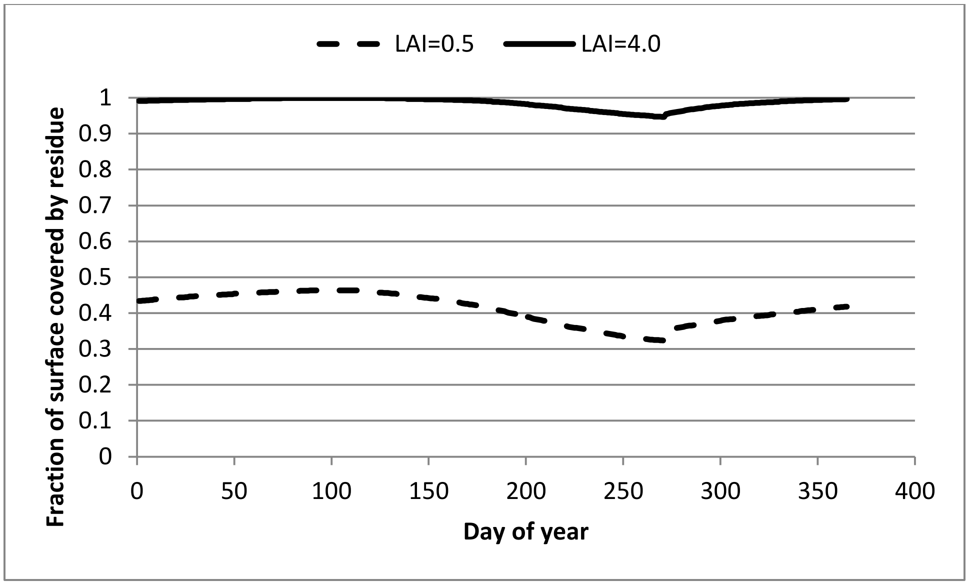
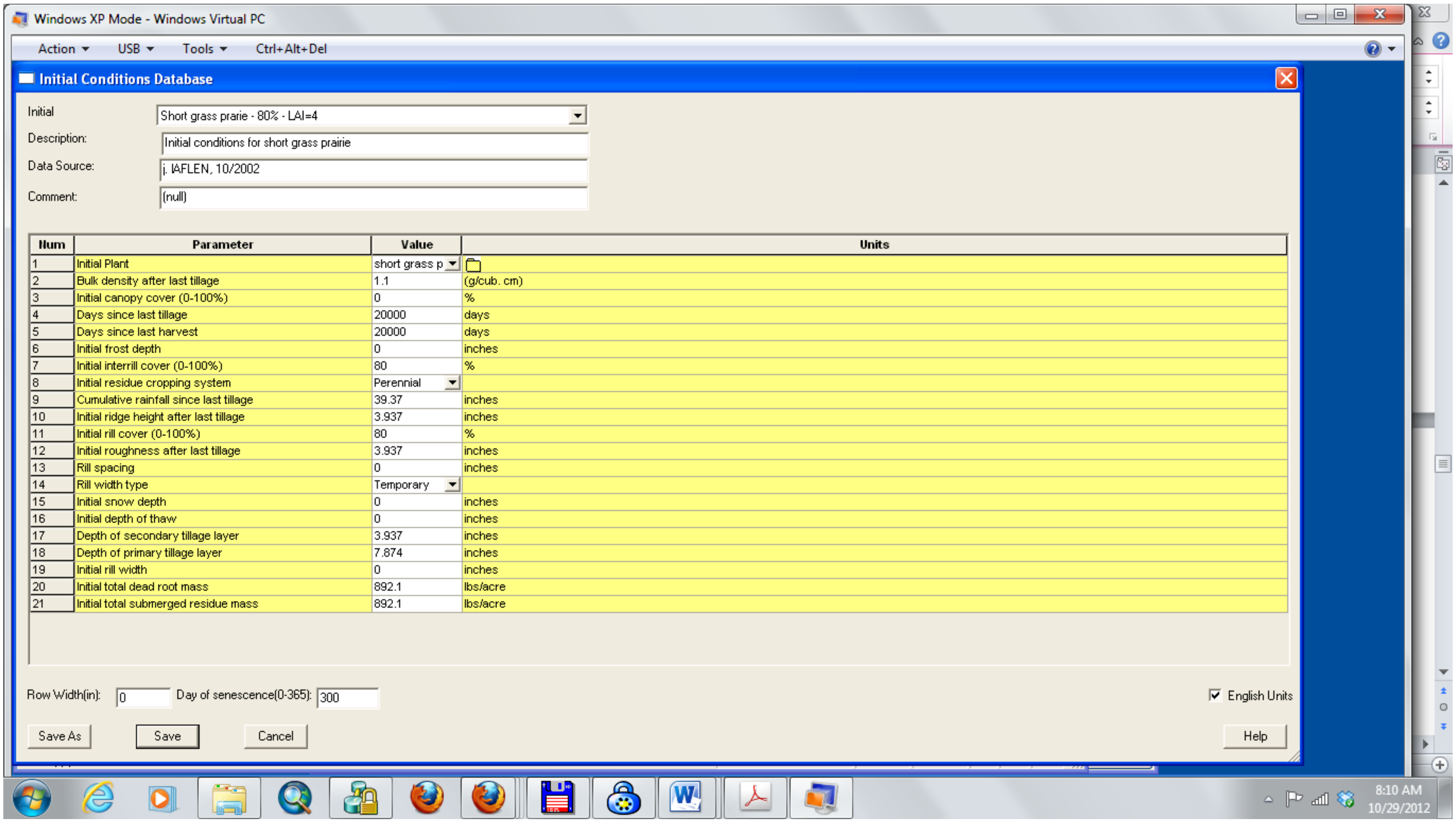
