Novel Applications of LiDAR for Climate Adaptation in the Red River Basin

RED RIVER BASIN COMMISSION

STRATEGIC SYSTEMS ENGINEERING INC.

Executive Summary

The Red River Basin Commission in collaboration with key partners has provided leadership, outreach and training to Canadian stakeholders in the Red River Basin on the use of LiDAR for Climate Adaptation since 2019. Key contributions are the following:

- ensuring 100% 1m LiDAR coverage in the Canadian portion of the Red River Basin
- Facilitating extensive stakeholder engaging, including a key pre-Covid physical meeting that defined key themes on LiDAR for climate adaptation, specifically the use of LiDAR for Flood Mapping and Natural Infrastructure Systems Design as stakeholder priorities.
- New training and support tools, including a hands-on training manual for using LiDAR with free open-source software (QGIS).
- Through collaboration with the Global Water Futures program, and industry partner Strategic Systems Engineering Inc the first-ever seamless international hydrologic model of the Red River Basin, capable of ingesting ensemble global climate model. The hydrologic modelling produced high confidence results regarding climate impacts; a weaker spring flood, lower low flows in spring and summer, and lower overall water availability and thus the logic for LiDAR-based Climate Adaptation via Natural Infrastructure.

Two novel applications of LiDAR for Climate Adaptation in the South Canadian Red River Basin (Pembina Valley Watershed District), and the North Canadian Red River Basin (East Interlake Watershed District).

Though LiDAR and its abilities are not new to the world, some of the work that has been undertaken with this project is new to our Manitoba regions. The northern application review with the newly developed software from Strategic Systems Engineering (SSE) allowed for the whole region to be processed at once rather than piecing it together. In the south, where LiDAR did not exist, it was used to show whole regional storage capacities instead of sectioned areas. Making these two novel applications of LiDAR for Climate Adaptation in the South Canadian Red River Basin (Pembina Valley Watershed District), and the North Canadian Red River Basin (East Interlake Watershed District) the first of its kind in our Red River Basin region.

The preparation of this plan was carried out with assistance from the Government of Canada and the Federation of Canadian Municipalities. Notwithstanding this support, the views expressed are the personal views of the authors, and the Federation of Canadian Municipalities and the Government of Canada accept no responsibility for them.

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Introduction

What does the Canadian Federal Government have to say about the climate?

"The Prairies, and western Canada generally, have had the strongest warming to date across southern Canada, especially in winter. Further warming is projected, resulting in longer growing seasons, earlier spring peak streamflow, increasingly severe heatwaves, and increased wildfire risk. More frequent and intense drought are anticipated across the southern Prairies in the summer. While more precipitation is expected generally, summer rainfall may change little. More intense rainfalls are also projected."

The key impacts of climate change are changes in temperature and precipitation, changes in relative frequency of floods and droughts and change in the Red River Basin flow patterns. All the models agree that the Prairies will have much hotter temperatures and most models agree that the prairies will have more variable precipitation. The heat dominates causing thirstier crops, soils, and atmosphere. Precipitation will generate less runoff on average as moisture disappears into cracks in the ground and evaporates back into the atmosphere as an implication of higher temperatures.

Climate adaptation is building resilience to climate change. The adaptative priority is multi-functional storage otherwise known as natural infrastructure which provides both flood and drought protection. This is the most useful most high value tool to use and at all different scales.

What is Natural Infrastructure?

"existing, restored, or enhanced combinations of vegetation and associated biology, land and water, and naturally occurring ecological processes that generate infrastructure outcomes such as preventing and mitigating floods, erosion, and landslides; mitigating effects of extreme heat; and purifying groundwater… can be existing natural features or human-made and constructed" (ICF, 2018) Best Practices and Resources on Climate Resilient Natural Infrastructure

Loss of natural infrastructure increase both flood and drought risk. However, investment in natural infrastructure reduces both risks. LiDAR is important because it accelerates the natural infrastructure system design from field to basin-scale. Having access to this high-resolution free elevation data asset builds a culture of water harvesting which is what we need for climate adaptation.

Stakeholder Consultation and Project Orientation

The first major FCM-funded activity took a place on December 12th, 2019, in Portage La Prairie, MB. Approximately 120 municipal and watershed district staff attended a full day workshop on the origins of LiDAR technology, LiDAR's information content and an overview of how it can be applied. Based on feedback received at this meeting, stakeholder priorities were clearly on using LiDAR to inform practical municipal water resources management issues; primarily flood risk, drainage, and retention storage, and where retention storage could be developed using natural infrastructure design principles for an integrated approach to flood and drought risk.

Concurrently, several municipal and watershed funding mechanisms re-oriented towards natural infrastructure as new eligible funding category including:

- The Investing in Canada Infrastructure Program (Infrastructure Canada)
- The Lake Winnipeg Basin Program (Environment and Climate Change Canada)
- The Conservation Trust (Manitoba Habitat Heritage Corporation)

Given our own stakeholder consultation, and the orientation of these funding mechanism we took the strategic decision to orient the project towards the use of LiDAR for Natural Infrastructure Systems Design as a key climate adaptation technology.

Case Study Overview

In the midst of the 2020 pandemic lockdown and the impossibility of convening physical meetings, we pivoted towards producing on-line LiDAR training and resource material. Simultaneously technical partner, Strategic Systems Engineering (SSE) began developing new LiDAR-based Natural Infrastructure design approaches using recently acquired 1m LiDAR for the Pembina Valley and East Interlake Watershed Districts. The distinctly different topographies of these regions motivated different approaches to extracting value from the high-resolution LiDAR-derived Digital Elevation Models. The south case study area is in heavily incised valleys of the Pembina Watershed uplands, whereas the north case study area is much flatter, subtly undulating terrain with glacial striations oriented in a NW-SE direction.

In December 2021, the North and South case studies were presented to stakeholders along with an overview of all new the applications of LiDAR in the Manitoba portion of the Red River Basin

South Region Climate Adaptation Case Study

A Message from the Pembina Valley Watershed District

LiDAR is gold for the work of the Watershed Districts. Our District is starting to use this invaluable toolset, thanks to the LiDAR data and educational materials provided by the Red River Basin Commission (RRBC) led project.

Our municipal partners are also keen to start using this product although full adoption will take some time. The time savings are incredible as a full-scale field survey is not required. The Pembina Valley Watershed District still does some ground-truthing and field survey pickup in key areas to ensure that designs are accurate but 90% of the data can be brought into the project from the LiDAR dataset. This results in more potential projects that can be looked at and evaluated for effectiveness.

Another huge benefit is that the landscape modelling that directs and targets PVWD programs are more accurate as a result of using LiDAR-derived data. Predictions of water quality and quantity impacts from theoretical best management practices (BMP) adoption are being evaluated using these models and this would not be possible without the province's investment in this LiDAR data.

A big thank-you to the RRBC, Strategic Systems Engineering (SSE), the Federation of Canadian Municipalities (FCM), the Province of Manitoba and the participating municipal partners to make this happen. This investment in LiDAR data will pay dividends in watershed health and that is happening now.

Cliff Greenfield
Manager, Pembina Valley Watershed District

The south climate adaptation case study focused on developing 3D solid modelling techniques for rapid evaluation of storage sites. Methods using a standardized classic PFRA-style earthen dam cross-section extruded through the 1m LiDAR-derived DEM were developed and allowed evaluation of storage alternatives based on which sites minimized earthworks per unit of storage developed.

Through the Global Water Futures collaboration, the first-ever seamless international Red River Basin hydrologic model was constructed, and a sub-model in the Pembina Watershed, both of which revealed similar seasonality shifts in river flows (less in spring, more in fall) and reduced overall flow volume. The hydrologic modelling and the LiDAR-based storage reconnaissance tools formed the technical foundations of the case study reported in detail in Appendix x. Essentially, the new hydrologic LiDAR processing tools proved invaluable for a fast hydrologic and hydraulic evaluation of new water supply options for the City of Morden, MB which is currently dealing serious climate change-induced water scarcity. The full case study is reported in Appendix 4.

North Region Climate Adaptation Case Study

A Message from the East Interlake Watershed District

LiDAR data has been hydro-conditioned in the Netley, Grasmere, Willow and Shoal Lake Watersheds, this data has helped pin point and plan benefitable management practices that improve and maintain soil and water quality. An innovative GIS planning tool is being created to target investments for highest Value for Money Natural infrastructure projects and Natural infrastructure networks, high nutrient loading zones will be identified.

The hydro-conditioned LiDAR data has enabled the East Interlake Watershed District (EIWD) to work with over 101 landowners to develop enhancement and protection management plans (bids) on their property. 39 landowner management plans/landowner agreements have been approved by the EIWD executive board/GROW committee and are currently in development phase of the management plans (bids). When completed EIWD will have helped enhance and protect 250 acres of wetlands, 66 acres of native grasslands, 94 acres of riparian areas, and excluded 2,175 cattle from riparian areas.

Armand Belanger
Manager, East Interlake Watershed District

The North adaptation case study took place in much flatter, subtly undulating terrain in the Interlake Region of Manitoba, straddling the East and West Interlake Watershed Districts. The Interlake region has in recent years also endured serious drought conditions, with pasture and forage shortages common during drought years. A major hydrographic feature of the region is the Shoal Lakes (North, East and West Shoal Lake), which sit on a high limestone plateau.

Prior to European settlement, the Shoal Lakes were a single hydrographic feature and functioned as a terminal lake with no outlet. In 1912 construction of the Wagon Creek Drain created a drainage pathway to Lake Manitoba, the lake level dropped 3 meters, with separation into three distinct lakes. In subsequent wet years, high levels on the residual three Shoal lakes have flooded pastureland and prompted calls for improving the original Wagon Creek Drain for fear of uncontrolled spilling into the Netley-Grassmere Watershed to south-east. However, recent drought years have prompted a more integrated climate-resilience orientation on how the Shoal Lakes can be managed. Partner organization the East Interlake identified the potential for the Shoal Lakes to function as a managed storage reservoir, with controlled releases into the upper reaches of the Netley-Grassmere watershed during droughts, if a feasible hydrographic connection could be identified.

The availability of a continuous 1m LiDAR-derived Digital Elevation Model for the entire region allowed for the first time, the necessary hydrographic analysis. Analytics partner Strategic Systems Engineering developed custom high-performance hydrographic processing software capable of processing this large region as a single unified domain using specialized sort, memory management, cloud compute methods. The entire domain (8 billion cells) was processed on Amazon Web Services in under 8 hours. The results of the analysis confirmed that a feasible hydrographic connection does exist to link the Shoal Lakes with the upper Netley-Grassmere, therefore a relatively low-cost intervention that dramatically increases water supply and thus climate resilience for the Southern Interlake Region of Manitoba exists and is based on transforming the existing Shoal Lakes into managed Natural Infrastructure.

The North case study domain is larger than anything in the geo-processing literature, and we believe these algorithms are a major value-add contribution that benefits other municipalities and regions contending with hydrologic variability and hydrographic complexity.

Training and Outreach Videos

In 2020 and 2021 a series of training videos were planned and produced and released in December 2021, along with a hands-on training manual for using 1m LiDAR-derived DEMs within the powerful, free open source QGIS software package. The topics covered by the videos included LiDAR basics, key physical impacts of climate change including higher frequency floods and droughts. The logic of Natural Infrastructure as low-cost, high value climate adaptation, and the value of LiDAR for designing Natural Infrastructure systems.

The videos covered key funding eligibility issues with respect to the Investing in Canada Infrastructure Program and provisions within the Climate Lens guidance document regarding the use of the best available climate science and monetization of ecosystem co-benefits for developing the investment case for Natural Infrastructure. The videos also covered the implications of the 1m geomatics standard for flood mapping published (March 2021) by Public Safety Canada. With the complete LiDAR coverage now in place, municipal Manitoba and New Brunswick are the only provinces that can conform with the new federal standard.

Appendix 1: LiDAR and Climate Adaptation Video Series

The Video Topics and YouTube playlist is provided here:

- Video 1: What is LiDAR?
- Video 2: How is LiDAR Data Collected?
- Video 3: LiDAR data in Manitoba
- Video 4: Introductions to QGIS
- Video 5: QGIS in Detail
- Video 6: Nutrient Mobility Estimation via PhosFinder
- Video 7: Reducing Climate Risk in Manitoba
- Video 8: Climate Risk Estimation Methods
- Video 9: How Climate Change Affects Weather
- Video 10: Flooding and Drought Impacts
- Video 11: How Climate Change Elevates Risk
- Video 12: The Past and Future of Climate Resilience
- Video 13: Natural Infrastructure for Climate Resilience
- Supplemental Video: LiDAR in Manitoba Virtual Launch
- Supplemental Video: North Region Climate Adaptation by Design – Harnessing the Power of LiDAR
- Supplemental Video: South Region Climate Adaptation by Design – Harnessing the Power of LiDAR

Appendix 2: LiDAR Training Series: Module 1

LiDAR Training Series: Module 1

Acquiring and Visualizing LiDAR-Derived Digital Elevation Models for Your Community

STRATEGIC SYSTEMS ENGINEERING INC.

RED RIVER BASIN COMMISSION

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Introduction

Francis Heron described the flood of 1826 by saying, “the forts now stand like a castle of romance in the midst of an ocean of deep contending currents, the water extending for at least a mile behind, and they are thereby only approachable by boats and canoes”. Today we would not think of it as a romance but understand the wording of “midst of an ocean”. This century has seen numerous floods which are still embedded in the minds of many.

The headlines of 1997 flood stated, “Grand Forks on fire” as the Red River in Grand Forks crested at 53.99 feet. The damage of flooding and fire scarred the city and efforts were on the way to never allow it to happen again. In Manitoba, damages exceeded 500 million dollars and it was the worst flood on record since the flood of 1852. The flood of ‘97 became known as the “Flood of the Century”.

Fast track ourselves to present day 2021 and we now are seeing drought, water restrictions and rivers at their lowest levels in 100 years. Add the effects of climate change, which this may be a part of, and you learn quickly that resilient and proactive thinking must happen. Gone are the days that you deal with it as it comes along, as it is now time to be proactively thinking of what is yet to come as it relates to weather and the changes occurring in our weather.

The answer to being proactive is far more affordable than being reactive and the use of LiDAR by Governments, First Nations, and businesses is one of the greater tools in the toolbox for planning. The data that LiDAR brings and the software that the data can be used with is the key for future planning, risk reduction and climate change adaptation.

It is the desire of the Red River Basin Commission, and its partners, to share, to assist and to support all those who wish for their communities to better prepare for the next century and what that century may bring as it relates to the changes and needs coming from climate change.

Steve Strang

Managing Director

Red River Basin Commission

The Red River Basin

The Red River is one of the few rivers that flows north. It meanders for over 800 kilometres, mostly through a flat plain of rich soil deposits which are some of the best agricultural lands in the world. The channel of the Red River forms the boundary between North Dakota and Minnesota and flows north into Manitoba and through City of Winnipeg before it reaches Lake Winnipeg. The drainage area for the Red River Basin is about 100,000 square kilometers and encompasses parts of eastern North Dakota, northwestern Minnesota, and northeastern South Dakota in the United States and southern Manitoba in Canada. It is also part of the larger Lake Winnipeg Basin.

The Red River being about 885 kilometres long, of which about 635 kilometres are in the United States and about 255 kilometres are in Manitoba, Canada. Over the course of the river, it falls 70 metres on its journey to Lake Winnipeg, where it first enters the largest coastal wetlands in North America called the Netley Marsh.

In 2007, the Government of Canada declared the Red River as a Canadian Heritage River as the historical role it played for First Nations, Metis, and the development of Western Canada.

For the last 40 years the Red River Basin Commission is proud to work along side its partners, in Canada and the United States, to maintain water quality and management of such a historical part of Manitoba, Minnesota, and North Dakota.

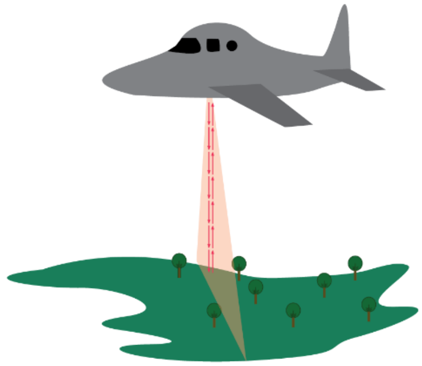
What is LiDAR?

LiDAR stands for ***Li**ght **D**etection **A**nd **R**anging.* LiDAR originated as a technology for military targeting with key advances made by Canadian Allan Carswell at York University, and later became available for academic and commercial uses. The central goal of LiDAR is to measure the elevation of the earth's surface at a high resolution while maintaining high spatial accuracy.

The word LiDAR is a portmanteau of "light" and "radar" and conveys the essence of how it works.

Collection of LiDAR

LiDAR acquisition is usually done with low-flying specially equipped aircraft that travels along a predetermined path, with sensors affixed to them. From the sensor, beams of infrared light are rapidly shot at the ground en-masse, over 150,000 times each second as the plane heads down a pre-defined path. Each pulse of light bounces off the earth's surface (or an object such as a building or vegetation) and heads back toward the sensor, where the angle and time delay are captured. The time it takes for the pulse to travel determines the distance to the spot on the ground, since it travels at the speed of light. Since the plane's elevation is known, the distance is subtracted to get the ground elevation.

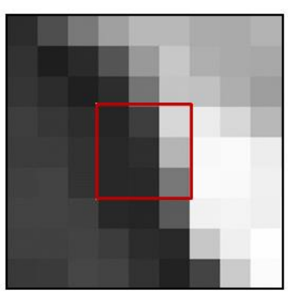


Two corrections have to be done at this point - distance has to be corrected using trigonometry since the pulses are almost never vertical, and secondly, the plane's elevation will have to be adjusted from it's Internal Measurement Unit and GPS since the height will be minorly inconsistent due to turbulence. Spring and fall are the best times to fly as the leaves and vegetation are minimal, but the snow isn't on the ground either – in which either act to distort accuracy.

The product of this LiDAR collection is a densely spaced network of geo-referenced points, called a 'point-cloud' that can be used as an input to generate a 3D representation of the earth's surface. Using specialized geospatial software, such as QGIS, the point-cloud can be converted to a gridded dataset of the area that was captured, which is called a Digital Elevation Model (DEM).

The raw DEM at this point is never a perfect representation of the landscape, and this is due to the nature of LiDAR acquisition being overhead. Certain features, mainly those that are hidden from above, will not be accurate and survey data will need to be used to adjust them. One example is a bridge over a channel – the channel exists and has a definition to it, but since the bridge blocks the lidar signal from reaching it, the result just shows the deck of the bridge.

DEMs are gridded and are pixelated, and fall under a class of data called *rasters* – like most digital imagery. Each square cell within the raster is called a pixel. Each pixel is a uniform size and holds a value (*digital number)* for the area that it occupies - from a range of allowable values. For DEM's the value is from elevation, which in Manitoba is published as above sea level.



43	102	169
35	58	191
38	44	155

Raster data can come in a single *band* (channel) or in three bands. LiDAR derived DEMs only use 1 band, while most satellite imagery uses 3.

Use Cases for LiDAR

LiDAR as a remote sensing technique has several advantages. High accuracy, large coverage areas and a high amount of data collection points, allow for the ability to produce large-scale inexpensive and efficient datasets. 2021 LiDAR acquisition prices have been below $30/km^2 and continue to decline as sensor sensitivity and signal processing power improve.

Some use cases for LiDAR include:

• Creating flood insurance risk maps. This is likely a strong driver of demand for more LiDAR capture.
• The planning of smaller scale civil engineering projects, that are related to surface water management.
• Wetland conservation strategies, along with flood and drought mitigation.
• Developing surface water retention strategies, and creating value from your assets.
• Developing an inventory of assets, such as culverts, bridges and other existing infrastructure, with important information about them such as dollar value.

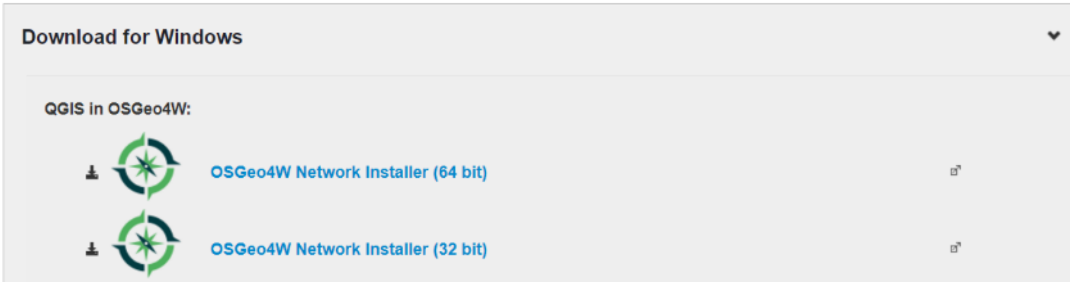
LiDAR provides the critical backbone of computational analytical operations that can be done to determine watershed boundaries, flow pathing and surface depressions in minute detail – much more refined than traditional survey data.

LiDAR-based mapping also helps you identify sensible areas for water retention, which are integral to climate adaptation plans. LiDAR-based risk mapping also helps you target the areas of your community that may be vulnerable to flooding and the benefit of flood protection projects.

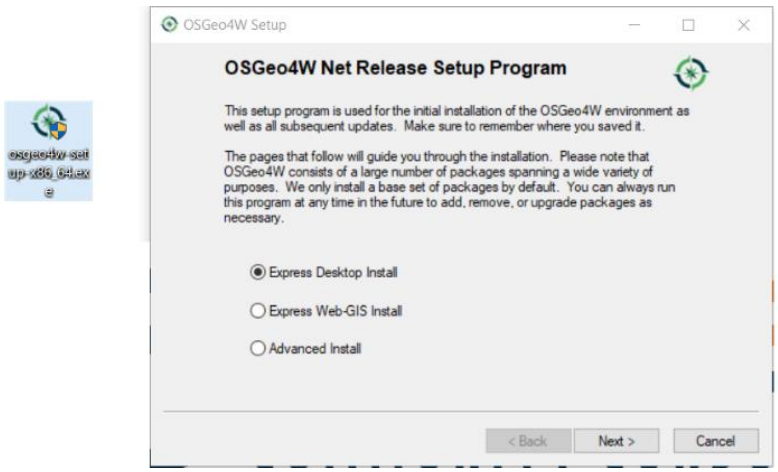
Installing QGIS

QGIS is free open source Geographic Information System (GIS) software, available for Windows, MacOS, and Linux operating systems. QGIS comes within a larger basket of apps – they are all are part of what is called the OsGeo4W project. QGIS provides the capability to import and process DEMs derived from LiDAR.

Navigate to the downloads page on **www.osgeo.org** and select the network installer. If your operating system is 32 bit, you will need to use the 32 bit installer. If your operating system is 64 bit you have the option to choose both, but using the 64 bit version is a better option as it offers more computational power to you. If you’re unsure, the packaging and installation disk or flash drive that came with your computer will have what bit system your computer has.



An installer icon should appear on the desktop. Click on it to bring the setup dialog box up and choose *Express Desktop Install*.



Next, from the list of download sites, choose *download.osgeo.org*

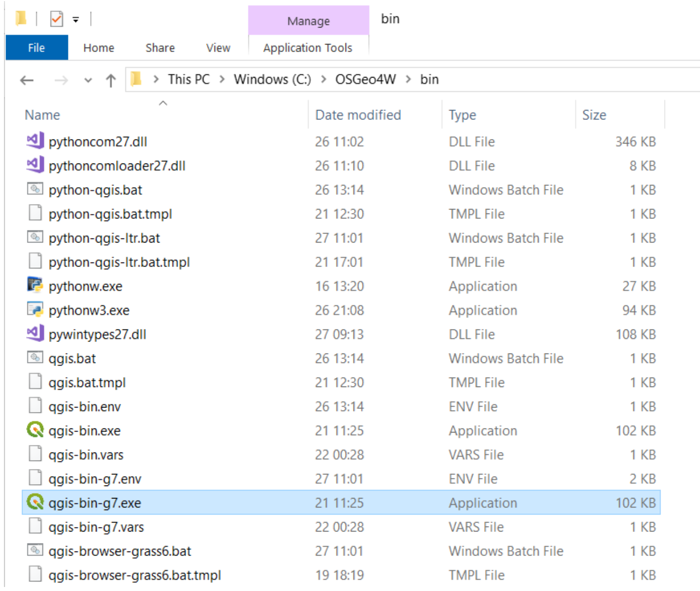
Next, a list of packages will appear – select all of them… and make sure that *QGIS*, *GDAL* and *GRASS GIS* are definitely checked off.