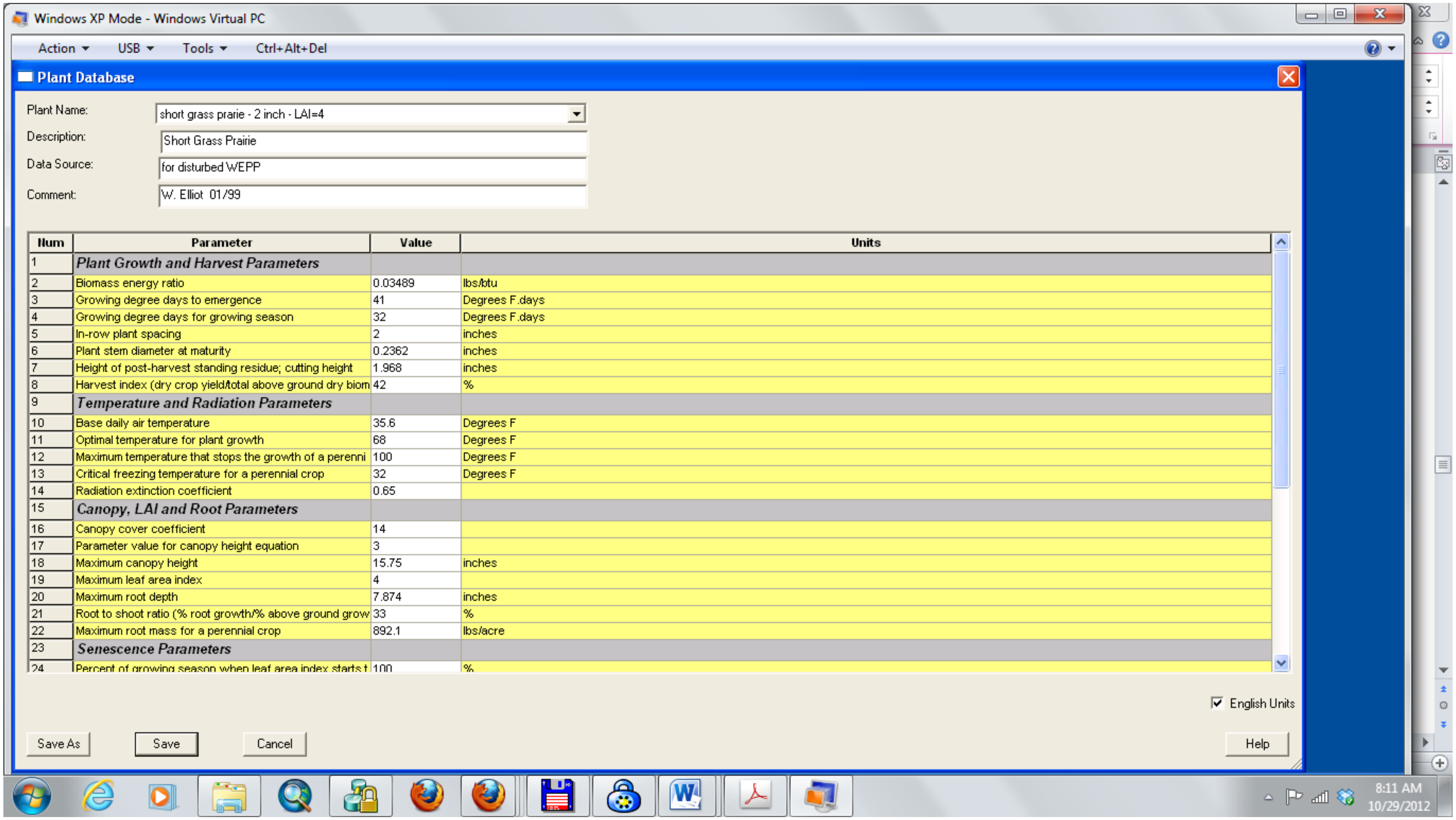