Now a warning should pop up informing that some dependencies are not met. Don't worry, this is fine…but make sure the check mark at the bottom is on to allow the installer to add packages that will patch everything up.

The last steps here are to fully integrate the QGIS environment into Windows Explorer so the file associations are set and everything runs smoothly.

Navigate to C » OSGeo4W and place any remaining shortcuts inside this folder. Now click on the bin folder and scroll down until you see ***qgis-bin-g7.exe*** and right click it. Make a shortcut and pin it on the start menu or taskbar.

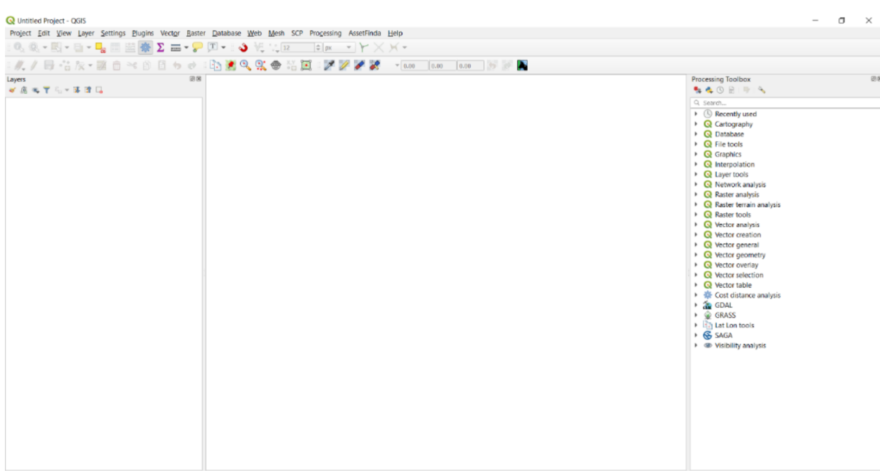
If there is an existing shortcut icon on the start menu, remove it and replace it with this new one to make things simple!



! Make sure you select the correct QGIS program, as there are two versions here. The standard *qgis-bin.exe* will have some tools missing (by design) and it is a simple quirk that is not super obvious later on when figuring out why some algorithms won't run.

It is critically important when working with GIS data that the filenames, and the entire file path has no spaces. The single best option to avoid this is using underscores_as_spaces and joinwordstogether as needed when creating files and folders in either Windows Explorer or in QGIS itself.

QGIS Interface and Basic Functions

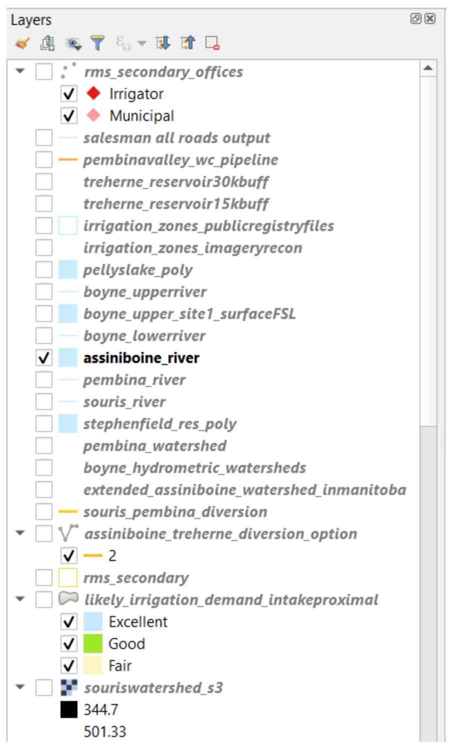


Pictured above is the QGIS interface when opening a new project. You'll see an array of panes and windows which hold information, tools and files. Let's go through each section here:

Layers list (left pane)

In the Layers list, you can see a collection of all the layers that you have connected into QGIS - this is similar to the list of layers you see in Photoshop. The drawing order moves from the topmost layer in the list to the bottom, so if you can't see a layer, move it upwards. You can toggle the layers on and off.

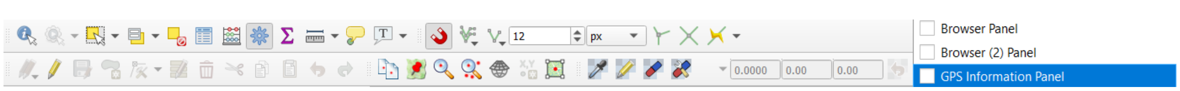
Expanding collapsed items will provide you with more information on the layer's current appearance. Right-clicking on a layer will give you a menu with lots of extra options such as opening the layer's properties or zooming to the layer.



Toolbars (top)

Similar to Microsoft Word and Excel, commonly used tools can be placed on a quick access toolbar. You can easily customize the toolbar to see only the tools you use most often via right clicking an area of empty space

Even if they are not visible on the toolbar, all of your tools will remain accessible via the menus.

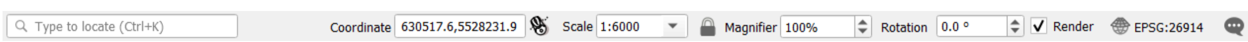


Map Canvas (centre)

This is where the map itself is displayed, in the large centre area. All the layers that are visible will be drawn here depending on what location you've viewing and what your zoom level is.

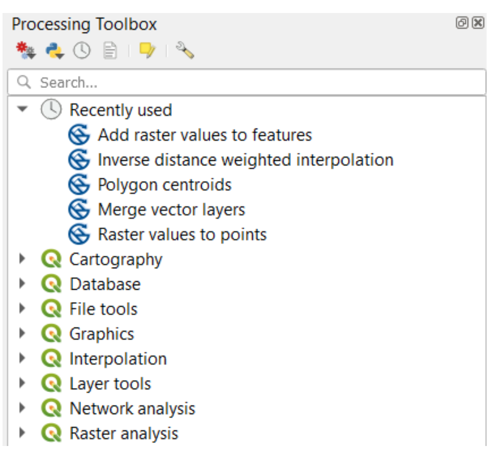
Status Bar (bottom)

This area allows you to adjust the map scale manually, verify georeferencing information and see the mouse's current geographic coordinates on screen.



Processing Toolbox (right pane)

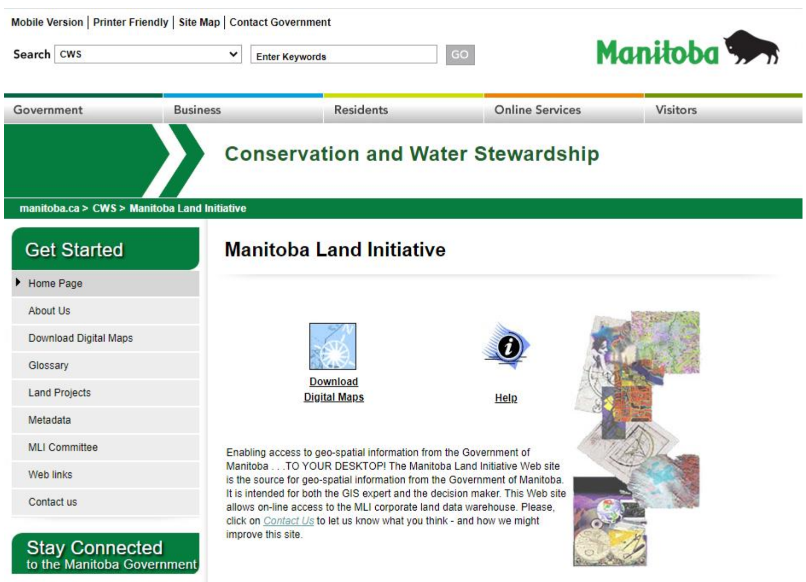
This area allows you to access a host of algorithms (computational operations) that process geospatial data. These will be discussed later.



Sourcing LiDAR for Manitoba

With support from the US Federal Emergency Management Agency, LiDAR was acquired for the US portion of the Red River Basin as a federal contribution to regional emergency preparedness in North Dakota and Minnesota in the aftermath of the 1997 Red River flood. Manitoba acquired some LiDAR at 5m resolution between 1999 and 2002 primarily along the main stem of the Red River, and utilized it for floodplain protection purposes. Since 2006, Manitoba has acquired LiDAR for much of southern Manitoba, generally at 1m resolution. The portion that is the Red River Basin was completed with the partnership of the Red River Basin Commission in 2020.

This LiDAR has been added to a valuable tax-funded public resource called the Manitoba Land Initiative, which is part of the Agriculture and Resource Development branch of the Manitoba Government. The site is easily searchable from Google, and the current website URL is: *https://mli2.gov.mb.ca*

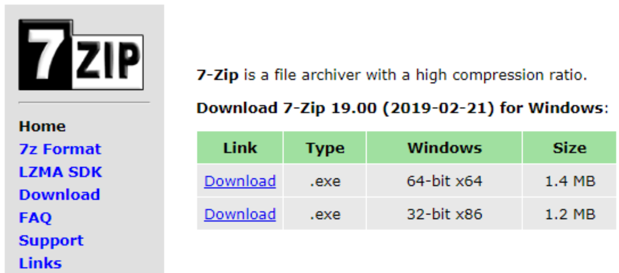


LiDAR datasets can be found under the Digital Elevation Models tab on the left side, which appear after clicking the ‘Download Maps’ button and accepting the disclaimer. At the bottom of the page that appears, there is a link called ‘LiDAR Various’ that points to a library of LiDAR datasets that are published as they become available. Shown below is an example piece.

Cooks Creek			
Cooks Creek LiDAR Raster	.GIF	metadata	DEM

For each publication, a graphic showing it’s extent on a sample map, a document showing technical specs and a link to the DEM are provided. In order to download any or all documents, click on the blue links.

Each Digital Elevation Model (DEM) file comes in a .zip folder, which are used to save space and reduce download time. The caveat is that it has to be unpacked, in order to be useable in QGIS. Several programs can do this but the one Strategic recommends is called 7-Zip.



Inside the zip archive is the DEM, which will come in the form of a .tif file. TIF files are image files, similar to .jpg and .png, which can handle a large range of pixel values, deal with transparency easily and not be affected by modifications due to it being a lossless format.

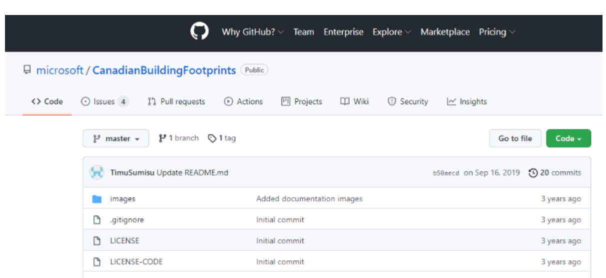
When unpacking files put them in a convenient location on your PC. Note that the file path can't contain spaces.

Once a .tif file is ready, it can be dragged and dropped into QGIS on-the-fly, just direct it to the 'layers' pane, which is on the left side by default. If all goes well, it will display and start loading.

Sourcing Building Data for Manitoba

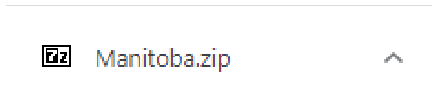
As part of an initiative to build a comprehensive geospatial inventory of building assets, Microsoft and Statistics Canada used satellite imagery and Artificial Intelligence (AI) techniques to derive building footprints across Canada, including Manitoba.

This can all be found on a code repository site called GitHub. The data can be found by searching "Canada Building Footprints Microsoft AI" and the URL is https://github.com/Microsoft/CanadianBuildingFootprints



In order to obtain the data, click on the link for Manitoba and a .zip file will begin downloading

Province/Territory	Number of Buildings	Unzipped MB
Alberta	1,777,439	389
British Columbia	1,359,628	301
Manitoba	632,982	135
New Brunswick	350,989	71
Newfoundland and Labrador	255,568	51



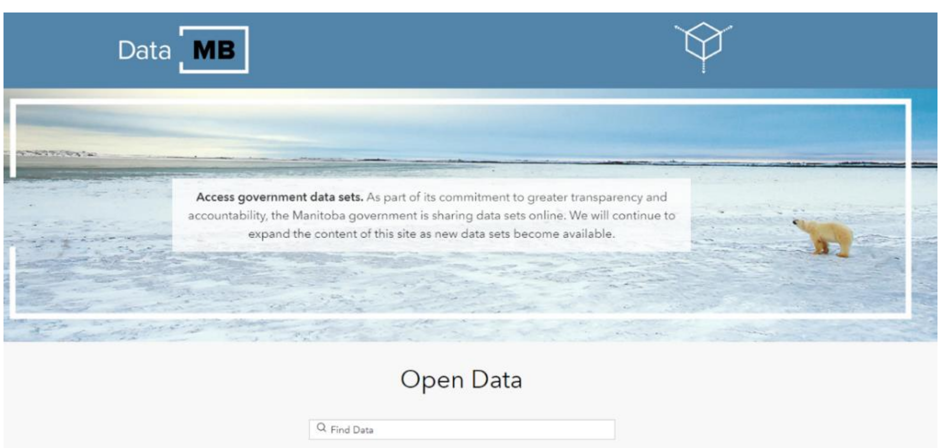
As before with the LiDAR data, the files inside the zip folder need to be extracted, so place them in a convenient location on your PC.

Instead of a gridded .tif file, inside this package is something called a geojson file. This essentially consists of a group of polygons - most of which being rectangles or whatever shape the buildings are located, which have ID's associated with them.

As with the .tif, the geojson can be dragged and dropped into QGIS on-the-fly, just direct it to the 'layers' pane, which is on the left side by default. If all goes well, it will display and start loading.

Sourcing Roll / Parcel Data for Manitoba

The Manitoba Government keeps records of the legal land parcel fabric, along with property values throughout the province (excluding Winnipeg, which has it's own survey records). The data is available on the province's GeoPortal, in which the URL is https://geoportal.gov.mb.ca/datasets/manitoba-property-assessment-information/explore



In order to use the data, click the 'view full details' button on the left pane. Then click on the 'download' button, and finally select 'shapefile' on the left.

As before, the data comes in the form of a .zip file, which the files inside will need to be extracted. Place all files in a convenient location on your PC. The Shapefile is officially the file with the .shp extension, but the others are needed to fully use and render the data in QGIS. Pictured below is an example shapefile of land parcels in a neighborhood (pink borders and transparent fill).

Due to the large number of features, it may take a while to render them all when dragged into QGIS. When doing any detailed examination, it's better to zoom way in, so less need to be loaded.

Both jeojson and shapefiles fall under a second data class called *vector* data. Data of this type is derived from equations, has a pen-stroke appearance and always has a corresponding relational database associated with it for each feature. There are three subtypes of vector data which influence the type of data that can be collected and analyzed.

• Point – Commonly used for trees, stations, towers, markers

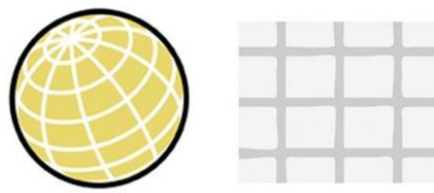
• Line – Commonly used for roads, waterways, utilities

• Polygon – Commonly used for buildings, land parcels, soil survey areas, forests, waterbodies

Importing LiDAR into QGIS

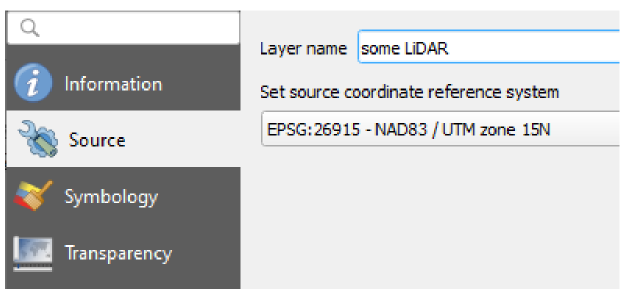
In order to work with the LiDAR downloaded in previous steps, it needs to be imported first. A crucial concept with spatial data is the spatial element of it, which is referred to as georeferencing.

The mathematics behind geographics are complex, but it essentially involves representing real-world locations on surface of the earth, which is approximately a sphere – an *oblate spheroid* to be precise – to locations on a flat map. To deal with this conversion, which is never perfect, a large number of map projections exist, which attempt to georeference data with most accuracy possible.



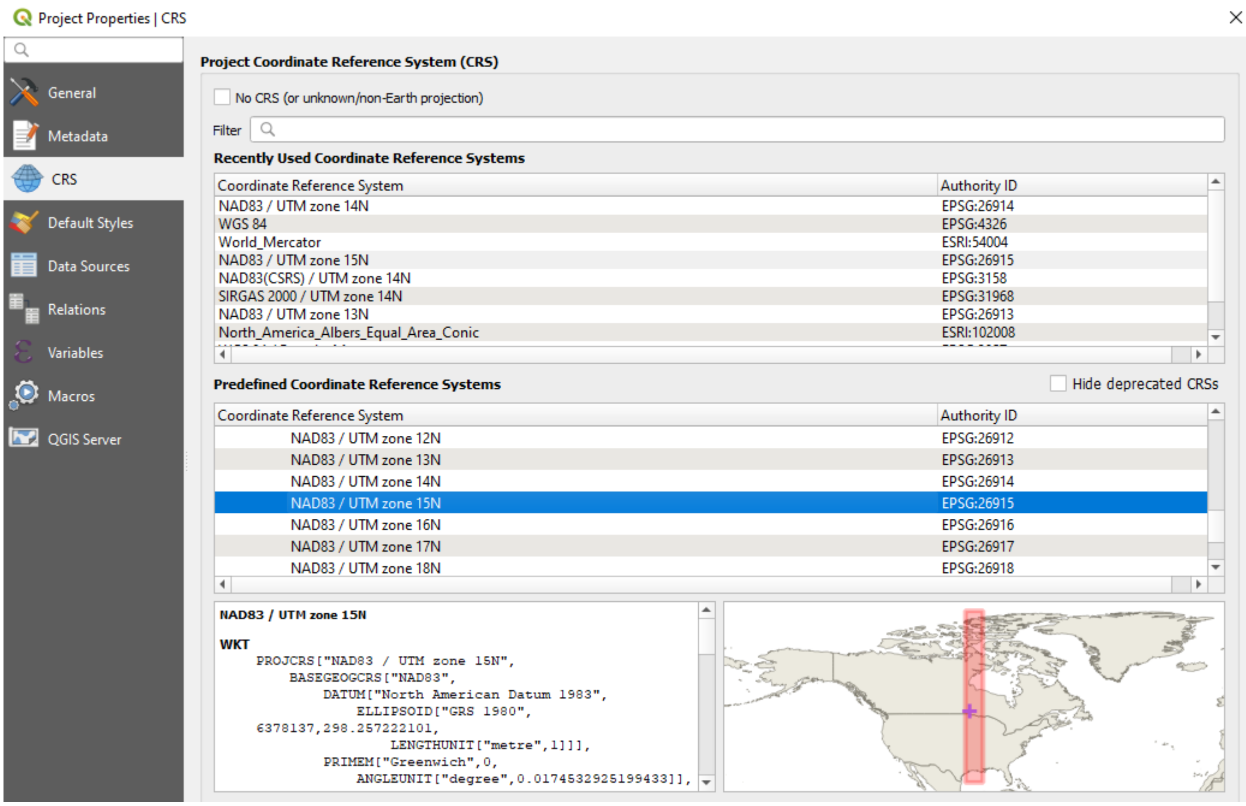
Geographic (3D) **Projected (2D)**

Importing a dataset is as easy as dragging and dropping the .tif file into the layers list on the left pane, where it will load and then display when done. If nothing displays on screen or data appears in the wrong location, that means there is some kind of issue with the data. Most often, the error is a georeferencing one, in which the math is incorrect. Many LiDAR pieces from the MLI and from elsewhere are able to be shown without issue, but the first thing to do is to check the georeferencing. To do this, right click on the layer on the left pane and select 'properties'.

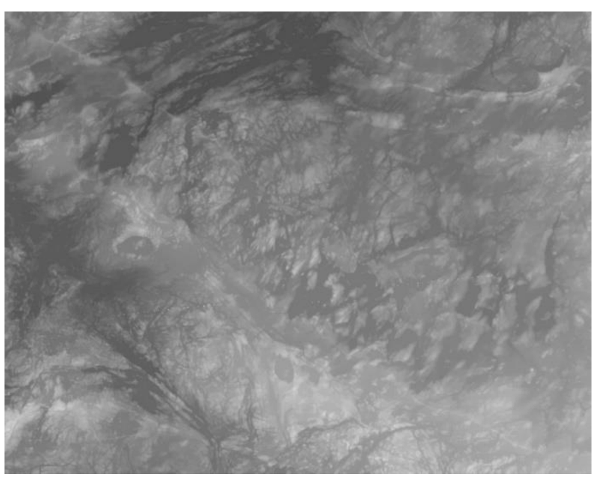


Under the source tab, select the reference system that the LiDAR was acquired in. Each dataset on the MLI has a metadata document which will specify this. The easiest way to determine the proper reference system is to look at what numerical id is used, which is called the EPSG code.

Secondly, on the bottom bar of QGIS on the right hand side lies the QGIS project spatial reference system, which is beside the CRS icon. This controls which 2D projection is displayed on screen, since there can only be one at a given time. It should match that of the LiDAR piece that already has been imported. Note that QGIS usually sets these automatically when dragging a LiDAR dataset onto a blank project.



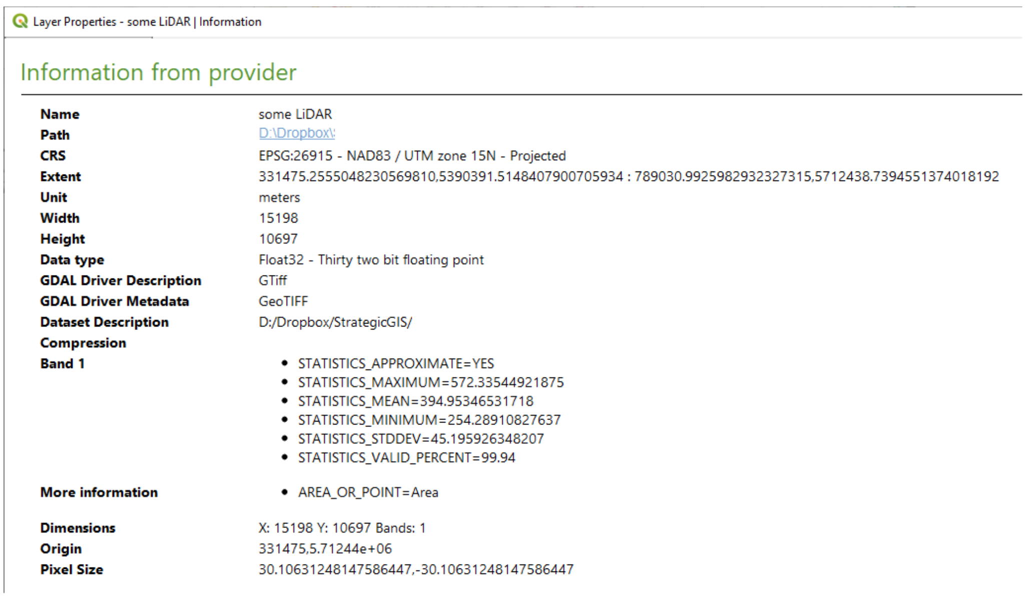
The LiDAR by default looks like a greyscale image, having darker and lighter areas which represent lower and higher elevations respectively.



Inspecting LiDAR for Quality Assurance

The next step is to confirm that the data itself makes sense and passes the ‘sniff test’. The approximate elevation of the area should be known beforehand, so the min and max values of the dataset area are reasonable. The pixel size should match the metadata, which in most cases from the MLI, is 1m by 1m.

These figures can be found through the information tab in the layer’s properties.



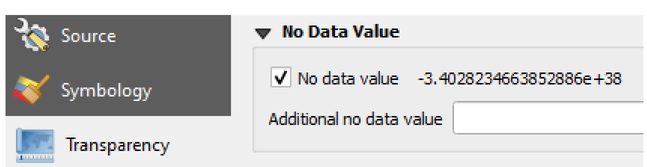
Layer Properties - some LiDAR | Information

Information from provider

Name	some LiDAR
Path	D:\Dropbox\
CRS	EPSG:26915 - NAD83 / UTM zone 15N - Projected
Extent	331475.2555048230569810,5390391.5148407900705934 : 789030.9925982932327315,5712438.7394551374018192
Unit	meters
Width	15198
Height	10697
Data type	Float32 - Thirty two bit floating point
GDAL Driver Description	GTiff
GDAL Driver Metadata	GeoTIFF
Dataset Description	D:/Dropbox/StrategicGIS/
Compression	
Band 1	• STATISTICS_APPROXIMATE=YES • STATISTICS_MAXIMUM=572.33544921875 • STATISTICS_MEAN=394.95346531718 • STATISTICS_MINIMUM=254.28910827637 • STATISTICS_STDDEV=45.195926348207 • STATISTICS_VALID_PERCENT=99.94
More information	• AREA_OR_POINT=Area
Dimensions	X: 15198 Y: 10697 Bands: 1
Origin	331475,5.71244e+06
Pixel Size	30.10631248147586447,-30.10631248147586447

Another figure to check is the *nodata* value for the dataset. Nodata is a special flag assigned to a single value in gridded data, which tells QGIS (or other programs) to effectively ignore pixels with that value and draw it as transparent on the map. This is usually a large negative number such as -3.40282e+38 or -9999, which guarantees it won’t interfere with analysis. If the nodata value is not what it should be, a perimeter of pixels in the grid will be counted in the min to max range and will be for all intents and purposes, useless – it will have to be fixed using geoprocessing tools before moving on.

The nodata value can be checked under the ‘transparency’ tab on the left in the properties.



Lastly, a visual inspection can be done by zooming in and examining features to see if they make sense. The identify tool can be used to tell the exact values upon clicking on a pixel to cross reference an area.

A basic water resources planning tool that be used in everyday analysis is the virtual application of a water plane, which can show which areas will likely be above and below the water line, whether the location is along a river or in a field depression. This isn't a perfect method but shows general risk.

Using the QGIS Raster Calculator

A very powerful tool in itself, the *raster calculator* lets you manipulate data by performing mathematical operations on each LiDAR pixels value. Calculations are quite quick, with millions of cells being able to be processed in a short amount of time! Open the raster calculator from the *Raster* menu. All rasters that are currently in the layer list will appear here in the space on the left, and the number after the 'at' symbol refers to the band number.

The way the calculator works is that an *expression* has to be supplied, where it will go over each pixel in the grid one by one applying it as it goes. Expressions can be simple or complex, but they have to follow what is called *syntax* – 'grammatical' rules of code in order to be carried out correctly.

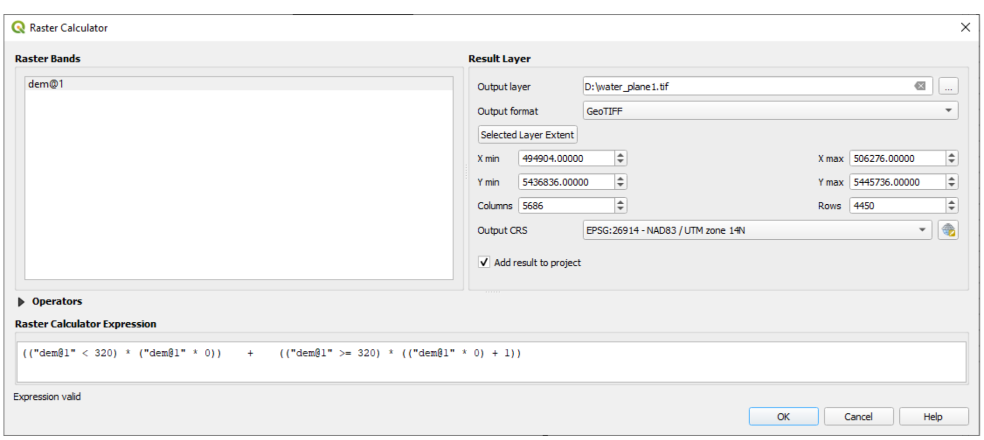
A simple way of calculating flood risk is using a flat plane representing the water's surface during a flooding event. The calculator can be used to create what's called a mask – this mask will show areas underneath the plane elevation and those above it.

The operation to do this is to assign two values to the output mask – 0 and 1 representing below and above the plane respectively. Using an example, the calculator expression would be done as follows:

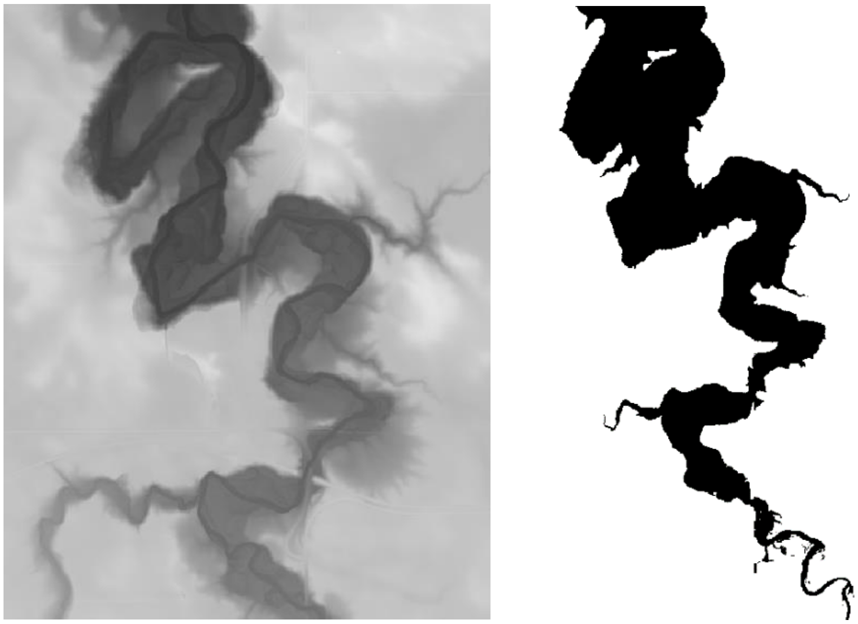
*(("dem@1" <= 320) * ("dem@1" * 0))   +   (("dem@1" > 320) * (("dem@1" * 0) + 1))*

Targeting values in the dem that are below 320, and multiply them by 0

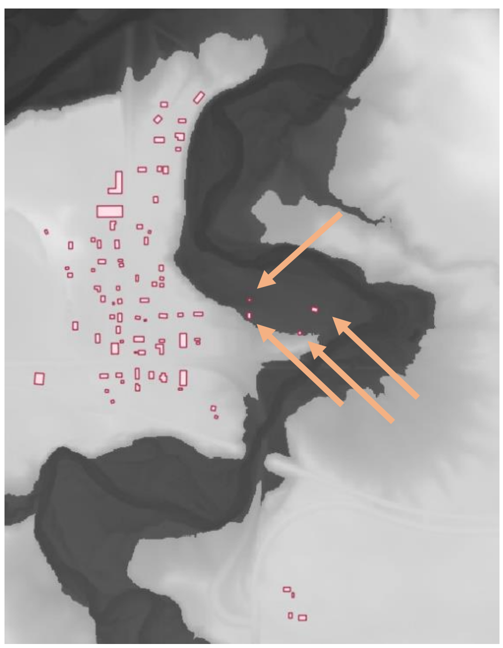
Additionally: targeting values above 320 in the dem, turn those pixels to equal 1



The output, by default, is displayed as a purely black and white grid. Using styling options, this can be changed to more accurately depict visual features such as water and green terrain.



Pictured above is a river valley with surrounding farmland – the left being the DEM and the right being the newly made mask. The DEM on the left has lightness corresponding to elevation – higher is lighter, and the mask on the right shows black as below the elevation cut-off (320 in this example) and white as above it.



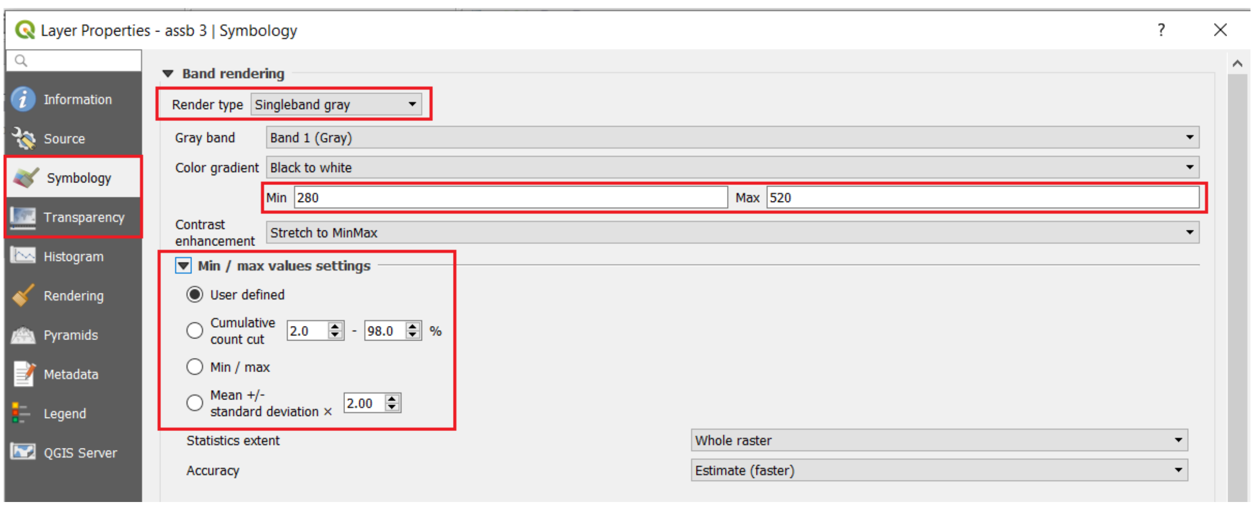
Here is the sample area with the flood masking applied to it by being overlain (semi-transparent at 50%) on top of the DEM, with buildings placed on it. What this significantly darker area here represents is the area of higher risk from flood inundation if the water level reached the elevation of the mask. The four buildings here would fall under this high risk zone.

Symbolizing Layers

QGIS maps and visuals would look bland and be completely uninformative without applying a sensible color and labeling scheme. Often the default randomly assigned symbology can be cumbersome to visually deal with not only for presentation purposes, but also for simply working with the data - especially with complex polygons!

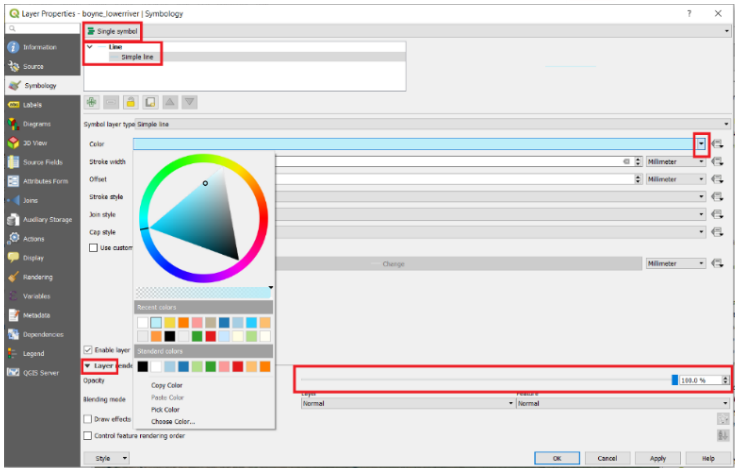
LiDAR and other gridded data

Raster data can be rendered in different coloured palettes. Greyscales can be shifted, and bands can be coloured differently. To change your raster, open its *properties* and hit *symbology* on the left tab. The *transparency* control is on a separate tab below it here, unlike for a vector layer.



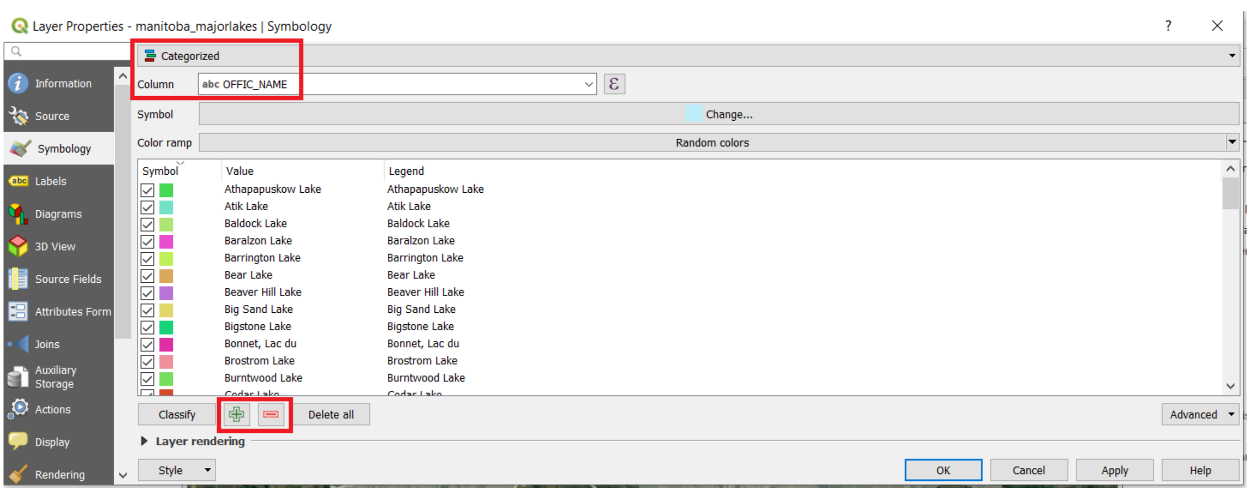
Vector based data such as the buildings

Select the file you want to re-colour and open its properties. Do this via right clicking the layer in the left layers menu and hitting *properties*. On the left tab select *symbology* to see the colour palette and display options.



Most often, simple quick tweaks can be done in this menu. The visual can be done either as a single colour or on a gradient based on a text or numeric value from the layer's attribute data. In using gradients, you can use any colour and outlines for fields and their values.

When you have a field selected, and a colour ramp chosen, hit *classify* to populate the table. You can leave the entries as is or change individual entries. When customizing an entry, click the colour bar for the *ramp* or *swatch* and click the arrow for the wheel. As with other image, spreadsheet and document programs, you can *pick* colours and save custom ones for later use.

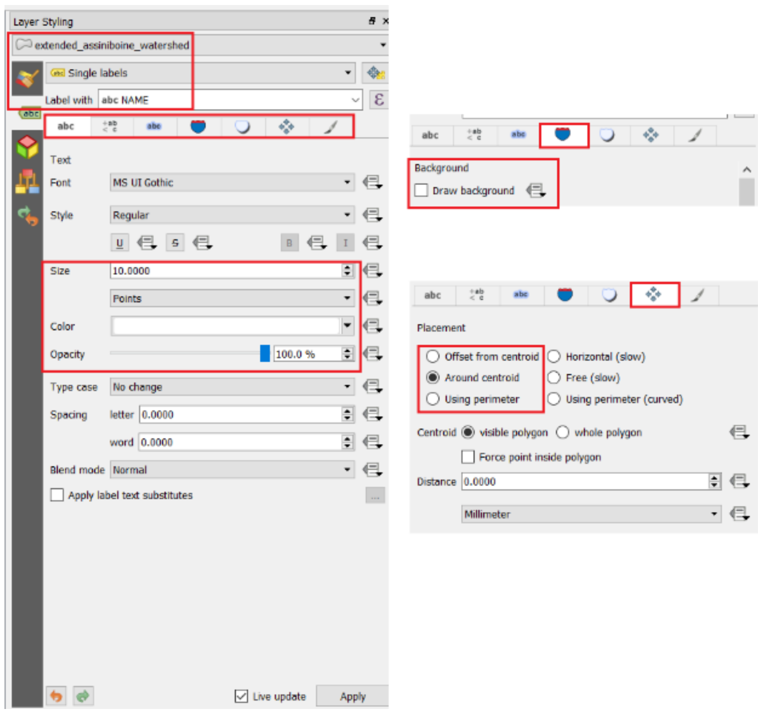


You can *add* and *remove* entries too, so you can show only the values you want to display. The *value* is the value in the attribute table to represent – the *legend* is the text that shows up on the left in the layers list, which can be whatever text you want. If a value isn't represented in the symbol list, it's shown as completely transparent.

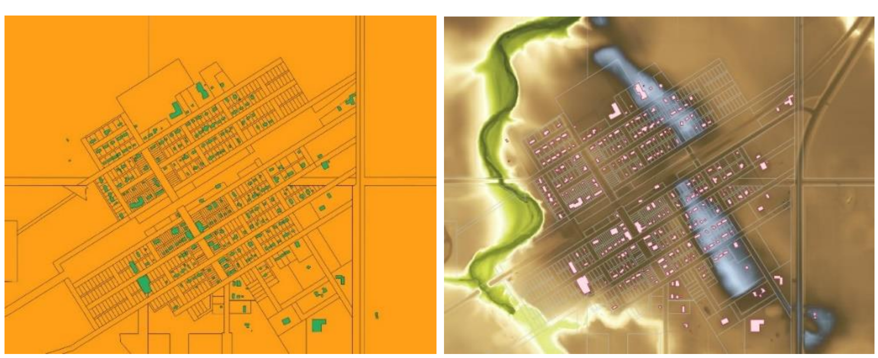
Labelling Layers

Simple labels can also be added for easy identification of features during and after making a map. Labels are applicable to vector files only.

To label your layer, pull up the labelling toolbar by right-clicking on the top area. Now hit the *label* button to pull up a separate window with labelling tools. Alternatively, you can click this tab in the layer properties.



Here you will be able to tell QGIS which field you want to symbolize, and its colour + location on the map. Alternatively for simple labelling work after publishing a map, other programs such as Photoshop, Gimp and MS Paint can be used. In any case, play around and see which placement option works the best for you.

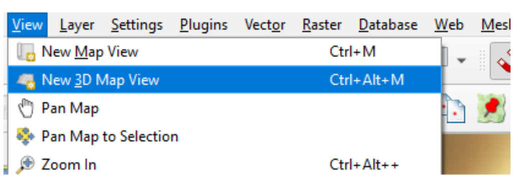


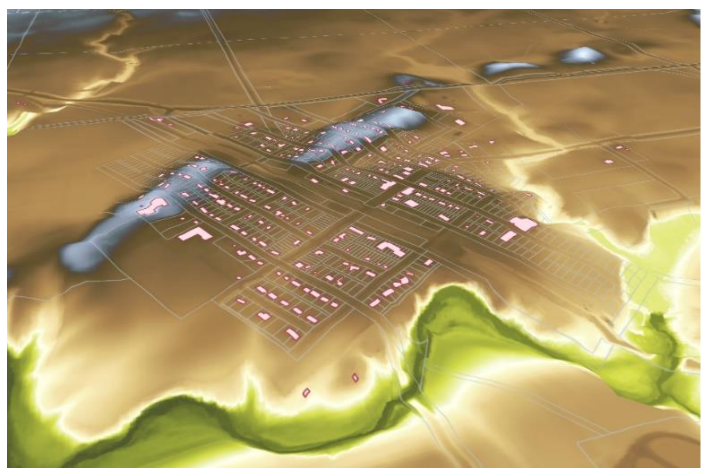
Here is an illustration of a town, with buildings, land parcels and DEM data showing how symbology can drastically change the visuals on a map. When vector layers are added they are given a random colour and are opaque - or in the case of raster data, they are greyscale. Note that the DEM is hidden in the before picture on the left.

Using the 3D Viewer

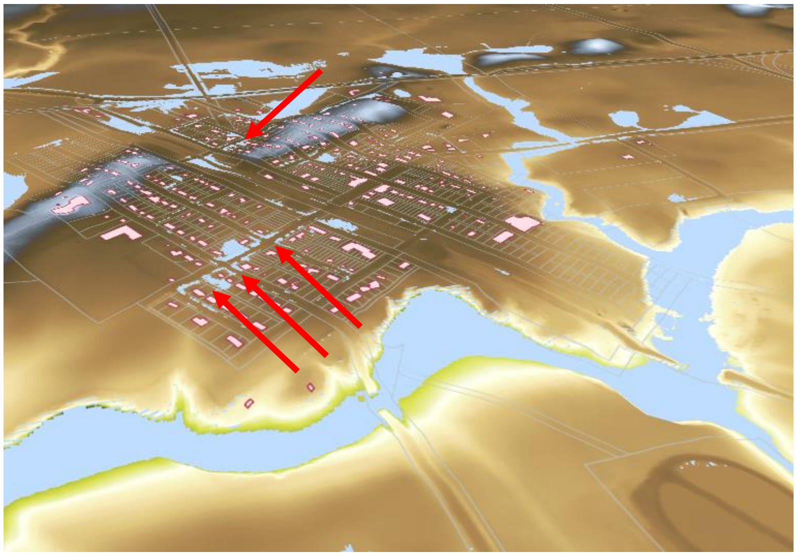
QGIS has a built in 3D viewer, which works well in showcasing elevation differences for a given area from an aerial view. To access it, click the *View* menu item and then hit *New 3D Map View*. The layers that you see on the regular map, will appear in the 3D viewport as well. You can resize and move the viewport to a more convenient location if you wish.

Under the settings, which shows at the top as a wrench icon, you can tell QGIS to use the DEM as the elevation, and set a vertical exaggeration factor (use between 1 and 14) to use. If the screen appears blank, you can use the mouse wheel to zoom out until your layers appear. You can rotate the camera by holding down the shift button while dragging the mouse around. To take a screenshot, click the picture icon.





Shown here is the graphic from above in the 3D viewer, with a small vertical exaggeration applied.



Here is the same 3D scene with a blue mask layer added, where several buildings appear in the flood risk zone.

Publishing A Map

After labelling and symbolizing are completed to your satisfaction, a mapping product can be created. First zoom and pan over to the extent you wish to show. Then once everything is in frame, hit the *Project* menu item, then *Import / Export* > *Export Map to Image* options. A menu will pop up with some settings – leave them as they are, with the exception of DPI, which can be increased to 300 if you want a hi-res image.

A 'Save As' window will appear where you can save the file. Once done the map product will be published.

Conclusion

LiDAR is an incredibly useful and affordable way to obtain elevation details on the landscape which was not feasible or even possible in the past. LiDAR is a game changer for being able to model fluvial and pluvial flood risk across vast domains, and the increased computational availability will make this easier as the years go on.

This section discussed basic operations with LiDAR, however in future publications, more in depth techniques and tools will be shown in order to more accurately provide estimations for:

- benefits, costs and risks of flood inundation and drought for every area of each land parcel
- detailed water retention storage and flow pathing from algorithms
- more detailed estimations of hydrological balance, given soil, temperature and vegetation cover

LiDAR will undoubtedly be ever more useful in the years ahead, and the increasing availability of it will help drive more jurisdictions to be able to use it in order to make sensible, informed decisions on how to mitigate risk and make climate-focused preparations.

This combined video series and manual was developed by the Red River Basin Commission and completed with the help of Strategic Systems Engineering. The focus is to assist and help develop user-friendly resources so that First Nations/Indigenous communities, Municipalities, and Counties can operate more efficiently and better adapt themselves for future weather events, whether that be flood, drought, or other climate adaptation needs.

It is our hope that this is the beginning of a series of manuals which will guide the user from the beginning stages to an advanced user level.

We wish to thank Strategic Systems Engineering, Town of Morris, City of Winnipeg, Manitoba Association of Watersheds, and the Red River Basin watershed districts and their managers for their assistance and guidance on creating this educational resource. We also would like to thank our funders, Federation of Canadian Municipalities, and the Royal Bank of Canada.

Appendix 3: Complete International Hydrologic Model of the Red River Basin

A Complete International HEC-HMS Hydrologic Model of the Red River Basin: Implications for flood and drought planning

Hank Venema, PhD, P.Eng
Scott Pokorny, MSc, EIT

STRATEGIC SYSTEMS ENGINEERING INC.

RED RIVER BASIN COMMISSION

American Acknowledgements

RED RIVER BASIN COMMISSION

US Army Corps of Engineers®

HEC-HMS

BOARD OF WATER AND SOIL RESOURCES

PTM App

HOUSTON ENGINEERING INC.