Figure B.2. Variation of surface cover provided by plant residue for two cases of maximum leaf area index, 0.5 and 4.0. Both of these cases are for short grass prairie.

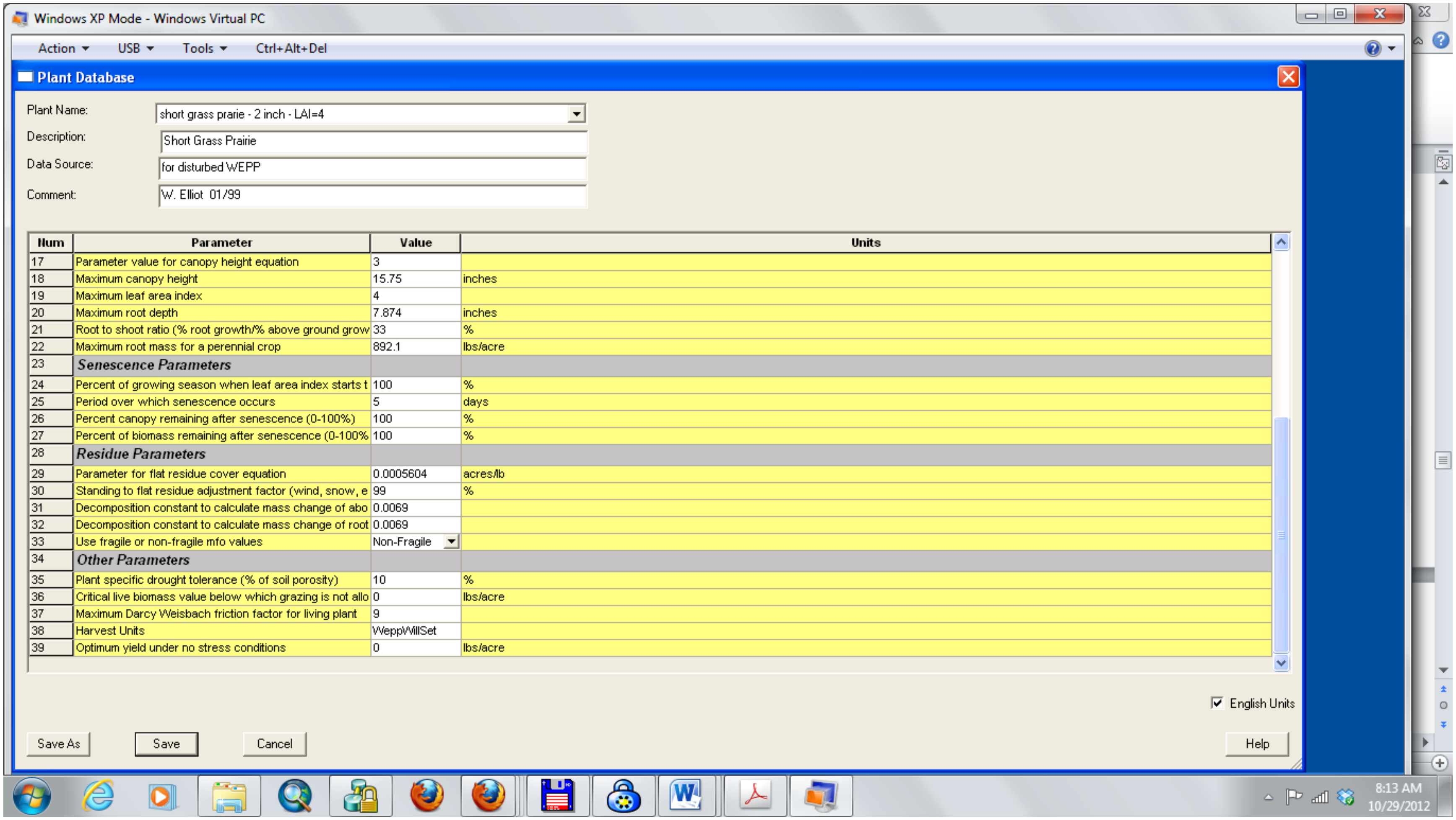
Screen shots for short grass prairie



Num	Parameter	Value	Units
1	Initial Plant	short grass p	
2	Bulk density after last tillage	1.1	(g/cub. cm)
3	Initial canopy cover (0-100%)	0	%
4	Days since last tillage	20000	days
5	Days since last harvest	20000	days
6	Initial frost depth	0	inches
7	Initial interrill cover (0-100%)	80	%
8	Initial residue cropping system	Perennial	
9	Cumulative rainfall since last tillage	39.37	inches
10	Initial ridge height after last tillage	3.937	inches
11	Initial rill cover (0-100%)	80	%
12	Initial roughness after last tillage	3.937	inches
13	Rill spacing	0	inches
14	Rill width type	Temporary	
15	Initial snow depth	0	inches
16	Initial depth of thaw	0	inches
17	Depth of secondary tillage layer	3.937	inches
18	Depth of primary tillage layer	7.874	inches
19	Initial rill width	0	inches
20	Initial total dead root mass	892.1	lbs/acre
21	Initial total submerged residue mass	892.1	lbs/acre