International Water Institute

LiDAR

Canadian Acknowledgements

GLOBAL WATER FUTURES
SOLUTIONS TO WATER THREATS IN AN ERA OF GLOBAL CHANGE

Integrated Modelling Program for Canada
Global Water Futures

WINNIPEG METROPOLITAN REGION
20 TO 50 Securing Our Future

NRC Industrial Research Assistance Program

RED RIVER BASIN COMMISSION

PACIFIC CLIMATE IMPACTS CONSORTIUM

Agriculture and Agri-Food Canada
Agriculture et Agroalimentaire Canada

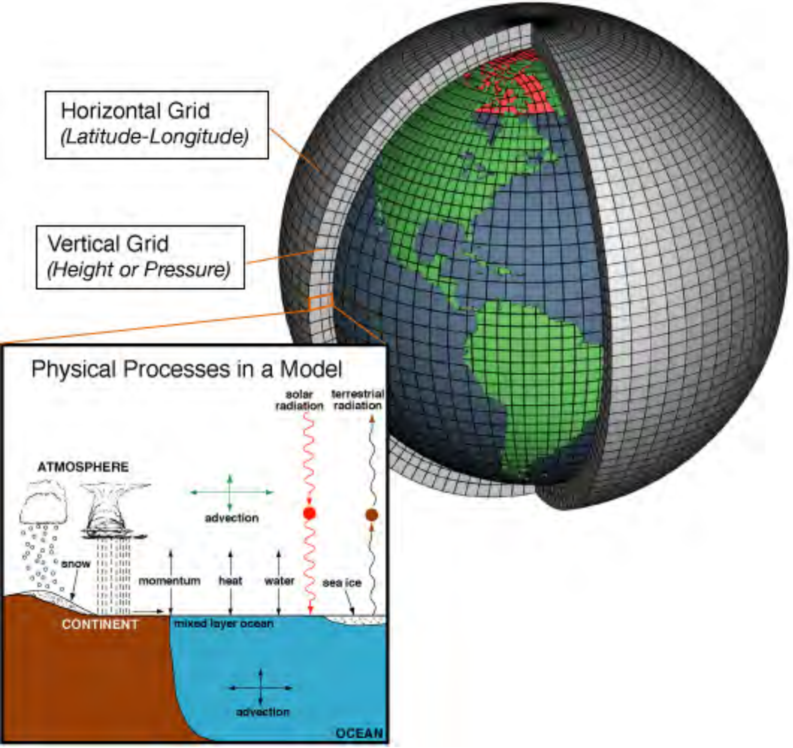
Environment and Climate Change Canada
Environnement et Changement climatique Canada

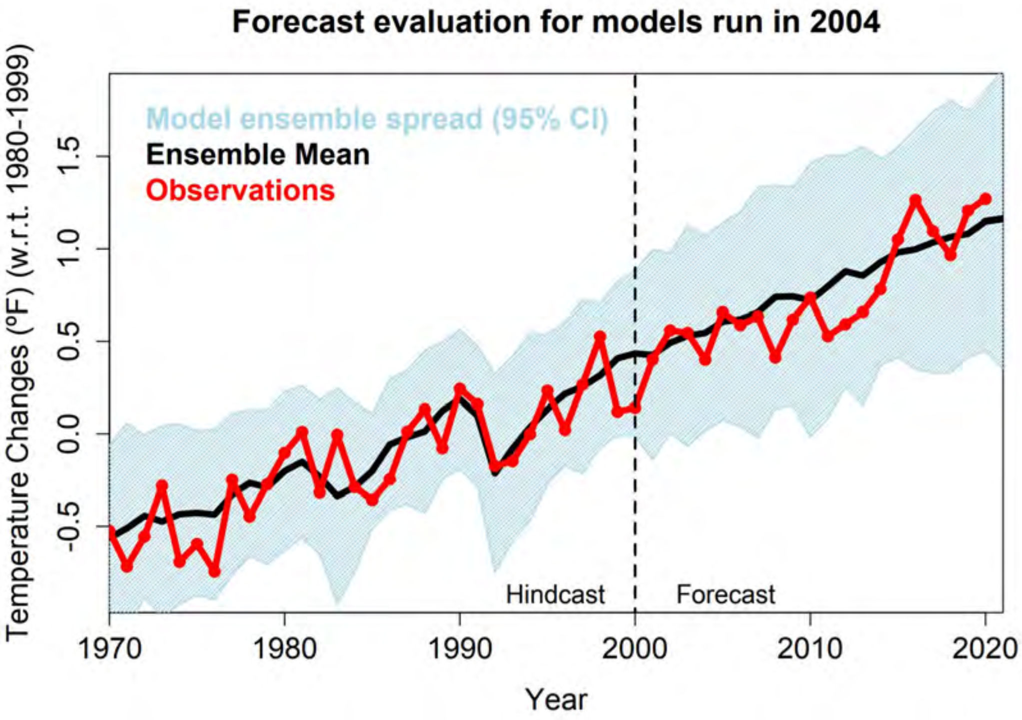
Manitoba

Research Manitoba

What are our key Climate Change Impacts?

Should We Believe the Science of Global Climate Models? (YES)



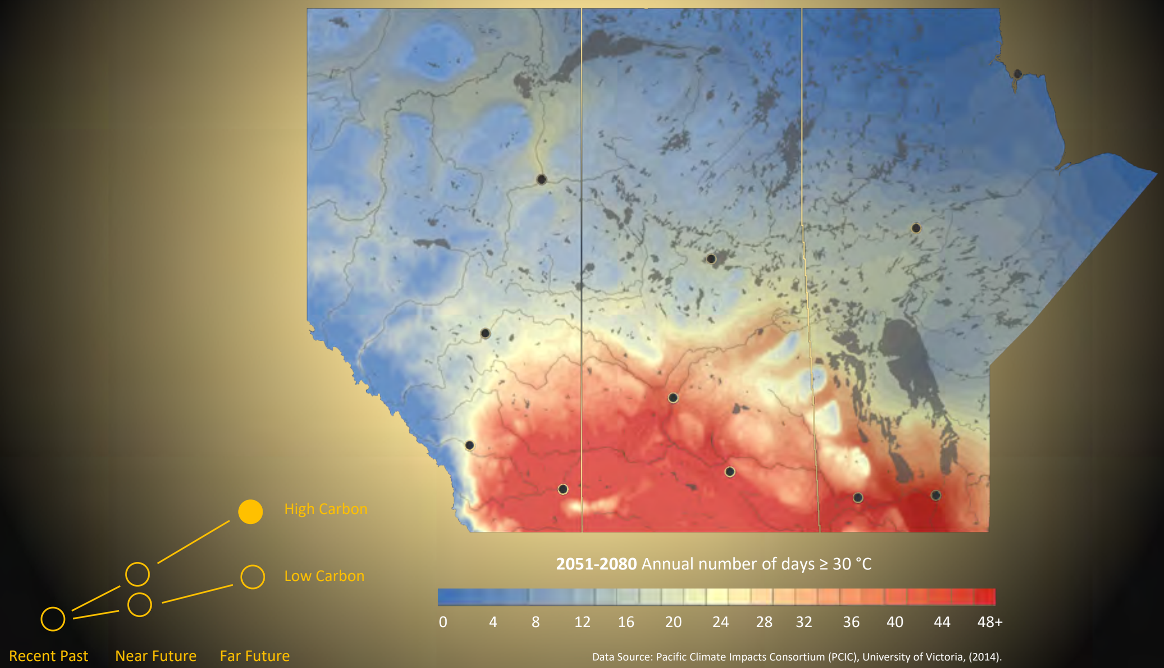


Source: https://climate.nasa.gov/news/2943/study-confirms-climate-models-are-getting-future-warming-projections-right/

Shifting Extremes

Change in the Number of Very Hot Days

Prairie Climate Centre



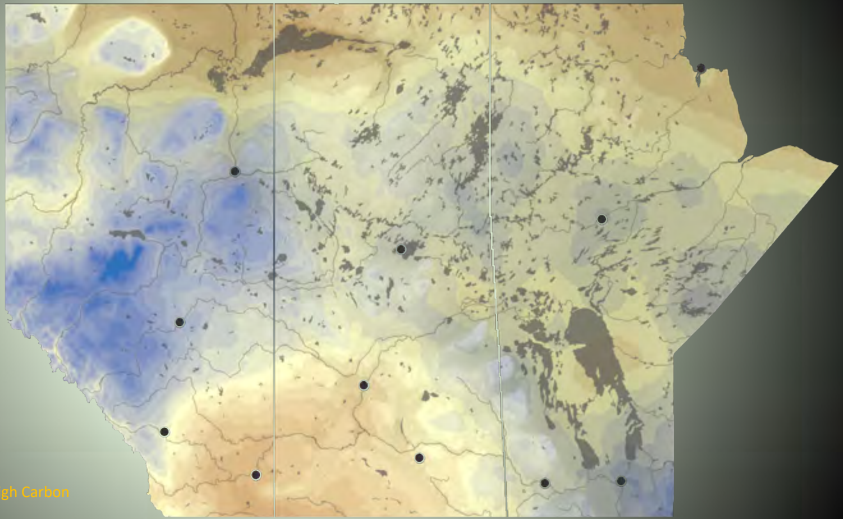
Data Source: Pacific Climate Impacts Consortium (PCIC), University of Victoria, (2014). Statistically Downscaled Climate Scenarios. Downloaded from pacificclimate.org.

Prairie Climate Atlas (circa 2015)

Prairie Precipitation

Projected Changes in Total Summer Precipitation

Prairie Climate Centre



High Carbon

Low Carbon

Recent Past Near Future Far Future

2051-2080 Total Summer Precipitation (mm)

70 90 110 130 150 170 190 210 230 250 270 290+

Data Source: Pacific Climate Impacts Consortium (PCIC), University of Victoria, (2014). Statistically Downscaled Climate Scenarios. Downloaded from pacificclimate.org.

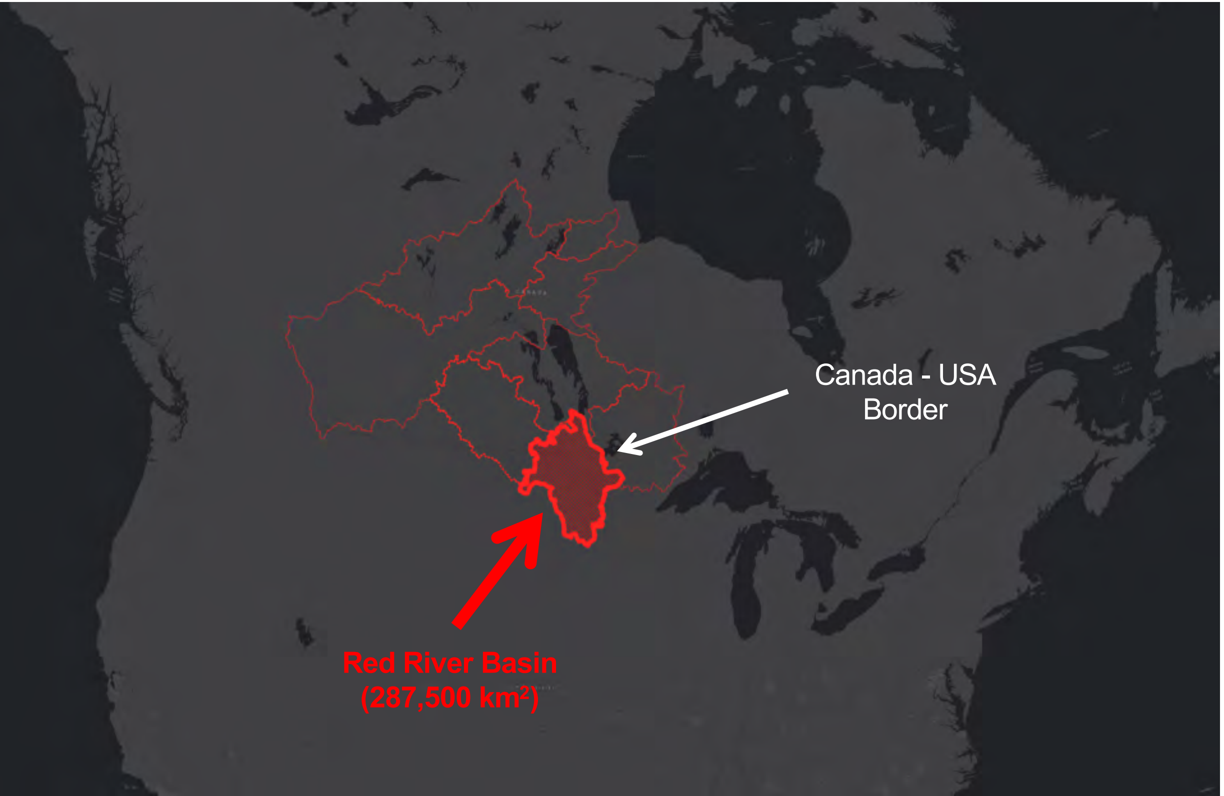
Key Messages

- Much hotter (all models agree)
- More variable precipitation (most models say more)
- Heat dominates; thirstier crops, soils and atmosphere
- Precipitation will generate less runoff on average; moisture disappears into cracks in the ground and back to atmosphere

Red River Basin Hydrology

Modelling the joint effect of temperature and precipitation changes

Red River Basin



The Red River presents a challenging case study, which must confront data discontinuity at the Canada-USA border

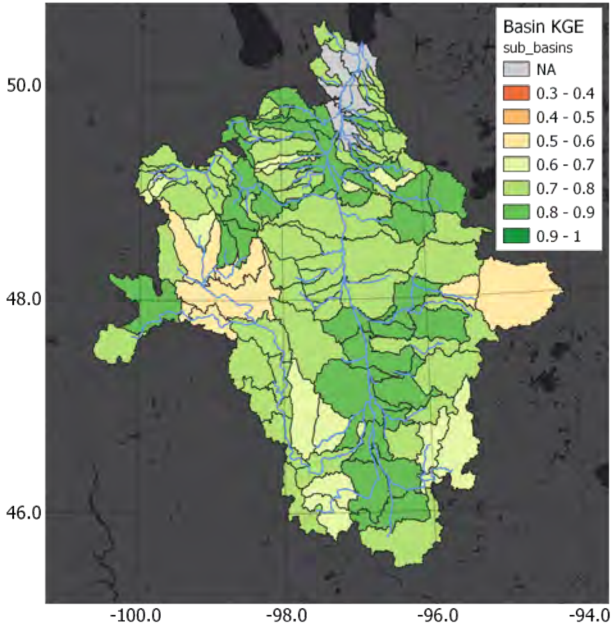
Many International datasets used to overcome boarder impacts

Red River Hydrologic Model
A Seamless International Model

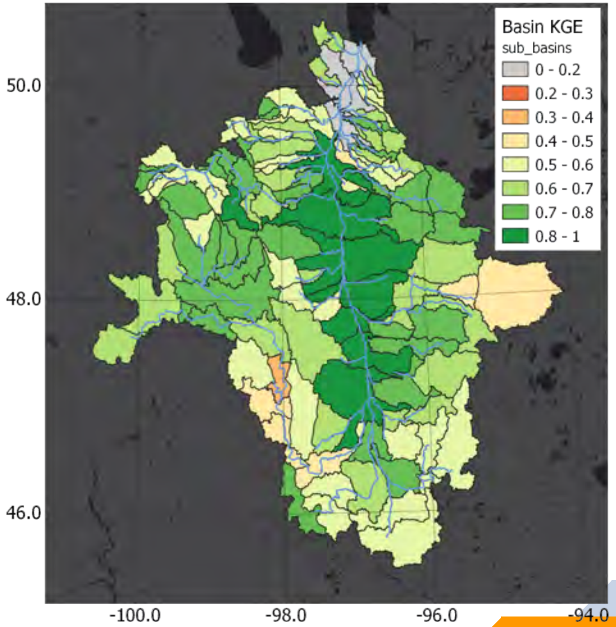
Calibration goal > 0.7
Validation goal > 0.6

Strong model performance

Calibration KGE Scores



Validation KGE Scores



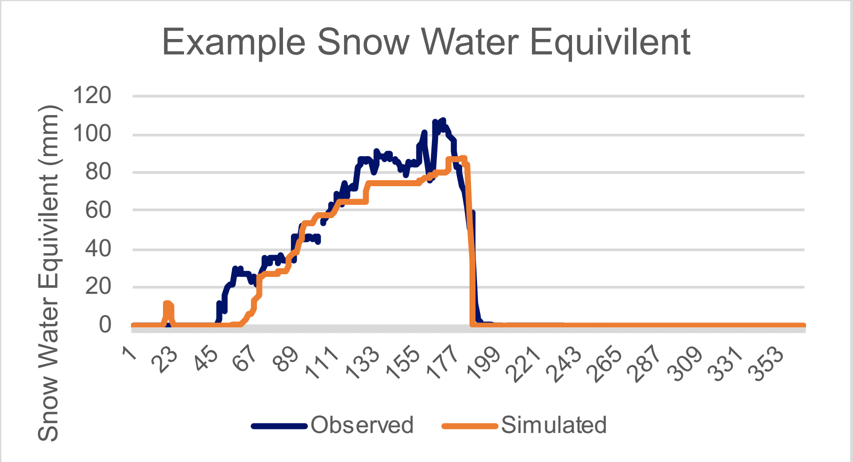
GLOBAL WATER FUTURES
SOLUTIONS TO WATER THREATS IN AN ERA OF GLOBAL CHANGE
GHENT
esa
Integrated Modelling Program for Canada
Global Water Futures
HEC-HMS
US Army Corps of Engineers

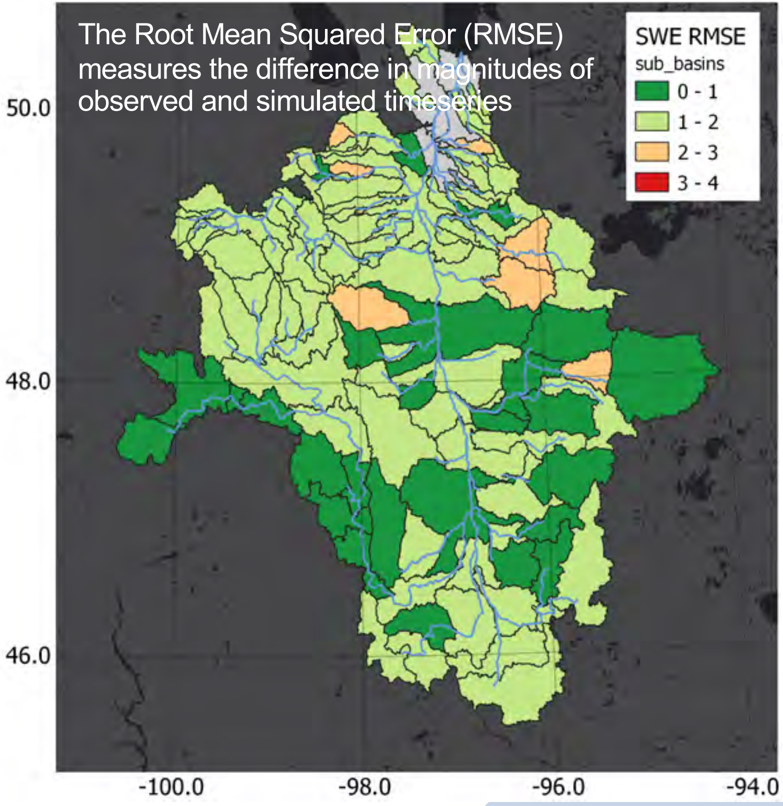
Snow Accumulation, Snow Water Equivalent modelling on a daily time step

Snow is a major driver of spring flooding and water harvesting potential

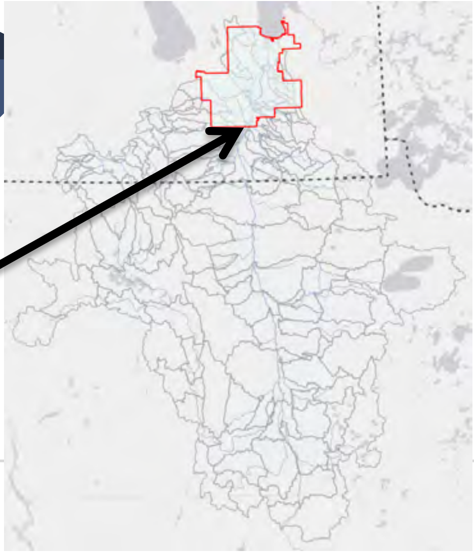
Its tracked in equivilent water volume

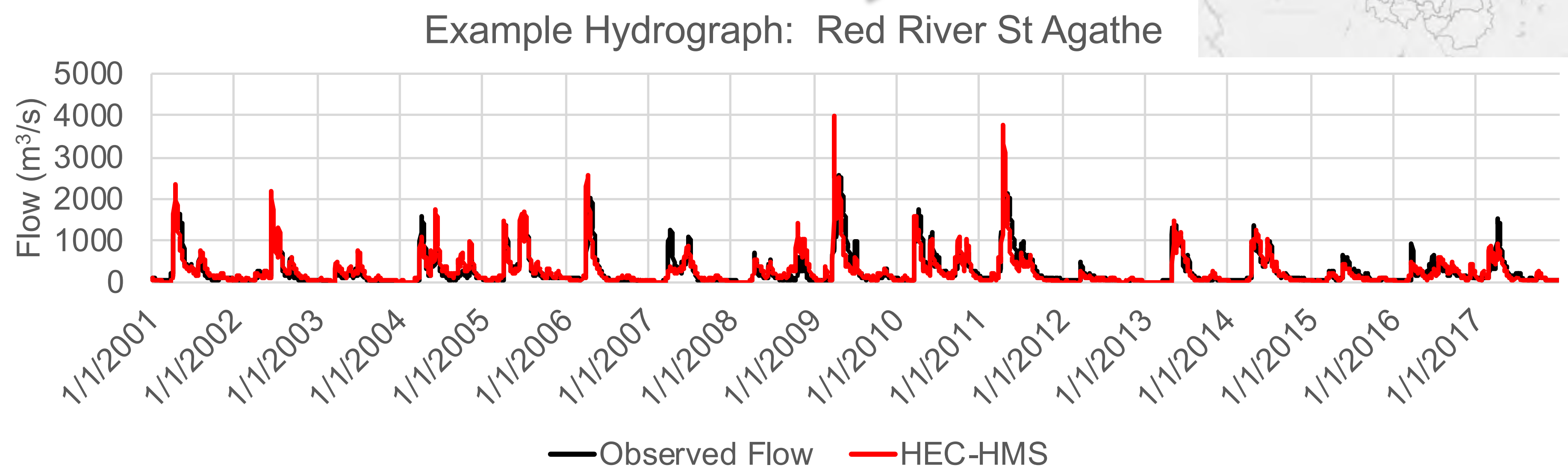
RRB average winter bias = 4%





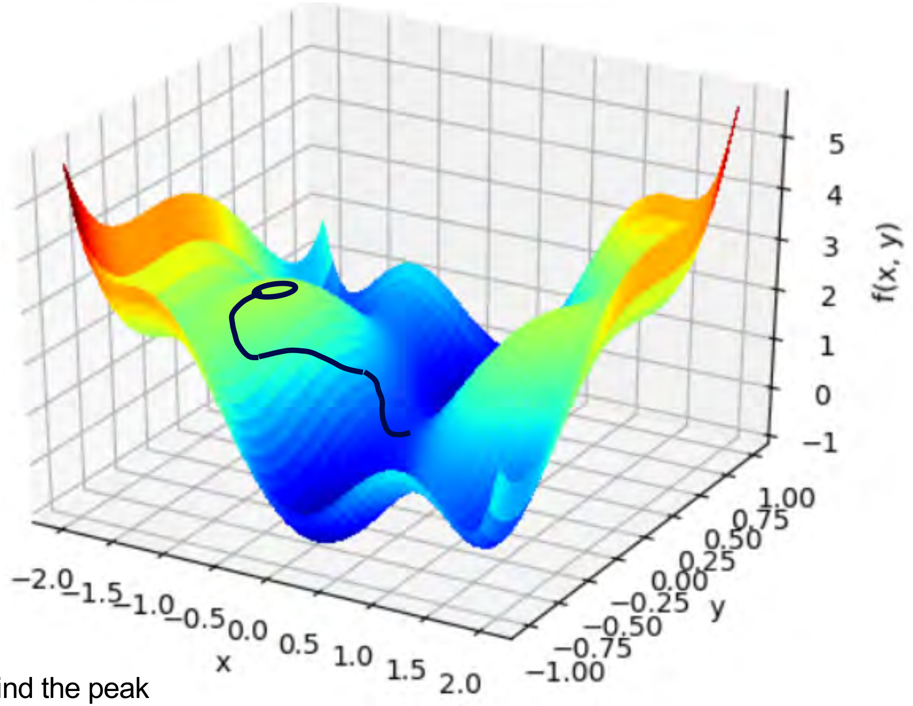
Q. How Did We Do?
A. Very good -> Excellent, high KGE scores in calibration and validation:





Q. Why is this model so good?
A. Multi-objective Optimization for Parameter Selection:
Pareto Efficiency concepts

Parameters (calibrated for each sub-basin)
1 surface storage parameter
11 soil parameters
2 overland transport parameters
1 evapotranspiration parameter
2 snow melt process parameters
2 river routing parameters
2 lake routing parameters



Calibration is like trying to find the peak of a mountain, but blind folded. The higher you get, the better your performance

Climate Change Impacts on Red River Basin Hydrology

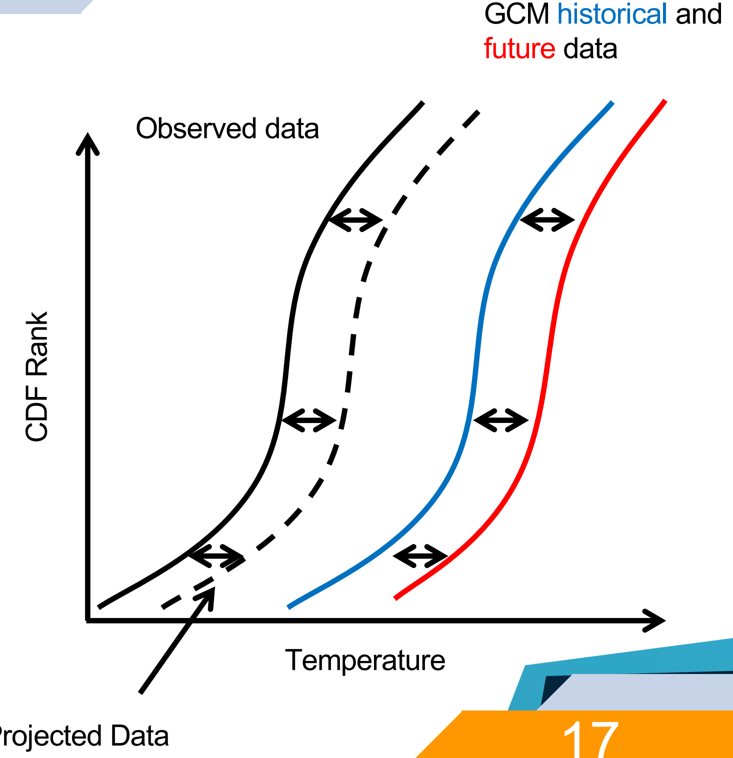
Collaborative North American Climate Data Product: Seamless @ 49th parallel

NA-CORDEX

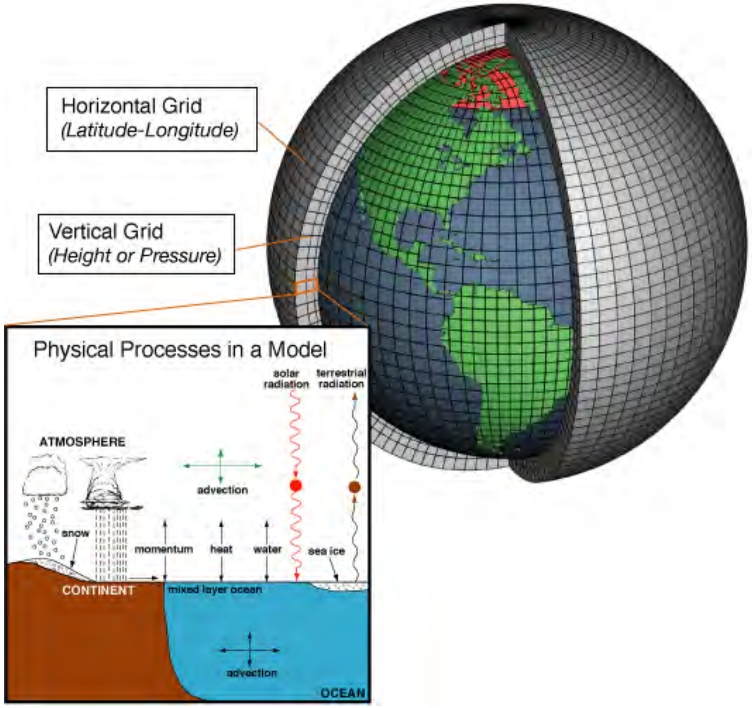
Iowa State
University of Arizona
National Center for Atmospheric Research (NCAR)
Ouranos
L'Université du Québec à Montréal
Canadian Centre for Climate Modelling and Analysis

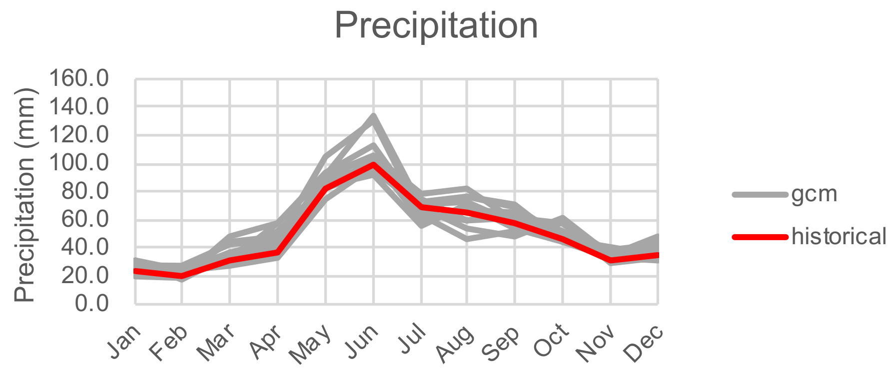
CORDEX-NA simulation domain, 0.44°/50km resolution

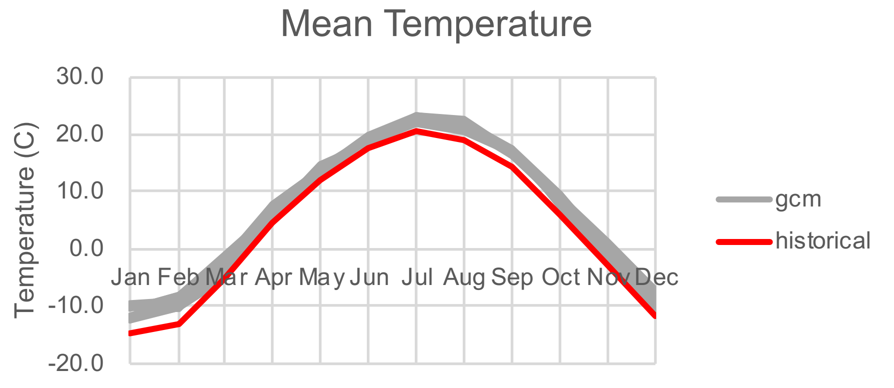
Equi-distant quantile mapping for GCM bias correction



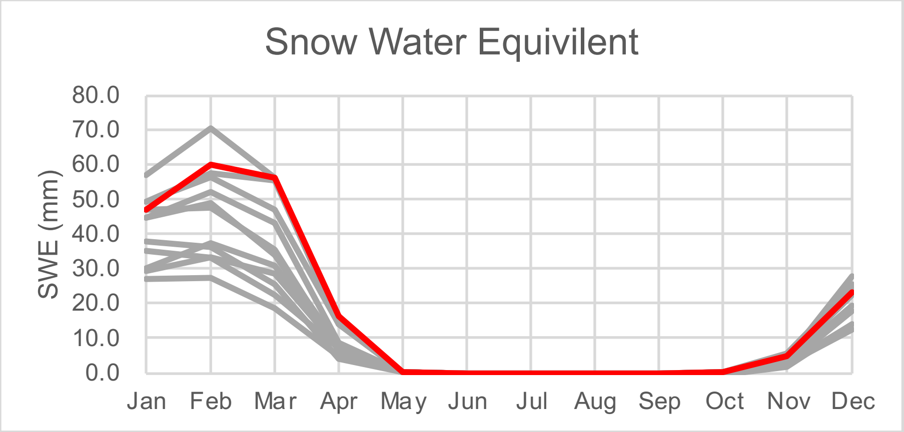
Global Climate Model Projections For Red River Basin

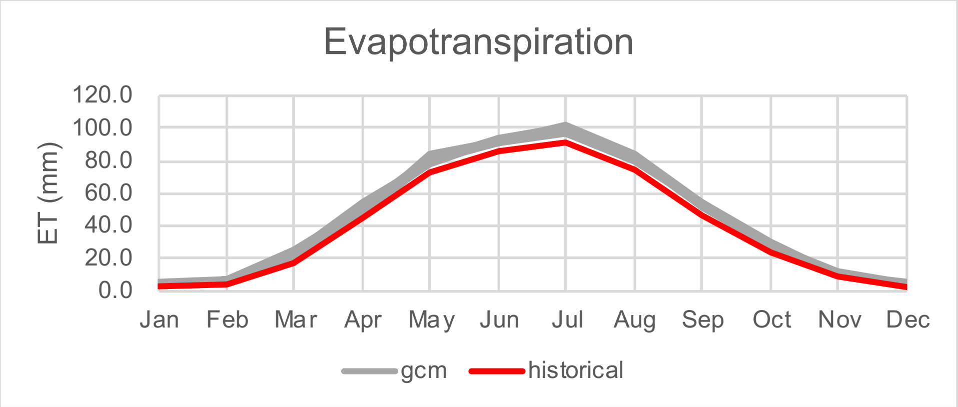


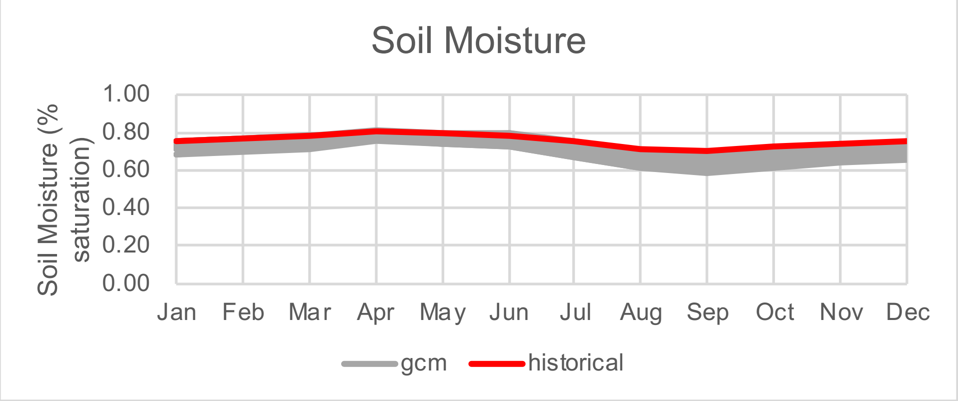




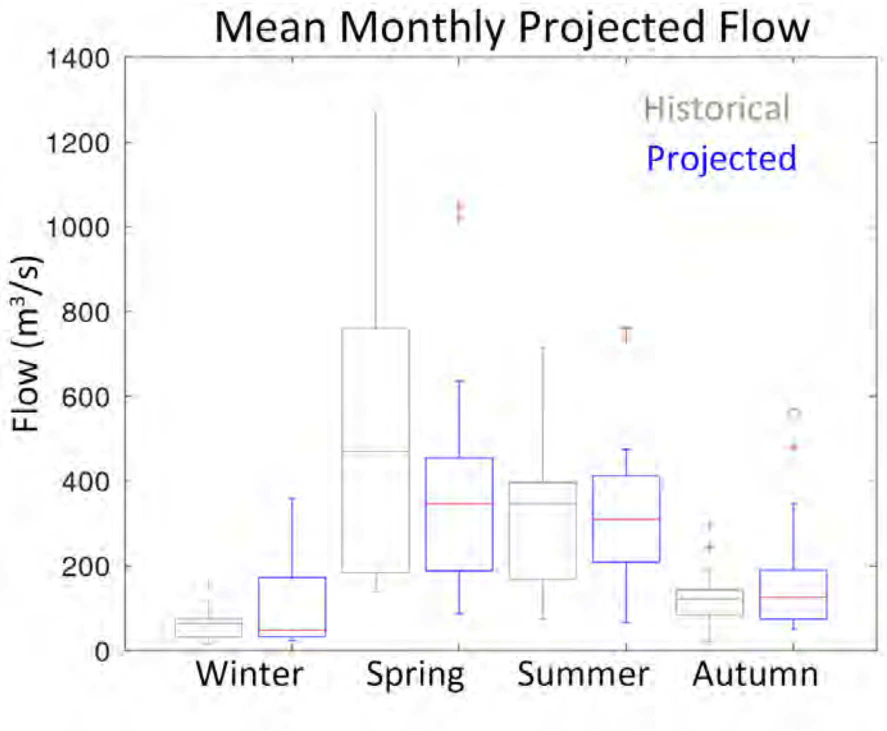
Shifts in water availability are driven by changes in hydrologic processes







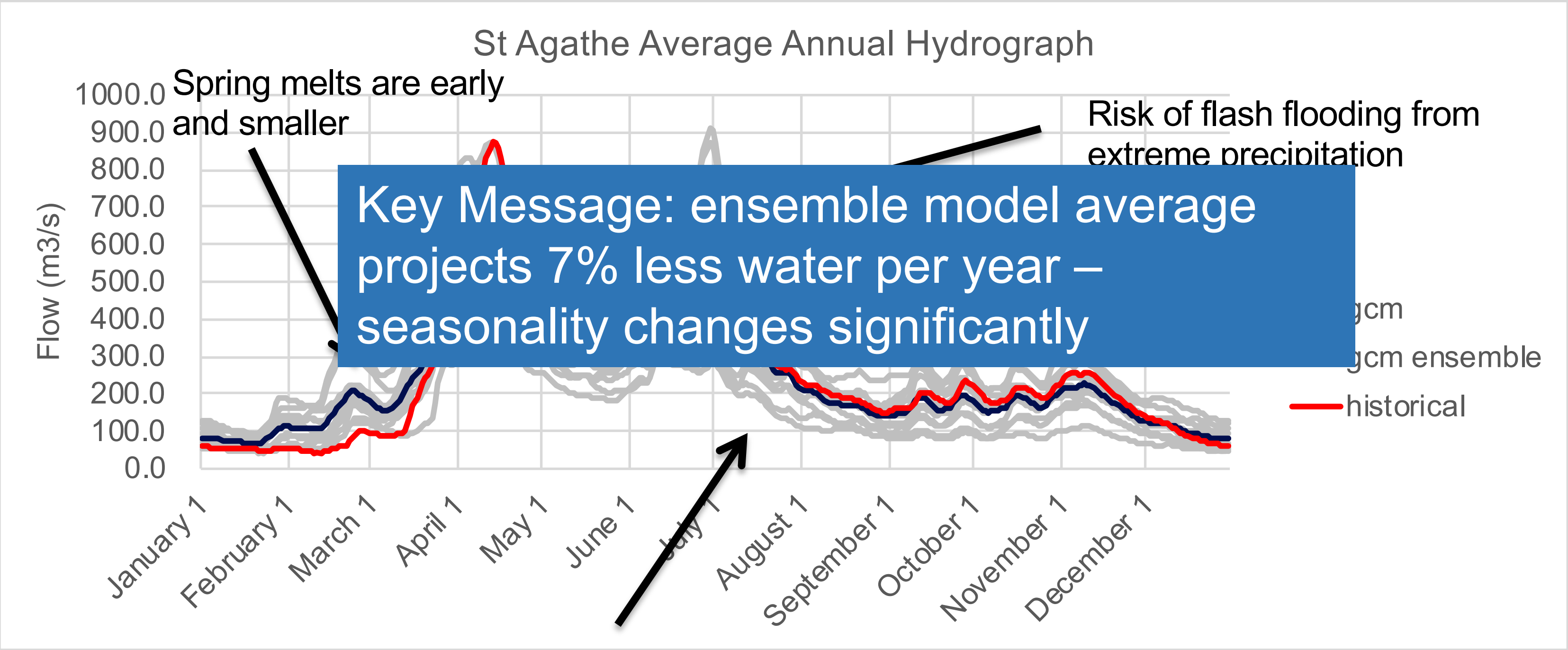
Seasonal Shifts: Spring Drought Risk, Fall Recharge Potential Evident



- Average flow volumes from the ensemble of GCMs are lower in Winter, Spring, and Summer

- Lower high flow risk in Spring, but some high flow risk remains in Summer

Climate Impacts on Red River Hydrology (@ St. Agathe)



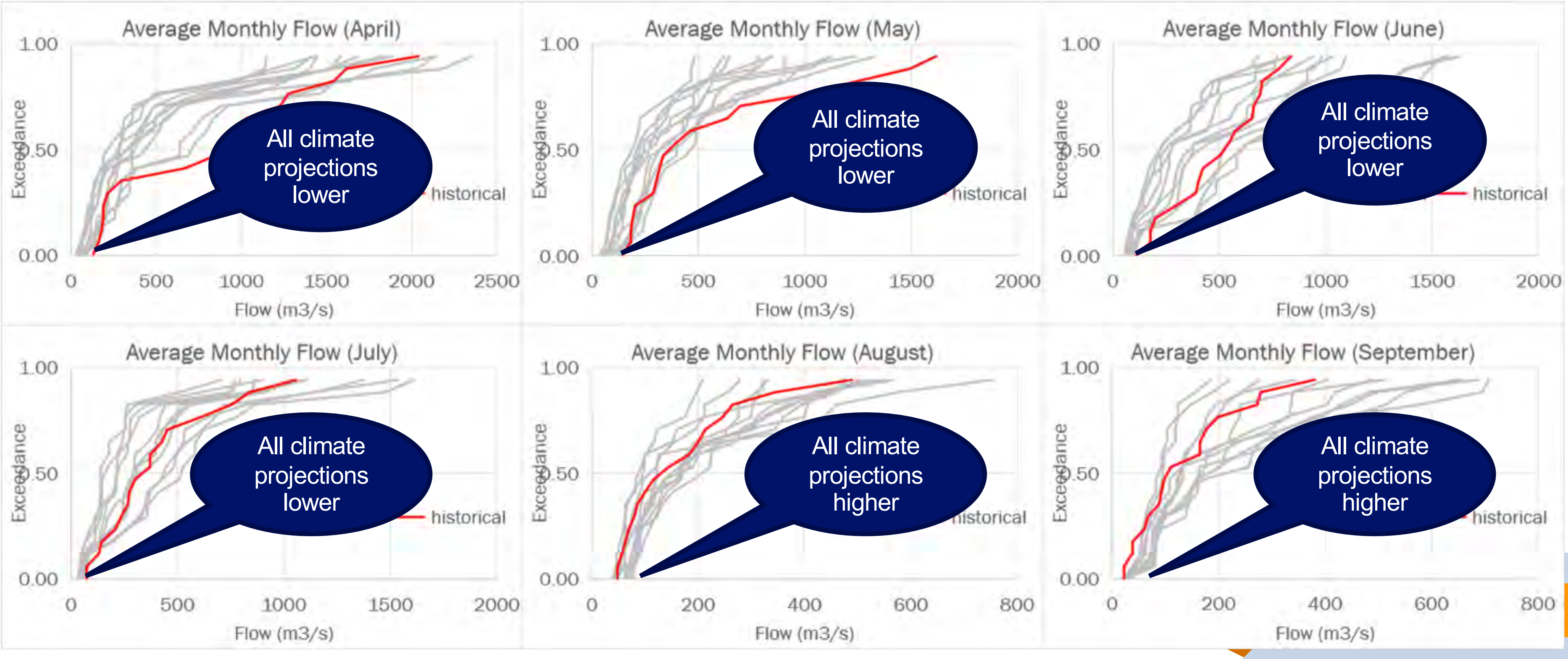
Key Message: ensemble model average projects 7% less water per year – seasonality changes significantly

Most models suggest lower runoff volumes

Extreme Low Flow Risk Analysis: Red River @ St Agathe (April – September)

Left of red = Drier

Right of red = wetter



15 PhosFinder

Phosfinder is a Canadian Alternative to PTMapp ingests 1m LiDAR-derived DEMs

Developed Collaboratively

Environment and
Climate Change Canada
Environnement et
Changement climatique Canada

IISD
International Institute for
Sustainable Development

RED RIVER BASIN COMMISSION

Phosfinder is a Canadian alternative to PTMapp – designed to use the high resolution 1m LiDAR available in Manitoba

15 PhosFinder

PTMApp

STRATEGIC SYSTEMS ENGINEERING INC.

PhosFinder

Can be used to locate and size nutrient phyto-extraction projects

Biomass Harvesting for:
Nutrient Phyto-extraction via
Composting, combustion,pyrolysis
(biochar)

MacDon

The Harvesting Specialists.

Learn and Download PhosFinder

- OVERVIEW: https://strategicsystemsengineering.ca/tools/
- EXPLANATORY VIDEO on the RRBC Youtube Channel

- FACT SHEET: https://strategicsystemsengineering.ca/wp-content/uploads/2022/01/Phosfinder_fact_sheet_for_distribution.pdf.
- SOURCE CODE: https://gitlab.com/strategic_systems_engineering/phosfinder.

Lets Work Together

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Appendix 4: South Region Climate Adaptation Case Study: City of Morden Water Supply

Morden Water Supply

Phases 1+2 Pembina Diversion Feasibility Study: Hydrologic and Hydraulic Analyses

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December 2, 2021

Strategic Systems Engineering Incorporated

Contents

1 Introduction

1.1 Context

The City of Morden, in conjunction with the Pembina Valley Watershed District and the Rural Municipality of Stanley, has retained the services of Strategic Systems Engineering Inc.(SSE) for feasibility-level analysis supplying water to the Town of Morden via diversion from the Pembina Watershed. SSE recommends an 8.4 km pipeline route, with a discharge point in the upper reach of south branch of the Deadhorse Creek, which is forward-compatible with construction of an additional storage reservoir to compliment Lake Minnewasta.

The City of Morden currently meets its water demand through treating water stored in Lake Minnewasta, a large reservoir constructed on the Deadhorse Creek (DHC), upstream of the city. With particularly severe droughts, however, Lake Minnewasta can fail to meet demand. This occurred during 2021 where spring snowmelt and summer precipitation were significantly below normal, requiring widespread community water restrictions and construction of additional booster stations to supplement water from the Pembina Valley Water Cooperative.

A recent study by Associated Engineering[1] reviewed water needs projected 20 years into the future. Associated Engineering determined that approximately 1,000,000 m^3 of additional water will be needed. Climate change may further decrease Lake Minnewasta's reliability. Therefore, a pipeline transfer from the Pembina Watershed to the Deadhorse Creek Watershed is identified in this report as feasible given our hydrologic modelling. A preliminary cost estimate for the pipeline is also provided. The recommended pipeline discharge location is in the upper reaches of the south branch of the Deadhorse, where the valley is well-incised, thus constructing a second reservoir is technically feasible and also considered in this study as an additional measure to supply water for the fast growing population of Morden. The Pembina diversion concept is not new, having been identified as a key option for augmenting Morden municipal supply in a 1987 water supply master planning study led by the Prairie Farm Rehabilitation Administration[2]. The PFRA study also anticipated that a "balancing reservoir" would be constructed above Lake Minnewasta, but provided no details on the recommended capacity or specific location of this second reservoir.

[1] Morris, A., Anderson, K. (2021). Town of Morden Flow and Population Projections Technical Memorandum. Associated Engineering.

[2] PFRA, 1987. Prairie Farm Rehabilitation Administration Engineering Service. Assiniboine South – Hespeler Area Study. Appendix B Engineering.

The Pembina River is an international water body, entering the United States further downstream, and a diversion could produce negative downstream environmental impacts and significant regulatory scrutiny, thus the diversion scheme analysed in this report is assumed to divert water only during a two-month high-flow season (usually April and May), when reducing flow would generally benefit downstream communities.

1.2 Study Region

The Deadhorse Creek (DHC) watershed upstream of Lake Minnewasta has a catchment area of approximately 131 km^2, which it relies on to refill the reservoir with snowmelt and precipitation runoff. Comparatively, the Pembina River watershed upstream has a catchment of approximately 10,500 km^2 prior to the Red River confluence – 80 times larger.