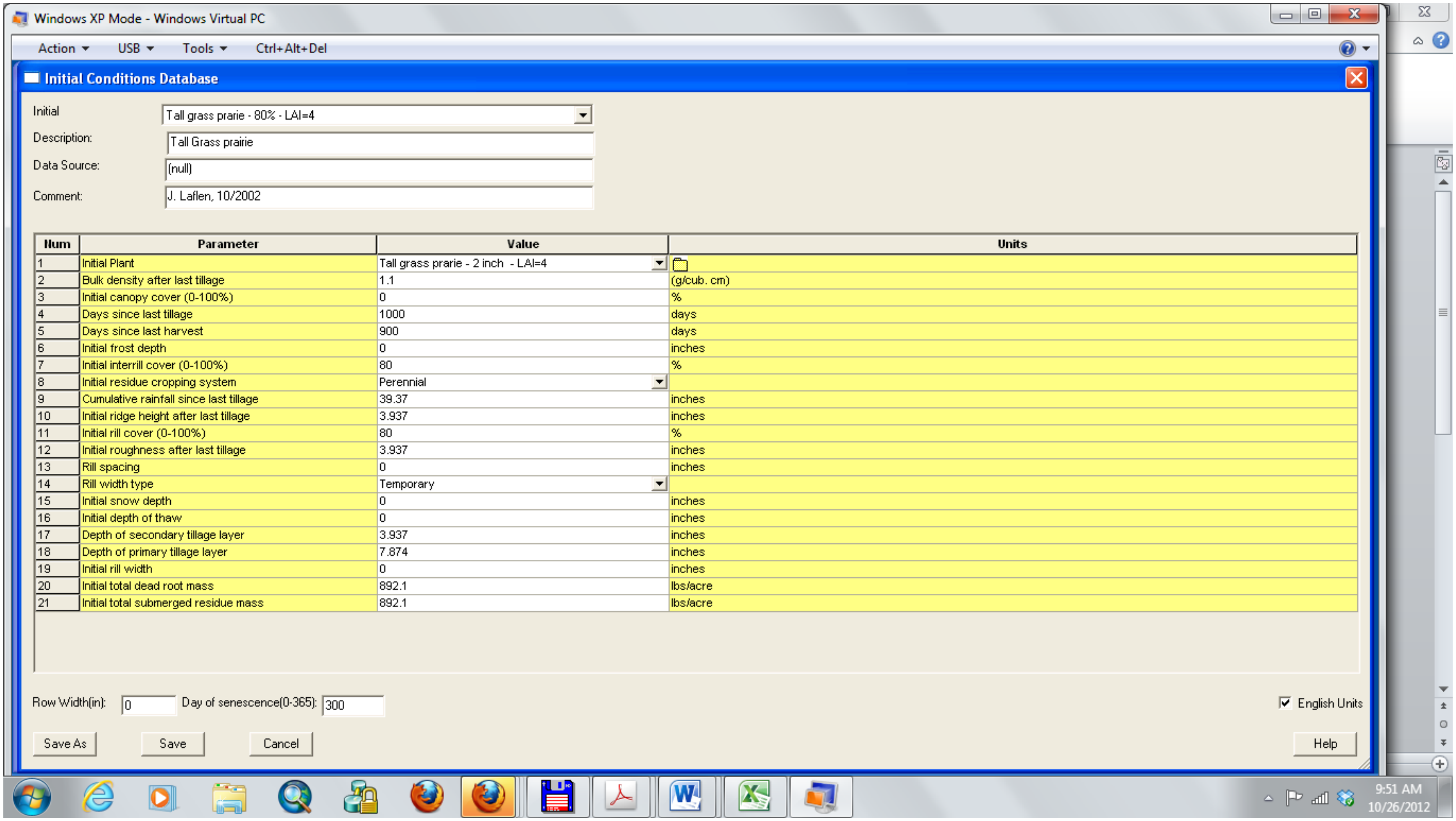


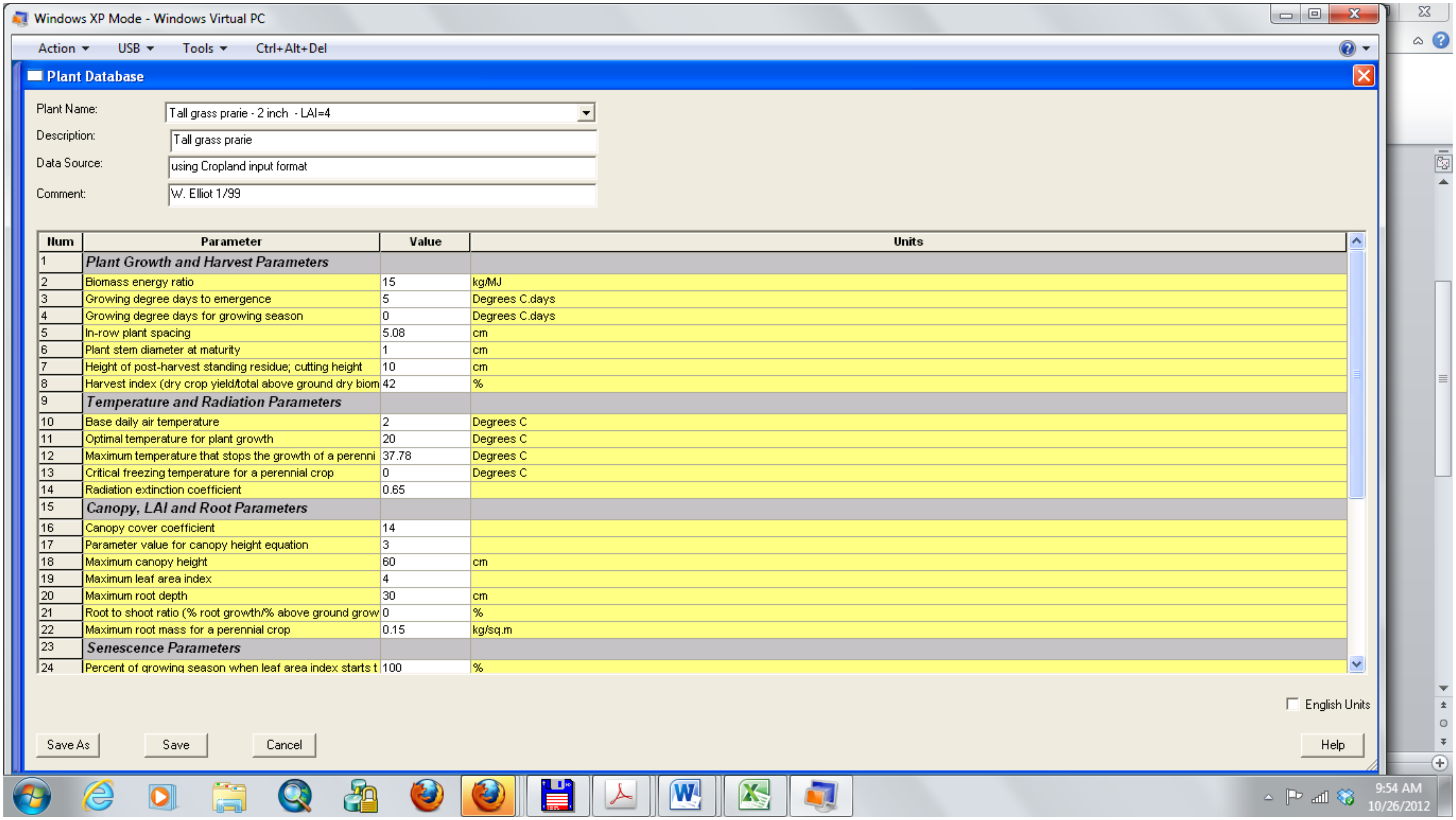
Num	Parameter	Value	Units
1	*Plant Growth and Harvest Parameters*		
2	Biomass energy ratio	0.03489	lbs/btu
3	Growing degree days to emergence	41	Degrees F.days
4	Growing degree days for growing season	32	Degrees F.days
5	In-row plant spacing	2	inches
6	Plant stem diameter at maturity	0.2362	inches
7	Height of post-harvest standing residue; cutting height	1.968	inches
8	Harvest index (dry crop yield/total above ground dry biom	42	%
9	*Temperature and Radiation Parameters*		
10	Base daily air temperature	35.6	Degrees F
11	Optimal temperature for plant growth	68	Degrees F
12	Maximum temperature that stops the growth of a perenni	100	Degrees F
13	Critical freezing temperature for a perennial crop	32	Degrees F
14	Radiation extinction coefficient	0.65	
15	*Canopy, LAI and Root Parameters*		
16	Canopy cover coefficient	14	
17	Parameter value for canopy height equation	3	
18	Maximum canopy height	15.75	inches
19	Maximum leaf area index	4	
20	Maximum root depth	7.874	inches
21	Root to shoot ratio (% root growth/% above ground grow	33	%
22	Maximum root mass for a perennial crop	892.1	lbs/acre
23	*Senescence Parameters*		
24	Percent of growing season when leaf area index starts t	100	%