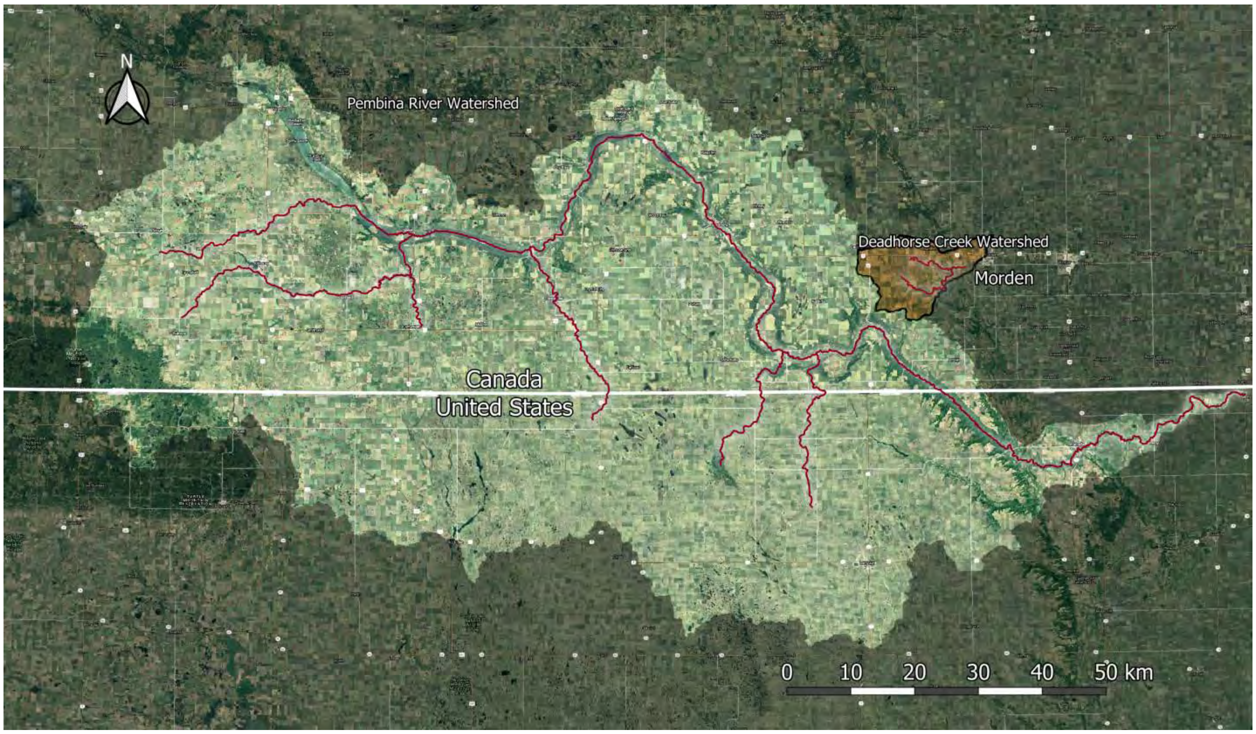

Figure 1 - Deadhorse Creek watershed (brown) and Pembina River watershed (green)

This study focused on the DHC watershed upstream of Lake Minnewasta. A small (~3 km) length of river exists directly upstream of the current reservoir, beyond which the river forks into two distinct reaches. Approximately 9 km of the northern fork was analyzed in section 5 of this report, for potential candidate locations of a second storage reservoir, while approximately 14 km was analyzed on the larger, southern fork. The southern fork of the DHC is also the reach which borders the Pembina River watershed, and therefore also a candidate discharge location for the diversion pipeline studied in section 4.

A continuous 1m Digital Elevation Model (DEM) derived from LiDAR was used for reservoir siting and for the pipleline hydraulics analysis. The DEM is publicly available from the Manitoba Land Initiative.

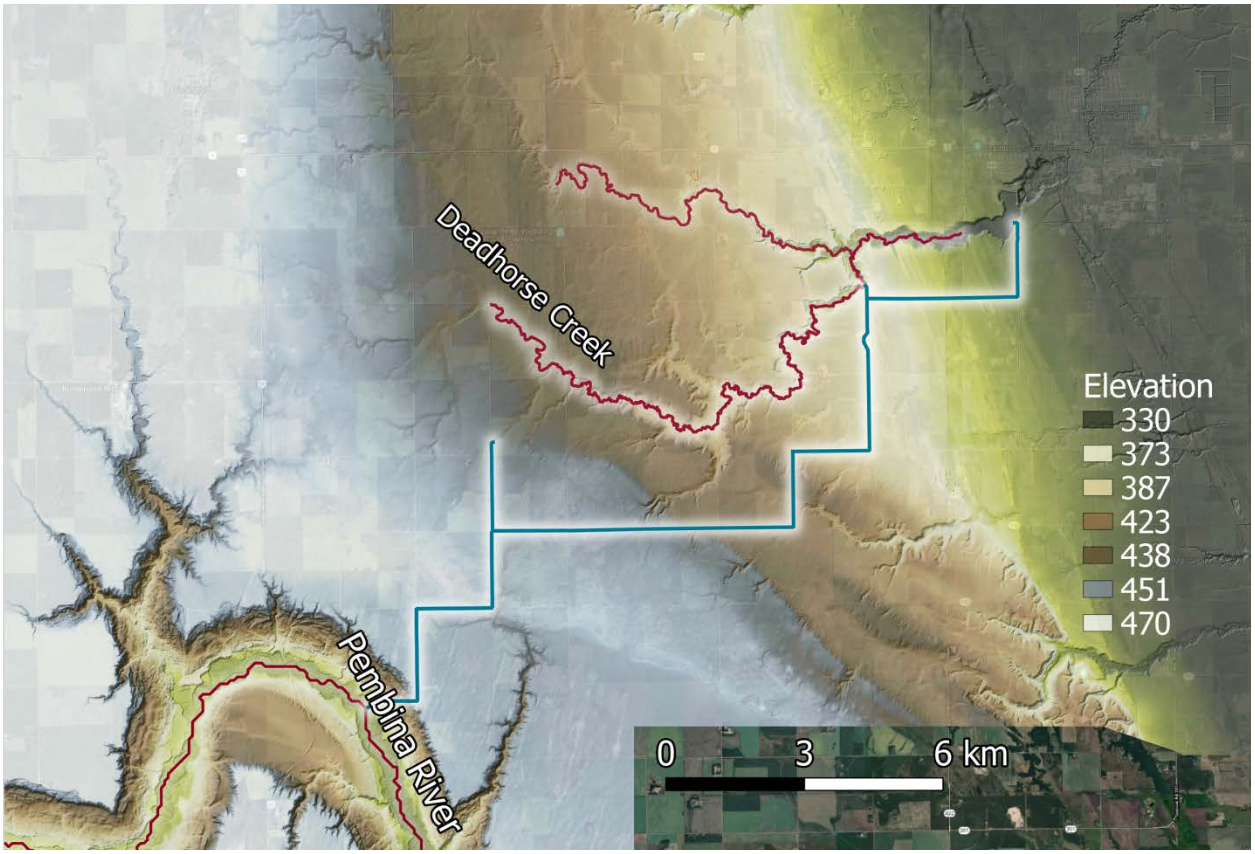

Figure 2 - DEM for the study area, from 1 m LiDAR.

2 Demand Estimation

2.1.1 Methodology

Morden's recent population growth and aspirations for continued growth are stressing surface water resources available from the town reservoir, Lake Minnewasta. At current growth rates of 3% per annum, Associated Engineering projects a demand for an additional 1,000,000 m^3 of water from Lake Minnewasta for Morden's recently upgraded water treatment plant. The additional water supply cannot be reliably supplied from Lake Minnewata.

Moreover, climate change is projected to further decrease overall water availability through increased evaporation, reduced spring freshets, and will increase water demand for irrigation.

A reliable estimation of the design flow required to meet Morden's projected demand will require full systems modelling, including hydrological modelling of both the Pembina watershed (future supply) and the Deadhorse watershed (existing supply) upstream of Lake Minnewasta, and systems modelling of Lake Minnewasta (existing storage) and potentially a second reservoir. For accurate estimation of design flows, and to satisfy funder (Infrastructure Canada) due diligence requirements, the hydrologic models were constructed to account for climate change impacts.

2.1.2 Transfer Rate Estimation

A firm flow diversion from the Pembina River is infeasible given existing hydrologic constraints and occasional extreme low flows. Therefore, a base assumption for the pipeline transfer that will occur in the spring freshet. A transfer schedule of between 45-60 days generates transfer rates of 255 L/s - 195 L/s respectively. A base transfer rate of 250 L/s is therefore used for initial pipeline design in later sections.

A second criterion is also considered for transfer rate estimation based on keeping Lake Minnewasta at full supply through the spring freshet. SSE assumes that it will be desired to finish the spring freshet with full supply in Lake Minnewasta. Therefore, water levels were analyzed for May 31st using the historical Water Survey of Canada (WSC) water level record and a conservative water level was selected at approximately 1 in 10 year low water level (Figure 3).

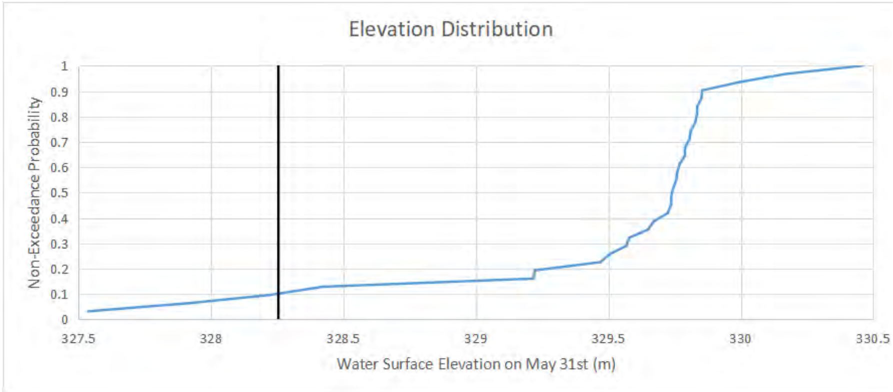

Figure 3: Distribution of water levels in Lake Minnewasta, generated from the WSC historical data.

The water level was then converted to a storage volume using a reconstruction of the bottom surface of Lake Minnewasta (Figure 4). Approximately 1,500,000 m^3 of water would be needed to fill the reservoir from a 1 in 10 year low during the spring freshet. This translates approximately to a more conservative 400 L/s flow rate, assuming a 45 day pumping schedule. The water availability for transfer must be assessed to evaluate the viability of these transfer rates. Similarly, a coupled model of the two river systems would be needed to further refine this estimate. As noted previously, SSE recommends systems and hydrologic modelling to accurately estimate the design flow for projected demands, and to reliably fill a second reservoir should it be constructed.

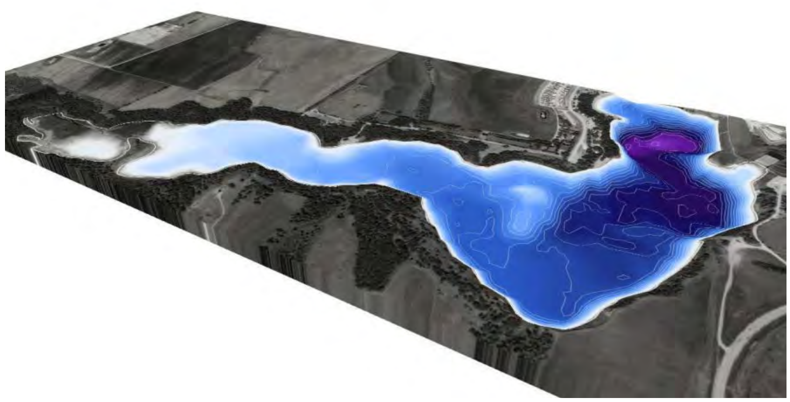

Figure 4: Visualization of Lake Minnewasta bottom surface elevations.

3 Hydrologic Modeling Study

3.1 Methodology

To estimate water availability under historical and future projected climate, hydrologic models have been constructed. The Hydrologic models are used to assess the viability of pump transfer rates by estimating water availability in the Pembina River and future shifts in the Deadhorse Creek system.

3.1.1 Model Structure

SSE has constructed models of the Pembina River and Deadhorse Creek basins using the HEC-HMS modelling platform. HEC-HMS is an industry-standard hydrologic model maintained by the US Army Corps of Engineers and is widely used in Manitoba. The model structure is presented in Figure 5. A hydrologic model is typically used to generate continuous streamflow records to describe system behavior when gauge data are sparse and to generate future streamflow records under different assumptions of temperature, precipitation, and land development. Hydrologic models are particularly useful for estimating future water supply. Demand exists for a pipeline transfer from the Pembina River to the Deadhorse Creek with population growth that will necessitate the addition of further storage in the future. A climate change analysis of the Pembina River and the Deadhorse Creek is needed to ensure the ongoing reliability of the transfer volume and to optimize the infrastructure used for transfer.

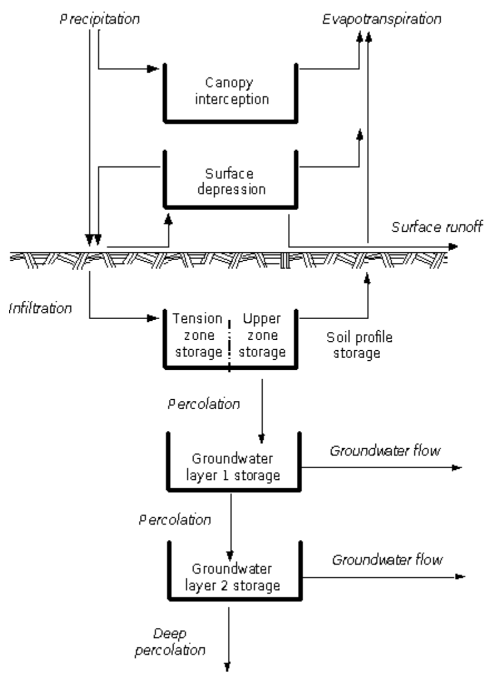

Figure 5: HEC-HMS model structure used for the Pembina River

The Pembina River model is constructed to assess water supply reliability for the Deadhorse Creek pipeline transfer following climate shifts. The larger Pembina River basin (Figure 1) is represented by 14 individual sub-basins, whose outlets correspond to Water Survey of Canada (WSC) hydrometric gauges (Figure 6). Delineation of the sub-basins used the Merit Hydro Digital Elevation Model (DEM, ~90m resolution), which was selected since it matched well with observed basin boundaries and is seamless in North America. HEC-HMS does not directly ingest flow paths generated from the delineations, just the delineated area. Therefore, there is no impact to model reliability caused by the low resolution dem for these models.

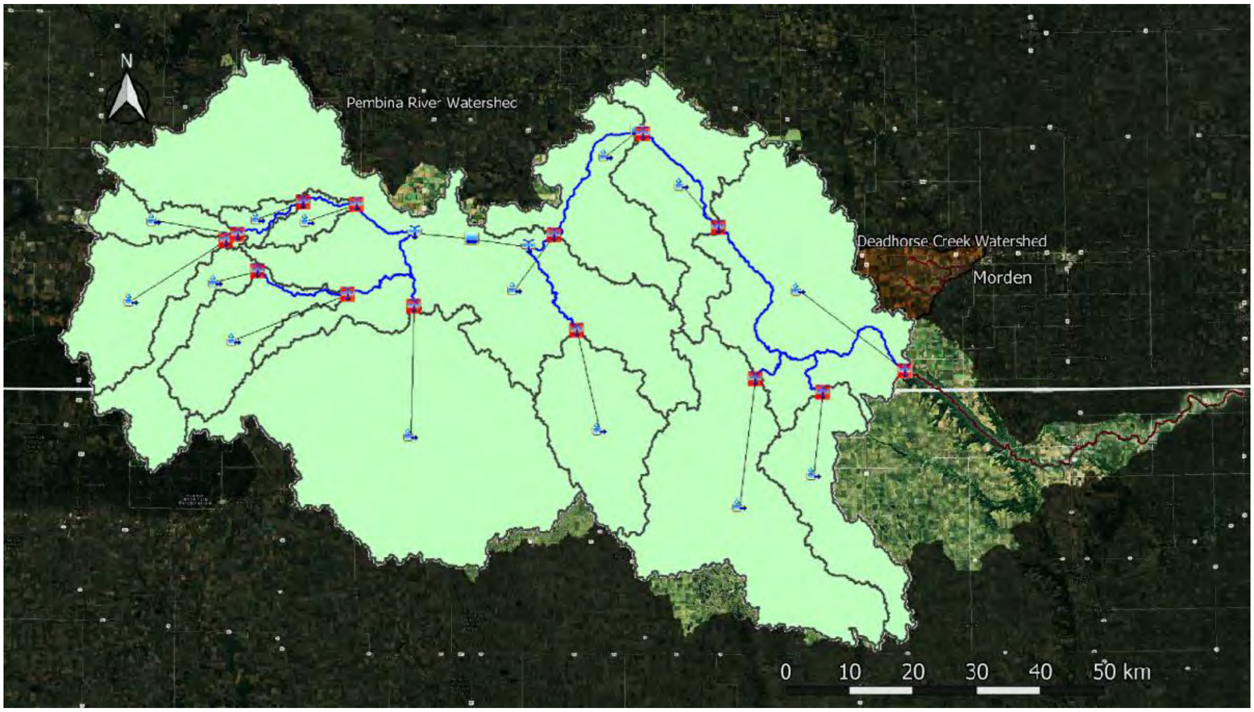

Figure 6: Hydrologic model basins and element structure overlaying the Pembina River basin delineation. Delineation was generated using the Merit Hydro Elevation dataset.

The Pembina River and Deadhorse Creek models were constructed as part of the Global Water Futures (GWF) Multi-basin Intercomparison Project (MIP). The entire Red River Basin (RRB) was modeled these models were extracted. A Deadhorse Creek model, which was modelled as a single basin, has been extracted for examination of water volume shifts with climate change. The Deadhorse Creek model was set up and calibrated to a gauge at the downstream end of the Deadhorse Creek near its connection to the Red River. Therefore, the RRB Deadhorse Creek model does not generate flows at the desired location, which are inflows to Lake Minnewasta. Results will be presented for the downstream gauge, but a scaled version will also be shown to suggest potential trends in water volumes. Delineation of the basins also used the Merit Hydro Digital Elevation Model (DEM, ~90m resolution; Figure 7).

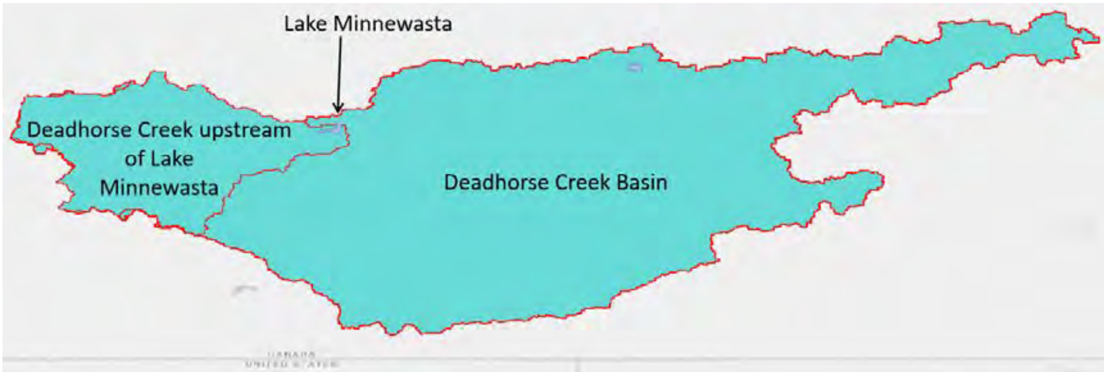

Figure 7: Hydrologic model basin delineations using the Merit Hydro Elevation dataset. The larger basin represents the modelled domain and the smaller nested basin represents the desired domain.

3.1.2 Data Sources

Hydrologic models require, at a minimum, data to inform the details of the physical landscape, like topography, land use, and soil classification data as well as precipitation and temperature data to drive the model simulations through the historic period and into future climate conditions. In addition to the Merit Hydro DEM, the HEC-HMS model utilized land use data from the North American Land Change Monitoring System (NALCMS; http://www.cec.org/north-american-land-change-monitoring-system/) and soil data from the Global Soil Dataset for Earth System modeling (GSDE; http://globalchange.bnu.edu.cn/research/soilw). Both products were selected for their seamless domain coverage.

Historical climate data were selected from the Regional Deterministic Reforecast System (RDRS), which recreates historical weather and climate conditions and is seamless across North America. The RDRS data covers the years 2000-2017 inclusively, therefore the simulation period was selected to match, with 2000 being a model spin-up year to initialize soil moisture. Future climate projections utilize Global Climate Models (GCMs), which recreate atmospheric physics across the Earth for the purpose of projecting climate into the future. A North American focused GCM dataset, the North American - Coordinated Regional Downscaling Experiment (NA-CORDEX, Figure 8) dataset, is used to supply future climate data to the HEC-HMS model. A total of 11 GCMs are considered from the NA-CORDEX dataset for the Representative Concentration Pathway 8.5 (RCP8.5), which represents an average (or slightly pessimistic) projection of emissions and climate. NA-CORDEX data are ingested into the HEC-HMS model using Equidistant Bias Correction, which is the process of transferring climate trends to shift historical data. The bias correction method preserves trends and distributions computed by the global models, while avoiding any fundamental differences inherent to the creation of the NA-CORDEX and RDRS datasets that could impact the simulation results.

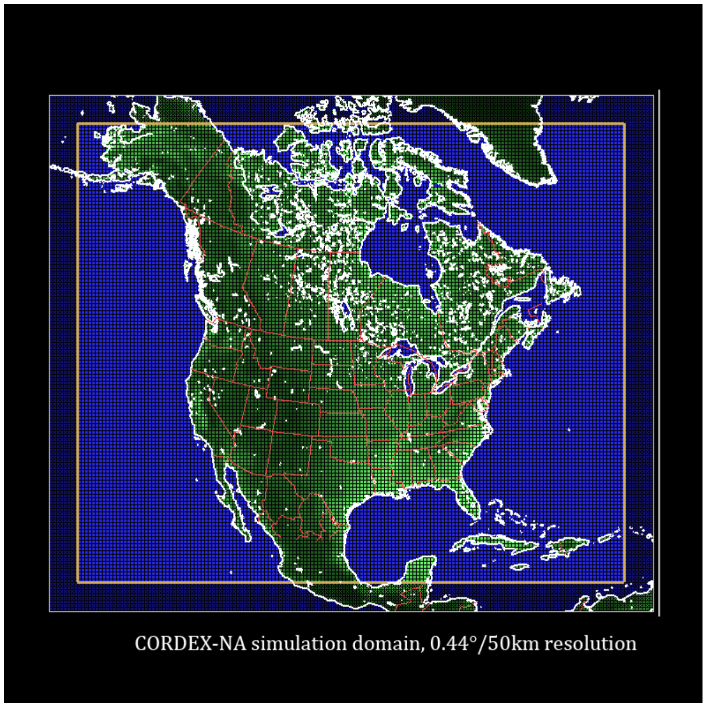

Figure 8: NA-CORDEX data domain.

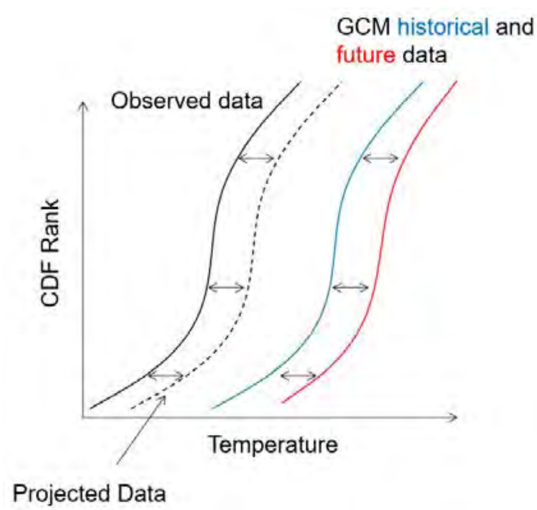

Figure 9: Equidistant Bias Correction process.

In addition, datasets of additional hydrological processes beyond streamflow were included in the output as benchmarks for simulation quality relative to observations. Evapotranspiration (ET) is the process of losing water to the atmosphere and to plants, which is driven, in part, by temperature. The Global Land Evaporation Amsterdam Model (GLEAM, https://www.gleam.eu/) dataset was used for assessing ET performance. GLEAM data were also used to assess model performance for soil moisture, and Globsnow data (https://www.globsnow.info/) were used to assess model performance for snow accumulation and melt.

3.1.3 Model Optimization

A hydrologic model is a general framework, meaning it requires tuning to best represent a target location. Each process in Figure 5 has parameters associated with it that need to be tuned to better represent the Pembina River and the Deadhorse Creek. The process of tuning those parameters is referred to as optimization.

A multi-objective optimization is used to calibrate the HEC-HMS model. Four objectives were considered: 1) streamflow in rivers at WSC hydrometric gauges, and basin wide performance with respect to 2) ET, 3) soil moisture, and 4) snow water equivalent. The Dynamically Dimensioned Search (DDS) algorithm was used for optimization. The DDS algorithm changes parameters in the model to look for combinations that improve model performance.

3.1.4 Estimating Lake Minnewasta Inflows

Since the basin structure of the RRB extracted Deadhorse Creek model does not support the direct generation of inflows to Lake Minnewasta, flow scaling can be used to create a rough estimate. Flow scaling is the process of adjusting flows by the ratio of areas. The following basin areas were used for flow scaling are presented in Table 1. To compare the RRB calibration of the Deadhorse Creek, the flows must be scaled up, however, to estimate inflows to Lake Minnewasta, flows must be scaled down. Results will be presented for the downstream Deadhorse Creek gauge with a supporting figure showing relative magnitudes of flow that are likely to be see upstream of Lake Minnewasta.