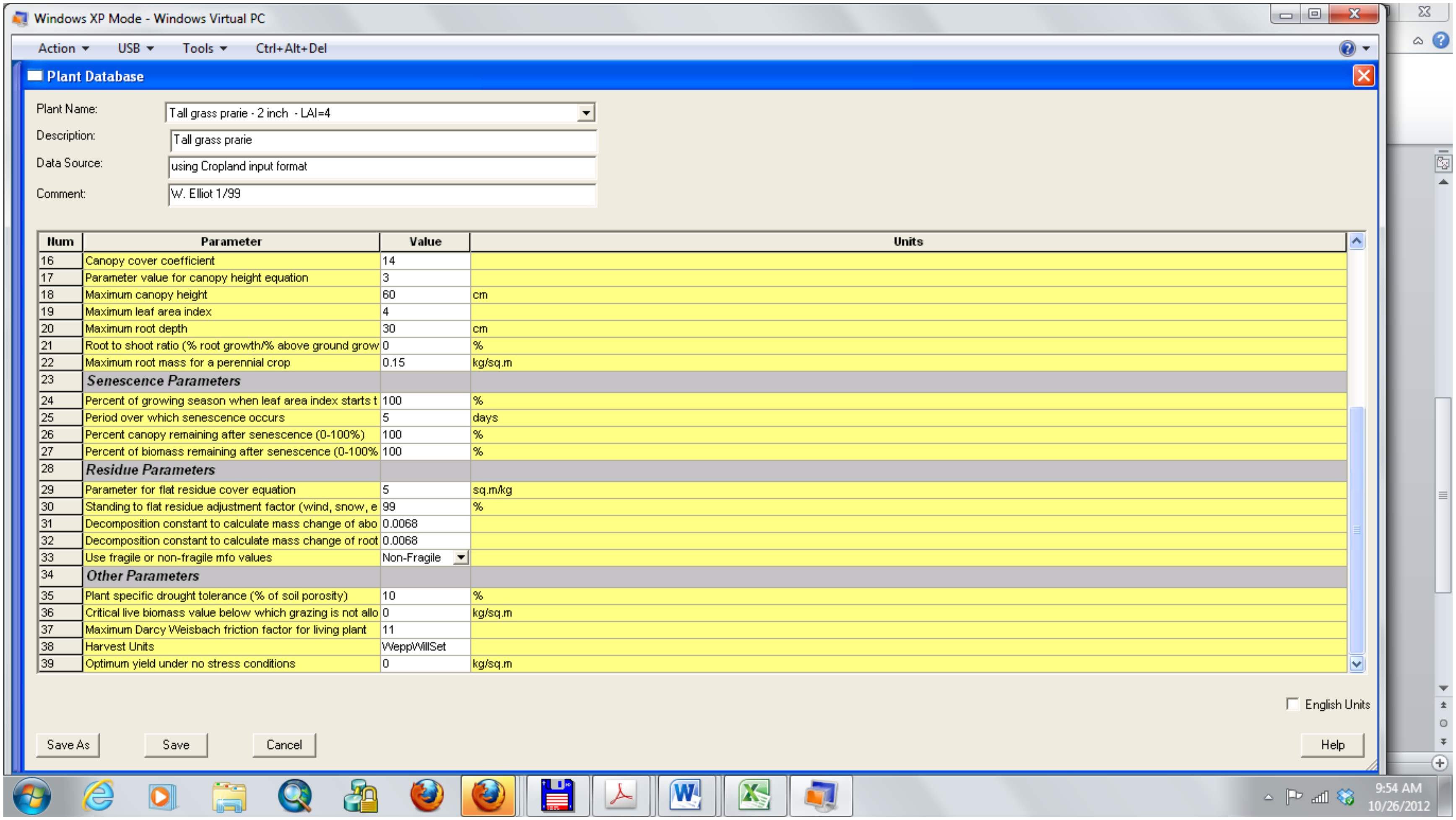
Num	Parameter	Value	Units
17	Parameter value for canopy height equation	3	
18	Maximum canopy height	15.75	inches
19	Maximum leaf area index	4	
20	Maximum root depth	7.874	inches
21	Root to shoot ratio (% root growth/% above ground grow	33	%
22	Maximum root mass for a perennial crop	892.1	lbs/acre
23	***Senescence Parameters***		
24	Percent of growing season when leaf area index starts t	100	%
25	Period over which senescence occurs	5	days
26	Percent canopy remaining after senescence (0-100%)	100	%
27	Percent of biomass remaining after senescence (0-100%	100	%
28	***Residue Parameters***		
29	Parameter for flat residue cover equation	0.0005604	acres/lb
30	Standing to flat residue adjustment factor (wind, snow, e	99	%
31	Decomposition constant to calculate mass change of abo	0.0069	
32	Decomposition constant to calculate mass change of root	0.0069	
33	Use fragile or non-fragile mfo values	Non-Fragile	
34	***Other Parameters***		
35	Plant specific drought tolerance (% of soil porosity)	10	%
36	Critical live biomass value below which grazing is not allo	0	lbs/acre
37	Maximum Darcy Weisbach friction factor for living plant	9	
38	Harvest Units	WeppWillSet	
39	Optimum yield under no stress conditions	0	lbs/acre