	Upstream of Lake Minnewasta	RRB Deadhorse Creek	Gauged area used for RRB Deadhorse Creek Calibration
Area (km^2)	131	786	926

Table 1: Basin area values used for flow scaling.

3.2 Results

3.2.1 Calibration

Results for the model optimization of the Pembina River met or exceeded literature-supported thresholds for model performance, which suggest the final calibration can be used to estimate climate change impacts (Figure 10). Performance for the Deadhorse Creek also met literature-supported thresholds for model performance (Figure 11).

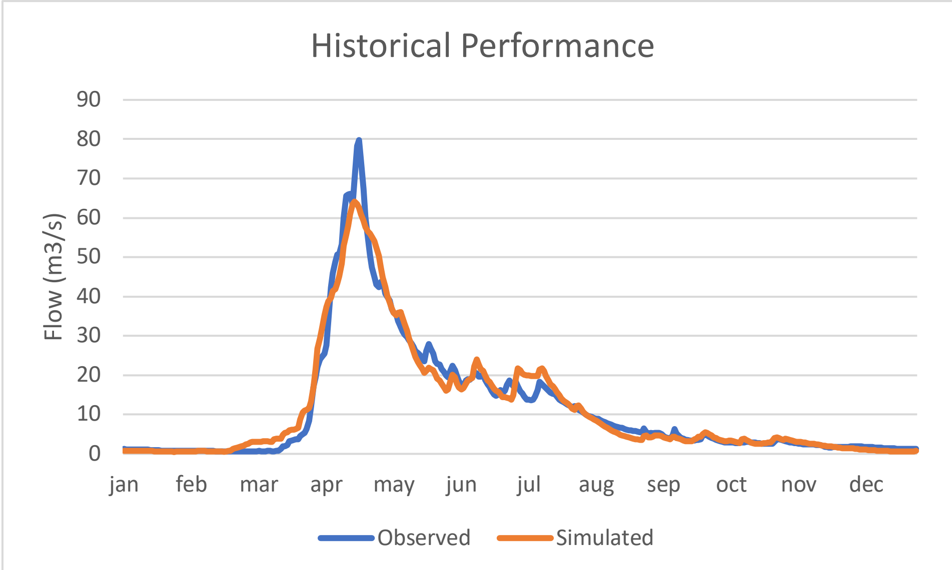

Figure 10: Comparison of simulated and observed flow on the Pembina River, just downstream of the proposed pipeline transfer point (gauge id: 05OB007).

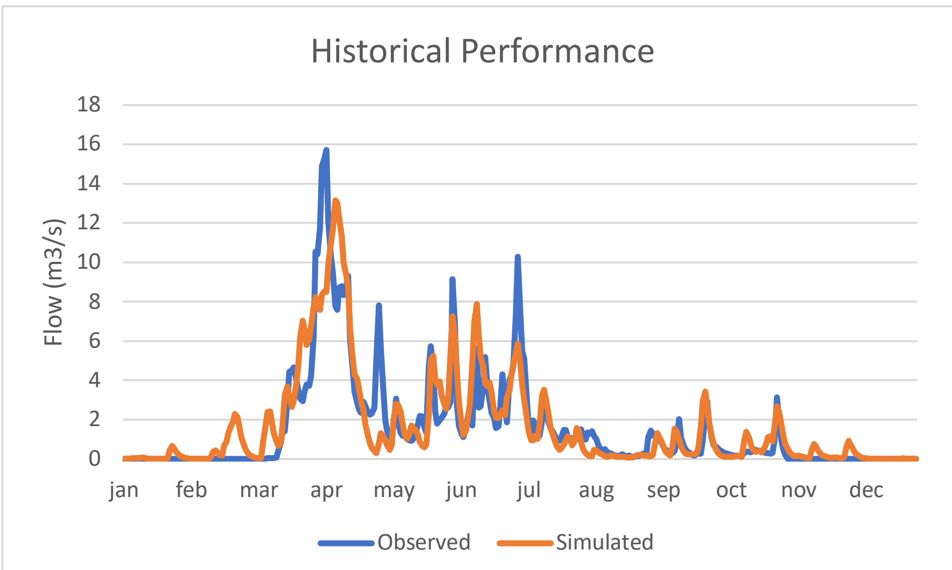

Figure 11: Comparison of simulated and observed flow on the Deadhorse Creek, near the connection to the Red River (gauge id: 05OC016).

Similarly, simulation of processes such as soil moisture performed comparably well in both models. This suggests that the HEC-HMS models generated strong simulation performance while representing the physically occurring processes well. Realistic climate change results require a reasonable representation of environmental processes, which further support the viability of the HEC-HMS model for climate change projections.

3.2.2 Climate Projections

Climate projections from the NA-CORDEX data suggest warming temperatures (Figure 12) but are more mixed on changes to precipitation relative to historic observations (Figure 13).

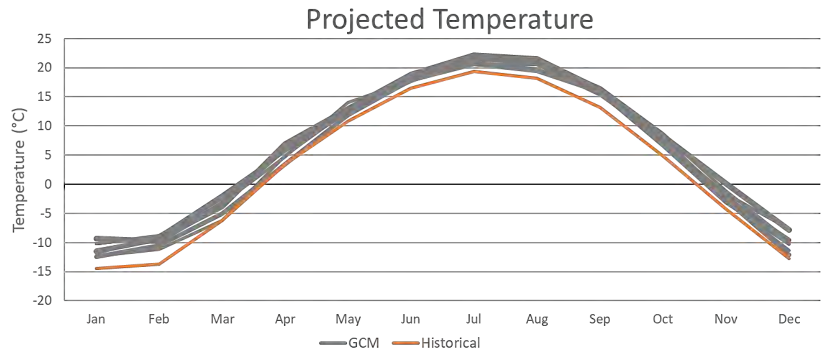

Figure 12: NA-CORDEX temperature projection for 2050's.

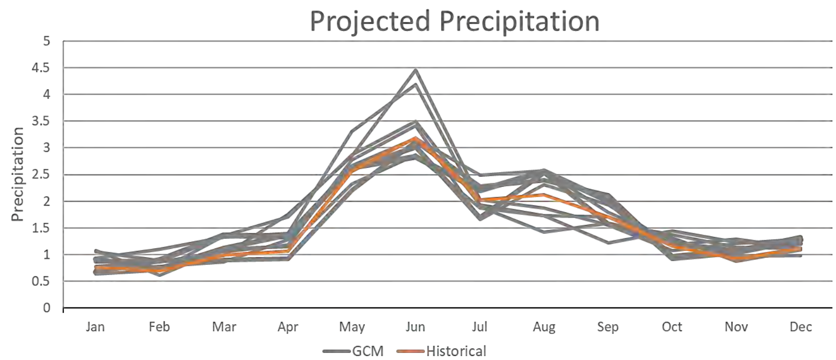

Figure 13: NA-CORDEX precipitation projection for 2050's.

ET is projected to increase due to the increasing temperatures and soil moisture is projected to decrease on average due to increased water loss from ET. Snow is projected to have the largest shift with a shorter snow-on-ground period and less maximum snow accumulation (Figure 14). The reduction in snow on the ground at the beginning of spring drives lower spring freshet volumes (Figure 15), highlighting the importance of assessing climate change impacts on the pipeline transfer. Similar results are also seen on the Deadhorse Creek (Figure 16).

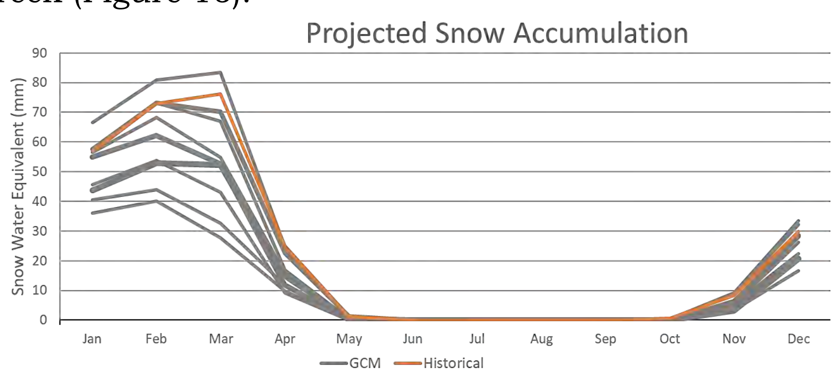

Figure 14: Projected snow accumulation and melt driven by the NA-CORDEX dataset.

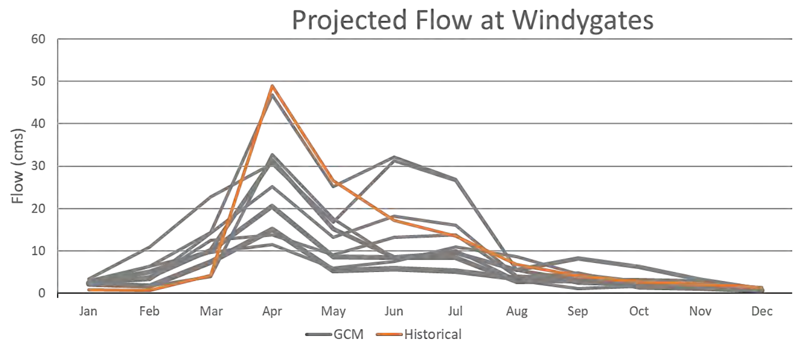

Figure 15: Projected streamflow at the Windygate hydrometric gauge on the Pembina River (05OB007) driven by the NA-CORDEX dataset.

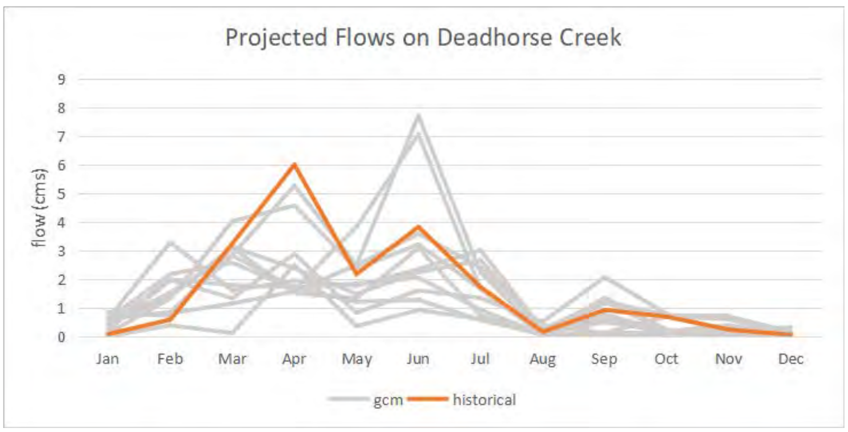

Figure 16: Projected flows at the Deadhorse Creek hydrometric gauge (gauge id: 05OC016) driven by the NA-CORDEX dataset.

There is only slight variation in the flow projections for both the Pembina River and the Deadhorse Creek. When considering the 11 simulations together (ensemble), the average for the Pembina River suggests a reduction of annual flow volume of 22%, while the Deadhorse Creek is projected to have an average flow reduction of 24%. Flow reduction is most notable in spring, when the diversion is expected to operate. The Deadhorse Creek similarly suggests flows near the rivers confluence with the Red River will be lower in spring. Both rivers see higher winter flows, which are generated by a shorter snow season and some risk of extreme precipitation events in summer.

3.2.3 Estimation of Lake Minnewasta Inflows

Results for the Deadhorse Creek near the Red River are likely a good reflection on projected flow in the Deadhorse Creek system, though some regulation features are not included in the model. In the time permitting, it was possible to construct a high-performing, validated HEC-HMS model of the entire DHC using the downstream WSC gauge, and therefore we have confidence in our climate change projections for the DHC. In order to get a high-resolution (daily time step) model of inflows to Lake Minnewasta, we need model Lake Minnewasta regulation, account consumptive uses upstream and at Lake Minnewasta, which were not available within the project time frame.

For the systems modelling phase of study required to define design flows, SSE proposes to use the WSC gauge immediately downstream of Lake Minnewasta, the new bathymetry available for Lake Minnewasta, the Lake Minnewasta stage data, and all consumptive use data to back calculate inflows to Lake Minnewasta on a daily time step. The back-routing method produces the equivalent of gauge data inflows to Lake Minnewasta, which enables the construction of a "pure" Lake Minnewasta hydrologic model simulating reservoir inflows on a daily basis.

For completeness, climate change-projected Lake Minnewasta inflows are shown in Figure 17, and is scaling of the DHC hydrologic model calibrated at WSC gauge 05OC016. Average monthly flows are generally under 1 m3/s throughout the year, with up to 50% reduction in flows in spring.

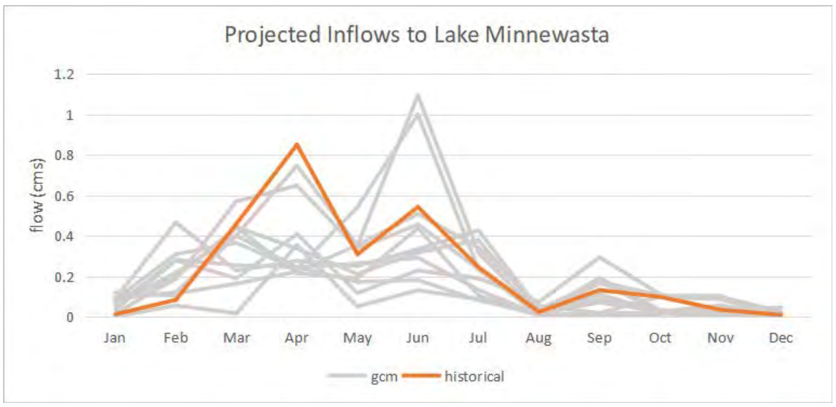

Figure 17:Projected, scaled flows at the Deadhorse Creek hydrometric gauge (gauge id: 05OC016), scaled down by drainage area to match the Lake Minnewasta inflow basin and driven by the NA-CORDEX dataset.

3.2.4 Pipeline Transfer Reliability

Two pumping schedules are considered, with the total volume distributed over a 45-day transfer and a 60-day transfer. Both transfers are applied only to the freshet period and end on May 31st, and both transfers assume 1,500,000 m^3 , which was the more critical case for water volume transfer. The 45-day transfer is approximately 385 L/s and the 60-day transfer is approximately 289 L/s. For an average flow year on the Pembina River, the flow transfer is less than 1% of Pembina River flow (Figure 18), even accounting for the dry climate change impacts (RCP 8.5).

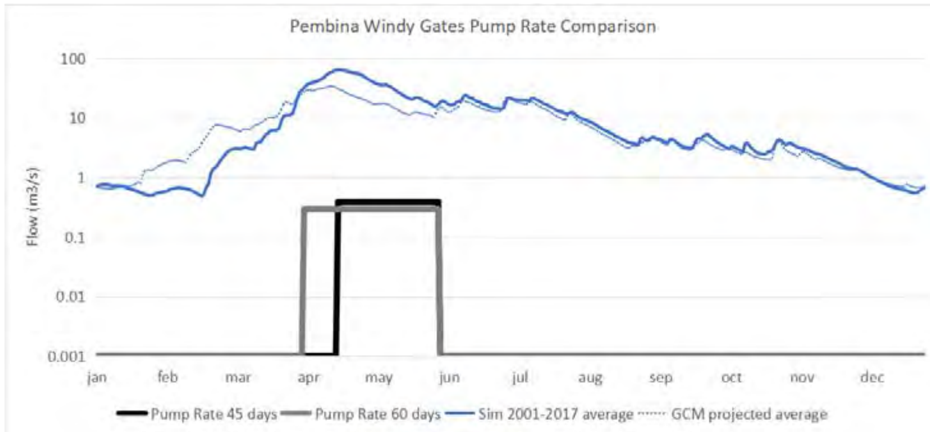

Figure 18: Pembina River hydrograph in log space for an average year from the 2001-2017 period and projected to the 2050's.

The pipeline transfer is more likely to be needed in a dry year rather than an average flow year. Therefore, a 1 in 10 year low flow year on the Pembina with and without the impacts of climate change is also considered (Figure 19).

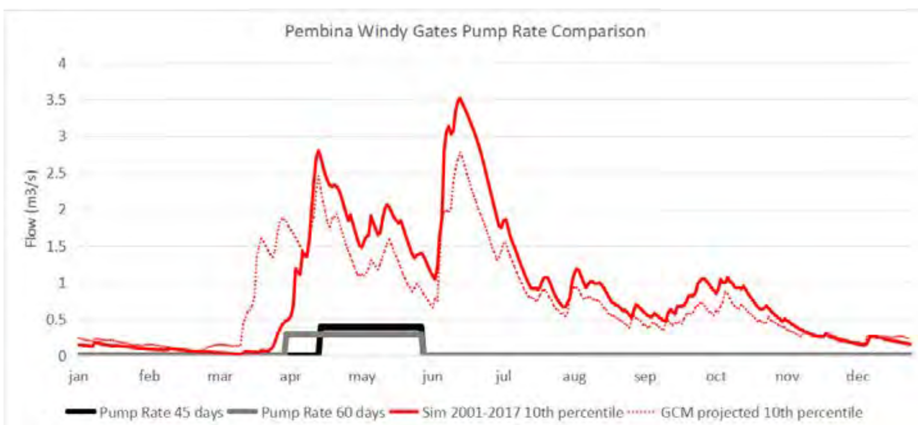

Figure 19: Pembina River hydrograph in for a 1 in 10 year low flow year from the 2001-2017 period and projected to the 2050's.

The relative volume pulled from the Pembina River is more significant in a low-flow year and represents closer to 30% of Pembina River flow at the time of transfer. Timing changes to climate-impacted snowmelt events further suggest that the timing of the transfer may require the diversion pumping schedule shift to earlier in March to make full use of the spring freshet.

The climate change analysis indicates that at least 1,500,000 m^3 of water supply is reliably available during spring freshet from the Pembina River even during low flow years. Precipitation is more likely to occur as extreme events throughout the year. This climate shift means that the value of new storage will increase climate change. Opportunistic harvesting of high flows on the Pembina for Morden will be possible with new storage construction, and may be necessary for Morden's continued growth.

3.2.5 Caveats

The Pembina HEC-HMS model was developed without a complete representation of Pembina River regulation on the Tri-Lakes. The DHC HEC-HMS model was calibrated and validated using a WSC gauge downstream of Lake Minnewasta near its confluence with the Red River.

Some hydrologic modelling refinements are recommended for use in the systems simulation model; improved representation of Tri-Lakes regulation on the Pembina, and modelling only DHC upstream of Lake Minnewasta with any consumptive upstream uses identified and accounted.

4 Pipeline Study

4.1 Methodology

4.1.1 Pipeline Routes

Two pipeline routes were analyzed, both of which attempt to best follow municipal right-of-way. Route 1 represents the shortest practical route between the Pembina River and the Deadhorse Creek watershed, with the outlet placed to discharge water into a small tributary creek. From there it can flow naturally through the drainage system until reaching Morden. This minimizes the amount of construction required; however, control of the discharged water is lost once it is in the natural channels. If operated in a very dry year as was seen in 2021, there will be a portion of flow which is lost as it evaporates or infiltrates into the dry soil. These losses could be avoided by piping the water all the way to Lake Minnewasta. Route 2 analyzes this option, resulting in a much longer pipeline and higher construction costs, but ensuring all the pumped water is made available to the city. These routes are shown below.

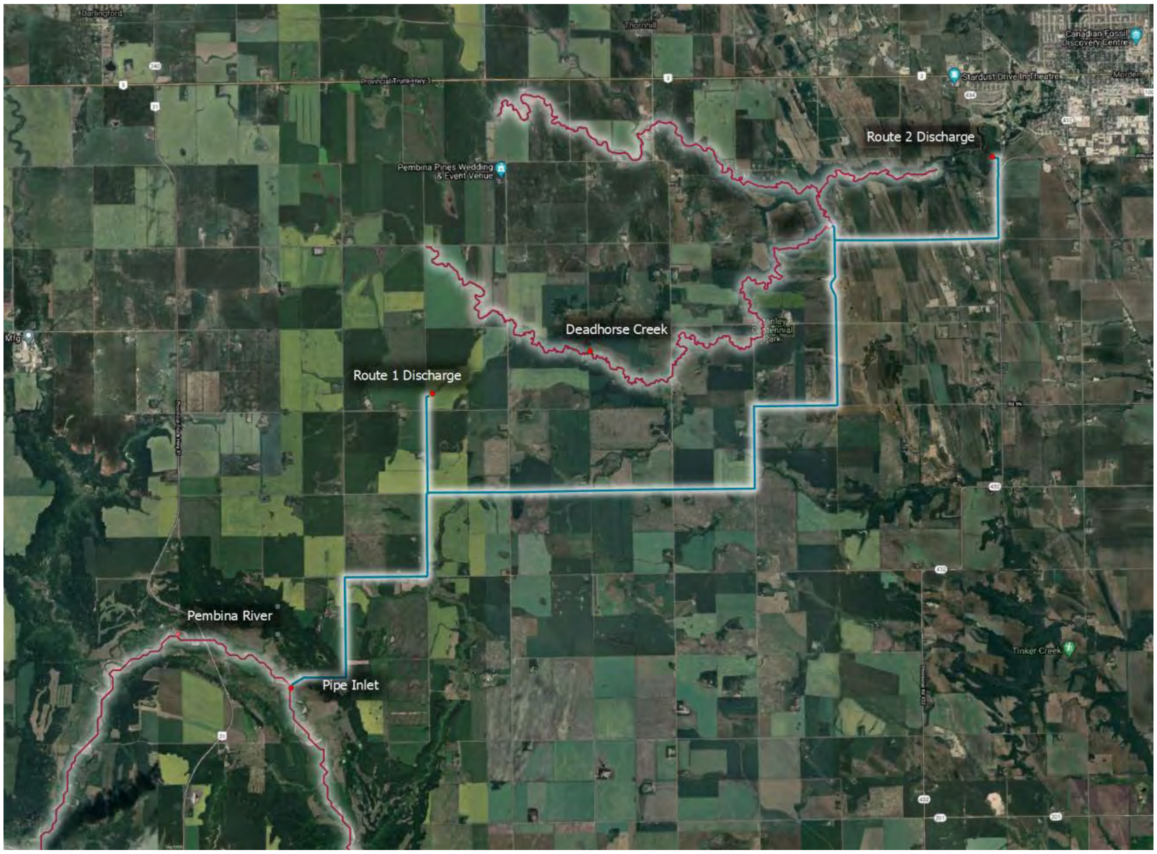

Figure 20 - Pipeline route options

4.1.2 Design Criteria

The primary design criterion for the pipelines is to ensure they will withstand the high pressures required to lift water from the Pembina River, as well as the extra surge of pressure that can be caused by sudden changes in velocity (from closing valves or powering off the pump). For the designs shown in this report, a design flow-rate of 250 L/s was used. This value was based on the 40 L/s that the City of Morden requires to meet its projected demands, but compressed into 2 months so as to only extract Pembina River water during the spring freshet when the extraction will not put strain on the water supply of downstream communities. It does not compensate for the increased water supply stress due to climate change effects on irrigation, evaporation, and drought duration, and could be more accurately estimated with the systems modelling approach.

The *working pressure (P_w)* is determined by the pump at the upstream end of the pipe, which must provide enough pressure to overcome the 116 m elevation gain out of the Pembina River and the hydraulic losses accumulated along the pipeline route. At all locations the *pressure class* (PC) for the pipe must be greater than the working pressure. The pipe changes elevation along its length, so the static pressure is expected to be greatest at the lowest elevations, such as immediately after the pump at the Pembina River. Pipes at higher elevations will have lower static pressures and can often be constructed with a lower PC section.