Screen shots for tall grass prairie





Num	Parameter	Value	Units
1	*Plant Growth and Harvest Parameters*		
2	Biomass energy ratio	15	kg/MJ
3	Growing degree days to emergence	5	Degrees C.days
4	Growing degree days for growing season	0	Degrees C.days
5	In-row plant spacing	5.08	cm
6	Plant stem diameter at maturity	1	cm
7	Height of post-harvest standing residue; cutting height	10	cm
8	Harvest index (dry crop yield/total above ground dry biom	42	%
9	*Temperature and Radiation Parameters*		
10	Base daily air temperature	2	Degrees C
11	Optimal temperature for plant growth	20	Degrees C
12	Maximum temperature that stops the growth of a perenni	37.78	Degrees C
13	Critical freezing temperature for a perennial crop	0	Degrees C
14	Radiation extinction coefficient	0.65	
15	*Canopy, LAI and Root Parameters*		
16	Canopy cover coefficient	14	
17	Parameter value for canopy height equation	3	
18	Maximum canopy height	60	cm
19	Maximum leaf area index	4	
20	Maximum root depth	30	cm
21	Root to shoot ratio (% root growth/% above ground grow	0	%
22	Maximum root mass for a perennial crop	0.15	kg/sq.m
23	*Senescence Parameters*		
24	Percent of growing season when leaf area index starts t	100	%



Num	Parameter	Value	Units
16	Canopy cover coefficient	14	
17	Parameter value for canopy height equation	3	
18	Maximum canopy height	60	cm
19	Maximum leaf area index	4	
20	Maximum root depth	30	cm
21	Root to shoot ratio (% root growth/% above ground grow	0	%
22	Maximum root mass for a perennial crop	0.15	kg/sq.m
23	***Senescence Parameters***		
24	Percent of growing season when leaf area index starts t	100	%
25	Period over which senescence occurs	5	days
26	Percent canopy remaining after senescence (0-100%)	100	%
27	Percent of biomass remaining after senescence (0-100%	100	%
28	***Residue Parameters***		
29	Parameter for flat residue cover equation	5	sq.m/kg
30	Standing to flat residue adjustment factor (wind, snow, e	99	%
31	Decomposition constant to calculate mass change of abo	0.0068	
32	Decomposition constant to calculate mass change of root	0.0068	
33	Use fragile or non-fragile mfo values	Non-Fragile	
34	***Other Parameters***		
35	Plant specific drought tolerance (% of soil porosity)	10	%
36	Critical live biomass value below which grazing is not allo	0	kg/sq.m
37	Maximum Darcy Weisbach friction factor for living plant	11	
38	Harvest Units	WeppWillSet	
39	Optimum yield under no stress conditions	0	kg/sq.m

Appendix C. Poplar River watershed soils

The information for these soil series was obtained from the NRCS web site on soils descriptors, http://soils.usda.gov/technical/classification/osd/index.html. Very detailed information is available at that site. A brief descriptor for each soil series is presented below.

QUETICO SERIES

The Quetico series consists of very shallow, well drained soils that formed in loamy noncalcareous glacial drift on uplands with relief controlled by the underlying bedrock. These soils have bedrock beginning at depths ranging from 4 to 10 inches. The saturated hydraulic conductivity is moderate in the loamy mantle. Slopes range from 2 to 90 percent. Mean annual precipitation is about 28 inches and mean annual air temperature is about 37 degrees F.

BARTO SERIES

The Barto series consists of shallow, well drained soils that formed in a 20 to 51 cm thick mantle of loamy till overlying unweathered bedrock. They have slopes of 2 to 45 percent. Mean annual precipitation is about 750 mm and mean annual air temperature is about 4.5 degrees C.

MESABA SERIES

The Mesaba series consists of moderately deep, well drained soils that formed in a mantle of loamy friable till over gabbro, basalt, or granite bedrock at depths of 51 to 102 cm. Slopes range from 2 to 45 percent. Mean annual precipitation is 750 mm and the mean annual temperature is 4.5 degrees C.

HIBBING SERIES

The Hibbing series consists of very deep, moderately well drained soils that formed in a thin mantle of loess and underlying fine, dense till on till plains and moraines. Slopes range from 3 to 45 percent. Saturated hydraulic conductivity is very slow. Mean annual air temperature is about 39 degrees F. Mean annual precipitation is about 27 inches.

FINLAND SERIES

The Finland series consists of moderately deep, well drained soils that formed in a friable loamy mantle and underlying firm loamy glacial till on moraines. Permeability is moderate in the upper layers and moderately slow to slow in the dense till. Slopes range from 1 to 35 percent. Mean annual temperature is 39 degrees F, and mean annual precipitation is 29 inches.

DUSLER SERIES

The Dusler series consists of very deep, somewhat poorly drained soils that formed in loamy glacial till on till floored lake plains, and moraines. Permeability is moderate in the mantle and slow in the underlying material. Slopes range from 0 to 3 percent. Mean annual air temperature is about 38 degrees F. Mean annual precipitation is about 28 inches.

DULUTH SERIES

The Duluth series consists of very deep, well drained soils that formed in a friable mantle of loamy eolian or glaciofluvial deposits and in the underlying firm loamy till on moraines and till plains. Slopes range from 6 to 45 percent. Mean annual air temperature is about 4.0 degrees C. and mean annual precipitation is about 711 millimeters.

AMASA SERIES

The Amasa series consists of very deep, well drained and moderately well drained soils formed in loamy materials underlain by sandy materials on outwash plains, stream terraces, kames, eskers, and moraines. Permeability is moderate in the loamy materials and rapid or very rapid in the underlying sandy material. Slopes range from 0 to 70 percent. Mean annual precipitation is about 30 inches, and mean annual temperature is about 43 degrees F.

HERMANTOWN SERIES

The Hermantown series consists of very deep, somewhat poorly drained soils that formed in a friable loamy mantle and the underlying dense loamy till on moraines, till plains and drumlins. Slopes range from 0 to 3 percent. Mean annual air temperature is about 4.0 degrees C. and mean annual precipitation is about 750 mm.

RUDYARD SERIES

The Rudyard series consists of very deep, somewhat poorly drained soils formed in clayey deposits on lake plains. These soils have very slow permeability. Slopes range from 0 to 4 percent. Mean annual precipitation is about 30 inches, and mean annual temperature is about 43 degrees F.

ONTONAGON SERIES

The Ontonagon series consists of very deep, well drained soils formed in clayey glaciolacustrine deposits on lake plains. Permeability is very slow. Slopes range from 6 to 50 percent. Mean annual precipitation is about 30 inches, and mean annual air temperature is about 41 degrees F.

BERGLAND SERIES

The Bergland series consists of very deep, poorly drained soils formed in clayey deposits on glacial lake plains and till plains. Permeability is very slow. Slopes range from 0 to 2 percent. Mean annual precipitation is about 30 inches. Mean annual temperature is about 44 degrees F.

AHMEEK SERIES

The Ahmeek series consists of very deep, well drained soils that formed in a friable loamy mantle and the underlying dense loamy till. These soils are on till plains, moraines, and drumlins. Slope ranges from 0 to 45 percent. Mean annual air temperature is about 4 degrees C. Mean annual precipitation is about 750 millimeters.