The *surge pressure* is determined by the velocity of the water in a pipe section. If the flowing water were to suddenly stop, this causes a sudden increase in pressure which is relative to the change in velocity. Pipe sections which are larger in diameter result in lower average velocities (Velocity = Q/A) and, by extension, lower surge pressures. The maximum expected surge pressure is calculated by the following equation:

$$P_s = \frac{\rho \Delta v}{144g}\left[\frac{\rho}{144g}\left(\frac{\rho}{K} + \frac{d}{bE}\right)\right]^{-1/2}$$

where P_s is maximum surge pressure in psi, ρ is fluid density in lb/ft^3, Δv is change in velocity (ft/s), g is the acceleration due to gravity (ft/s), K is the modulus of elasticity of water (psi), d is pipe diameter, b is pipe wall thickness, and E is bulk modulus of elasticity of the pipe material (psi). Results are then converted to metric units. The maximum pressure under working conditions *(MPWC)* is then calculated as the sum of working pressure, P_w, and surge pressure, P_s.

$$MPWC \ = \ P_s + P_w$$

The working pressure (P_w) must always be lower than the pipe's pressure class, while the *MPWC* must always be lower than 1.5 times the pressure class. In almost all cases, the *MPWC* is the limiting design criterion. In both cases, a *Factor of Safety* (FoS) is calculated based on the ratio of the pressure class to the maximum pressures. For example, the factor of safety for the working pressure is equal to PC / P_w and must always be greater than 1.0. The factor of safety for the recurring surge pressure is equal to 1.5**PC / MPWC* and must remain greater than 1.

4.1.3 Optimization

If either the working or surge pressures exceeded the required safety factors of a particular pipe section, there are two design changes which can be made to remedy the situation. The first is to simply increase the pressure class of the pipe. Pressure class is directly related to the relative thickness of the pipe walls compared to the pipe's diameter, such that thicker pipes have a higher PC. The *standard dimension ratio* (SDR) is defined as the ratio of the outer diameter of the pipe to the wall thickness, and the range of nominal SDR values allows for pipes to be chosen according to the desired PC. In many cases increasing the PC of a section comes with a significant cost increase due to the higher weight of material needed. Additionally, higher PC pipes have smaller internal diameter, which contributes to higher maximum surge pressures in the section as well as higher head loss. The second way to meet a pipe's pressure requirements is to increase the diameter. While this doesn't affect the PC of the pipe, a larger diameter reduces the water velocities and therefore reduces the maximum expected surge pressures. Increasing diameter also reduces head loss in the section, which can help to lower pressures upstream as a lower pump pressure is needed to achieve the design flow.

The material chosen for pipeline construction is high-density polyethylene (HDPE), which is an industry staple due to its corrosion resistance, surge tolerance, and ease of construction. The table of nominal HDPE pipe sizes is shown in Table 2. Nominal pipe sizes are based on those listed by Engineered Pipe Group, based in Saskatoon. During detailed design and construction planning, some of these nominal sizes may be unavailable at the time of construction, which would require sizing up to the next available pipe with some cost increases.

The total cost of the pipeline is related primarily to the mass of HDPE required, and is increased by both higher diameter pipes as well as higher PC. As such, a cost-effective design will minimize both the PC and diameter of as many pipe sections as possible. With the *MPWC* being the limiting criterion in most cases, an optimal design is therefore one which keeps the factor of safety for this criterion as close as possible to 1 without dropping below it. Changes in pipe size in one area has effects on head loss and consequently can break constraints in other sections, therefore the design is an iterative process trying many combinations until cost is minimized. Additionally, the increased headloss incurred by minimizing pipe diameters results in higher pump energy costs, which may require some redesign if available electric capacity is a limiting factor at the site.

SDR	PC (psi)	Nominal Diameters (mm)									Nominally Available / Unavailable					
		315	355	400	450	500	560	630	710	800	900	1000	1100	1200	1400	1600
32.5	50															
26	65															
21	80															
17	100															
15.5	110															
13.5	130															
11	160															
9	200															
7.3	250															
6.3	300															

Table 2 - Nominal diameters, SDR, and pressure class of HDPE pipe.

4.1.4 Cost Estimations

Cost estimates for HDPE pipes with trenching are extrapolated from 2019 values obtained from Accurate HD, in Winnipeg. The averaged costs per m^3 of HDPE for the range of quoted pipe sizes was $11,018 and is in line with 2016 and 2017 costs from the *Manitoba Water Services Board* (MWSB) averaging $11,247/$m^3$. This value was increased by a factor of 4% based on Bank of Canada inflation values as well as increased by an additional 50% to account for cost uncertainty and price increases of polyethylene over the last two years due to global supply shortages from the Covid-19 pandemic. This value of $16,526/$m^3$ was multiplied by the total volume of HDPE needed for the project. A cost estimate provided by the *Manitoba Water Services Board* (MWSB) had a maximum equivalent cost of $15,951/$m^3$ which is consistent with the escalated values in this report. It is likely that this pipeline estimate is high, however costs of pipe have increased dramatically in the last year and whether this trend will continue is uncertain.

Additional costs which must be refined in a detailed design include those of intake screens, pumps and the pump house, electrical, and erosion protection at the outlet. ***As the functional design of these features was not part of this project scope, a reconnaissance level estimate is provided based on what was required for similar diversion project undertaken by SSE***.

Since most of the intake and outlet requirements will be the same for each route option, they are listed below and applied equally to the total cost of each.

Item Description	Cost	Item Description	Cost
Screens	$ 208,000	Electrical Work	$ 468,000
Intake Platform	$ 156,000	Earthworks and Landscaping	$ 52,000
Pressure Reducing Valve	$ 52,000	Outlet Erosion Protection	$ 31,000
Concrete Work	$ 94,000	2x Intake Pumps	$ 230,000
Hydro Connection	$ 600,000	Flushout Assembly	$ 180,000

Table 3 - Fixed costs for pipeline intake construction (adapted from SSE, 2021).

The total cost for intake works is estimated at $2.09 million, which is in line with the estimate of $2.13 million performed by MWSB and shown in Appendix III. The assumption of two parallel pumps was used here, but depending on the configuration and design flow chosen, one larger pump may be feasible. At the advice of MWSB, extra costs of $80,000 was also included to help cover costs included with crossing buried utilities and surface drains, as well as 30% contingency attributed to feasibility level costing.

4.1.5 Pump Sizing (Preliminary)

A preliminary pump sizing based on curves provided by Gorman-Rupp Pumps showed several models which could provide the required flow and pressure. The high lift requirement makes most pumps operate outside their highest efficiency regions, and as such an increases in head loss can have significant effects on power requirements. In general, these pumps operated in the 475 to 750 kW range, depending on the route. Exact values are clarified in the route detail sections. During detailed design, further optimization of the pipeline and pump system could provide some efficiencies and reduce capital and/or operating costs. Commercial power rates will vary in the future, however using an illustrative $0.10/kWh and a 60 day pumping period, the annual energy cost for pumping will be between $70,000 and $110,000.

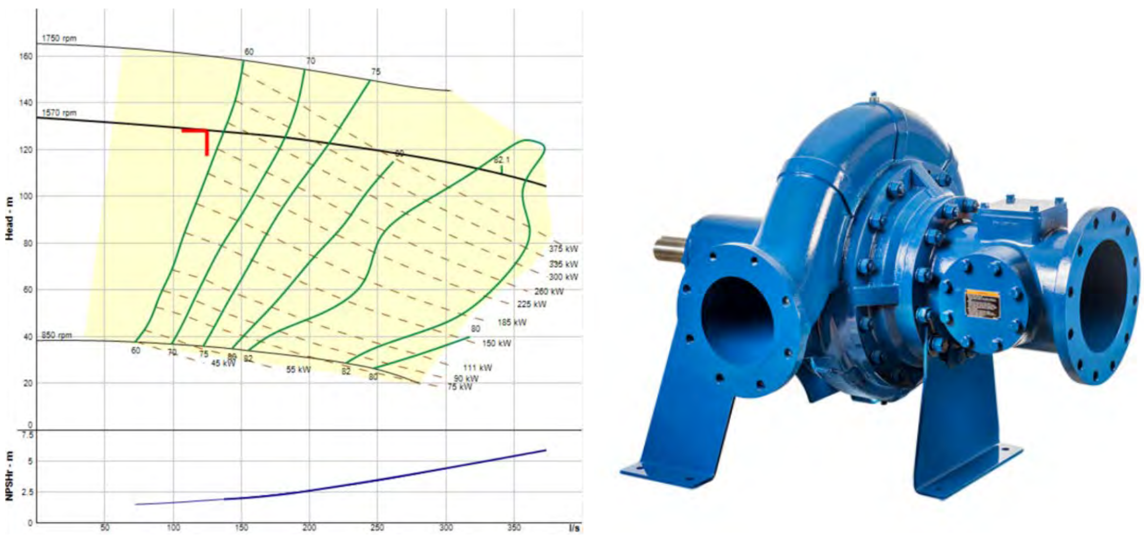

Figure 21 - Pump curve and image of example pump (GR 6519A-B-1) with highlighted operating point. (From Gorman-Rupp Pumps, https://www.grpumps.ca/)

4.2 Pipe Sizing

4.2.1 Route 1

Route 1 is an 8.4 km pipeline designed to provide the shortest reasonable route from the Pembina River to the Deadhorse Creek watershed, discharging into a small creek approximately 23 km upstream of Lake Minnewasta. Route 1 minimizes construction cost and head loss, however there is no control over the pumped water once it leaves the pipe. In the distance between the outlet and the reservoir, losses can be accumulated through evaporation, infiltration, or other unregulated extraction. The total cost of the pipeline and trenching is estimated at $3.42 million. Adding fixed costs from Table 3 brings the cost to $5.50 million.

The optimized pipe sizing for this route uses 198.6 m^3 of HDPE over 8.4 km of piping. The lift requirement of 116.5 m combined with 35.7 m of head loss, total pump head of at least 152.2 m is required to deliver the 250 L/s flow rate. Reaching this flow rate causes high velocities and consequently high surge pressures. In most cases this is not problematic as the working pressures are low enough to allow for these pressures. However, as can be seen in Figure 22, the first kilometre of the pipeline is in the Pembina River valley where elevations are much lower. This contributes to significantly higher working pressure and therefore requires a much higher pressure class or much lower flow velocities to reduce surge pressures. Using the high pressure, SDR 7.3 pipe of 500 mm diameter in this region allows for a single pipeline to carry the flow. This region could also be designed with twinned pipelines, however some cost savings can be made using a single, very-high PC pipe, mainly due to the potential energy savings of using a single, 475 kW pump instead of two 350 kW pumps. Using a single pipeline in this region is only feasible for a 250 L/s design flow, and would need to be twinned should the design flow be increased to, for example, 400 L/s. In the remaining 7 km where elevation is much higher, working pressures become low enough that a pipe with lower pressure classes can satisfy pressure requirements to provide significant cost savings compared to twinning the entire pipeline.

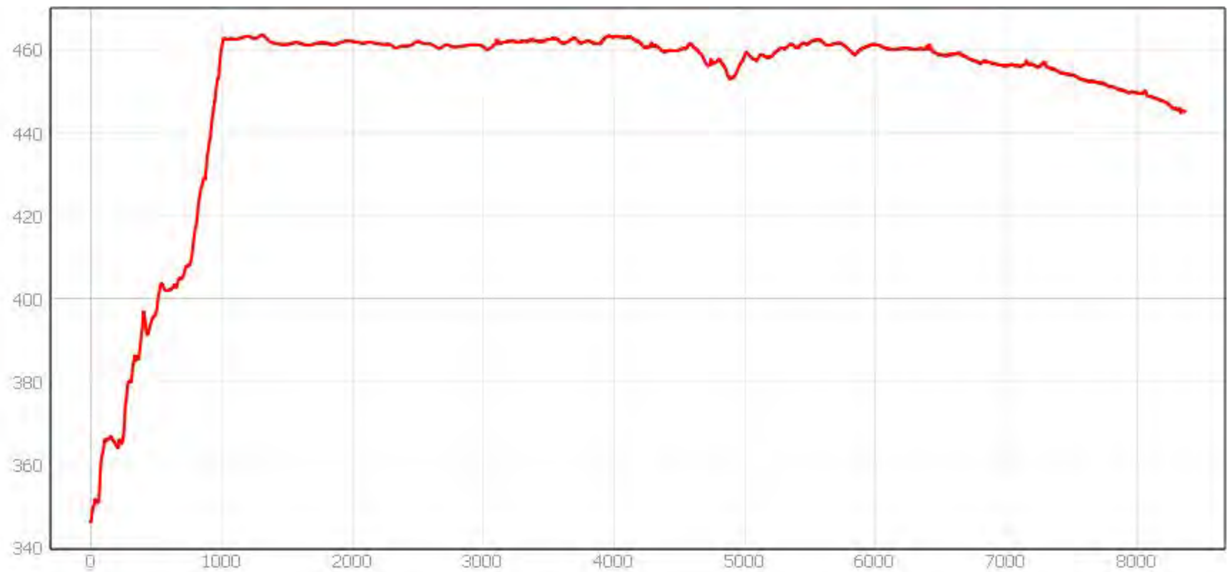

Figure 22 - Elevation profile for Route 1. Values are in metres.

Detailed sizing and factors of safety of each pipe section for Route 1 is shown in Appendix I. Table 4 shows a summary of each pipe section. While the pipes were analyzed in many granular segments to ensure constraints are met at all locations, the design was grouped into only a small number of pipe sizes for constructability. The route 1 pipeline was analyzed in 21 sections but was limited to 3 unique pipe types with two pipe transitions. More granular pipe adjustments save material cost, but could increase labour costs. While most of the pipeline is at a high elevation and very low pressure, pipes were constrained to a minimum pressure rating with SDR 17, beyond which pipe walls may become too thin for efficient construction.

Section	# Pipes	Diameter	SDR	Length (m)	Velocity (m/s)
1-11	1	500	7.3	1098	1.71
12-14	1	500	17	2827	1.44
15-21	1	450	17	4415	1.77

Table 4 - Route 1 pipe sizing summary.

Velocities in the pipeline are relatively fast to make best use of the higher pressure class, and consequently result in higher head loss. The system can be driven at 250 L/s by a single 475 kW pump for an estimated energy cost of $68,000/year.

4.2.2 Route 2

Route 2 is a 24.3 km pipeline designed to provide water directly into Lake Minnewasta. This route would ensure that all water that is extracted from the Pembina River is made available to the city without transmission losses. However, the route is approximately 3 times longer and comes with significantly increased cost. The estimated cost for the pipeline and trenching is $16.8 million. Adding fixed costs from Table 3 brings this to $18.9 million.

The Route 2 pipeline contains an estimated 975.4 m^3 of HDPE material over a total of 28.5 km of pipe. Lift requirements for this pipeline remain as 116.5 m but a larger head loss of 58.5 m results in a pump operating head of 174.9 m is required to drive the 250 L/s flow rate. The same high flow velocities and surge pressures as discussed for Route 1 are present here as well, however Figure 23 shows that in Route 2, a significantly larger portion of the route exists at low elevations similar to the Pembina River valley. In Route 1, the water is simply lifted up out of the river valley and discharged at the high elevation, whereas in Route 2 the elevation of the pipeline gradually declines toward the initial elevation, and discharges slightly lower than the Pembina River. As with the low elevation regions of Route 1, the low elevation regions of Route 2 experience very high static pressures which require very high-pressure class pipes. Additionally, some of the lowest elevation regions cannot be accommodated by a single pipe while also satisfying surge pressure constraints, requiring a total of 4 km of twinned, high PC pipeline. This contributes to a large increase in cost due to doubling the pipe required for over a significant portion of the route's length. Additionally, the higher route length contributes to higher total head loss and higher required pump pressures. This means that the pipe sizes throughout the entire length of the route must also be larger than those used in Route 1. These cumulative effects mean that approximately 4 times as much HDPE is required for construction, and approximately 4 times the trenching cost.

Figure 23 - Elevation profile for Route 2. Values are in meters.

Detailed sizing and factors of safety of every pipe section for Route 2 is shown in Appendix II. Table 5 shows the summary of the pipe sections in Route 2, with 9 unique pipe sizes and 8 pipe transitions. The Pembina River valley contains 720 metres of twinned pipeline in addition to 3290 metres of twinned pipeline in the Deadhorse Creek watershed.

Section	# Pipes	Diameter	SDR	Length (m)	Velocity (m/s)
1-8	2	450	7.3	1101	1.06
9-12	1	500	13.5	3631	1.49
13-16	1	500	17	3282	1.44
17-20	1	560	17	2447	1.15
21-24	1	710	17	3260	0.71
25-27	1	560	11	2490	1.23
28-35	1	630	11	3342	0.97
36-37	1	500	9	1637	1.61
38-49	2	400	9	3293	1.26

Table 5 - Route 2 pipe sizing summary.

While this design is the most cost-effective option for Route 2, it also construes significant head loss, requiring much more pumping energy to operate. This design would require two pumps of approximately 377 kW each, for an annual estimated operating cost of $108,000. If electrical capacity limitations arise, this route may have to be designed around head loss minimization to allow for smaller pumps, however this could increase pipe costs by a significant amount. Power limits are also likely to be reached if the design flow is increased.

5 Reservoir Site Reconnaissance

5.1 Methodology

The goal of the storage reservoir site reconnaissance portion of the study was to use high-resolution LiDAR and geoprocessing to perform detailed analysis of the Deadhorse Creek with regards to the amount of available water storage, as well as the earthworks that would be required, when constructing a storage reservoir at any given location.

Figure 24 - 3D DEM imported into Blender.

To begin this process, the LiDAR DEM of the watershed was imported into Blender, an open-source 3D modelling program. This creates a large, to-scale 3D model of the region's topography. An earthen embankment cross-section is then modeled in the software, using a standard 5:1 slope and 7 m top width and conforming with traditional PFRA design principles for Western Canada[3].

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[3] PFRA, 1987. Prairie Farm Rehabilitation Administration Engineering Service. Assiniboine South – Hespeler Area Study. Appendix B Engineering.

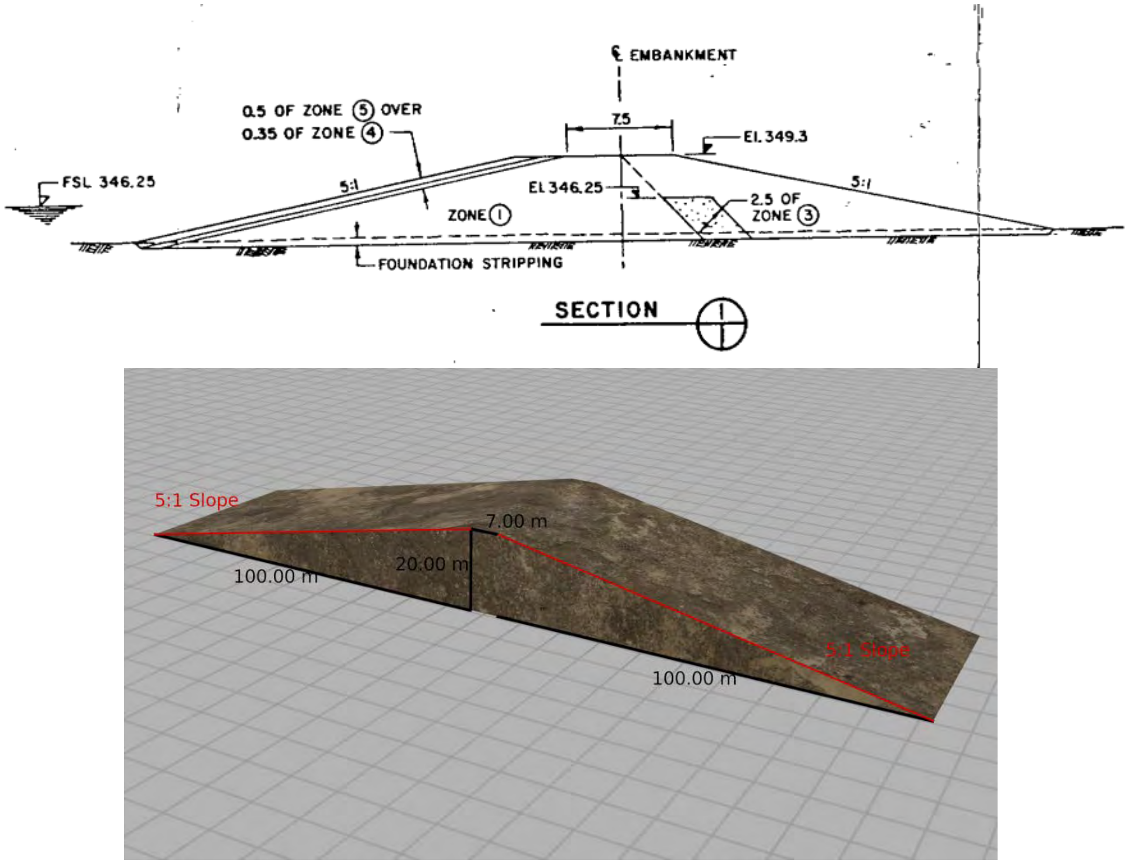

Figure 25 – Classic PFRA cross-section example (top), and its 3D Blender model representation (bottom).

This embankment model is then placed into the terrain model at a given point on the DHC with the top of the berm placed 0.5 m above whatever reservoir level is desired. The section is made arbitrarily tall so that it will always reach below the DEM surface, and is extruded long enough that it extends across the entirety of the river valley with no gaps. Using a modifier function built into Blender, the volume of the section which lies below the DEM (underground) is removed, such that the bottom of the cross-section will conforms to the terrain smoothly. When this is completed, the volume of the new 3D storage reservoir can be extracted, providing an accurate estimate of the amount of earthwork needed to construct the storage reservoir of that height, at that location.

Next, a large “water cube” is created upstream of the embankment. Similarly, as before, the top of this water cube is placed at the design reservoir elevation, and the bottom is extended such that it is below the lowest point of the DEM, ensuring that it fills the entire reservoir depth. This cube is then extruded in the horizontal directions until it fills the river valley to the design water level for as far upstream as required. As the upstream river elevations in the DEM gradually slope upward, the DEM will eventually reach a point where it is higher than the water cube, and this represents the furthest upstream extent of the reservoir. The same built-in modifier is then used to remove all parts of the water cube which are below the ground elevation or the embankment, giving an accurate estimate of the volume of water that can be stored in the reservoir.

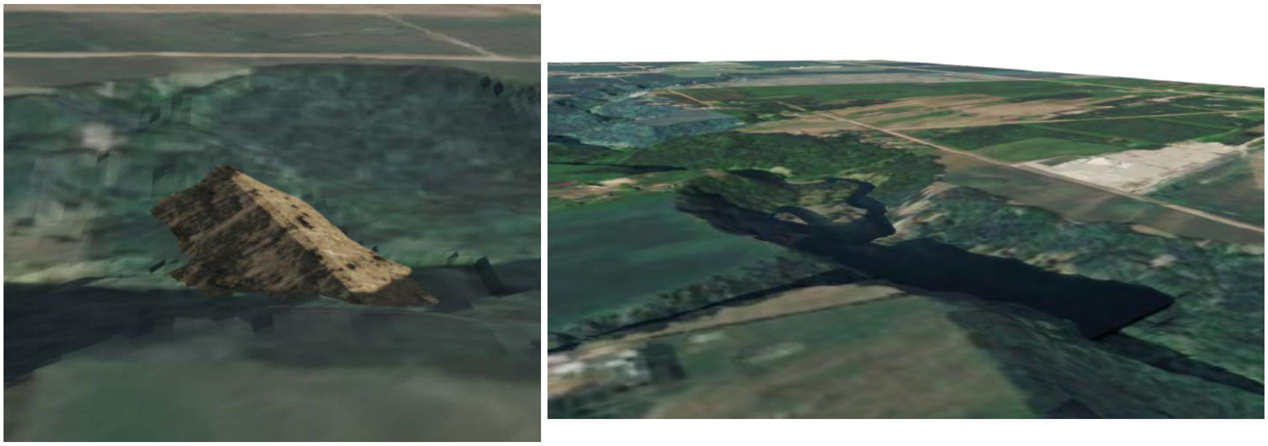

Figure 26 - Example embankment section within the model (left) and water cube showing reservoir extent (right).

The procedure described above will result in a storage volume and earthworks volume for a single storage reservoir location of a single height. To analyze the full range of possible reservoirs on the Deadhorse Creek, this process must be repeated at many locations with a range of storage reservoir heights. An in-house python script was developed to create storage and earthworks volumes for storage reservoir sites throughout the entire study area by automatically moving the embankment and water cube vertically through a range of potential heights and recording the results, then moving them slightly upstream and iterating the process. In total 138 potential storage reservoir sites were investigated, shown in Figure 27, and were investigated at heights between 0.5 and 15 meters above the river level. Crest heights of 15m have traditionally been regarded as the practical limit for earth embankment construction in Western Canada[4]. Higher crest elevations are possible with more complex geotechnical design, however within this study domain the large majority of sites could not support crest elevations higher than 15m without the reservoir encroaching on adjacent infrastructure.

4 Peters, N., & Lamb, K. N. (1979). Experiences with alluvial foundations for earth dams in the Prairie provinces. Canadian Geotechnical Journal, 16(2), 255-271.

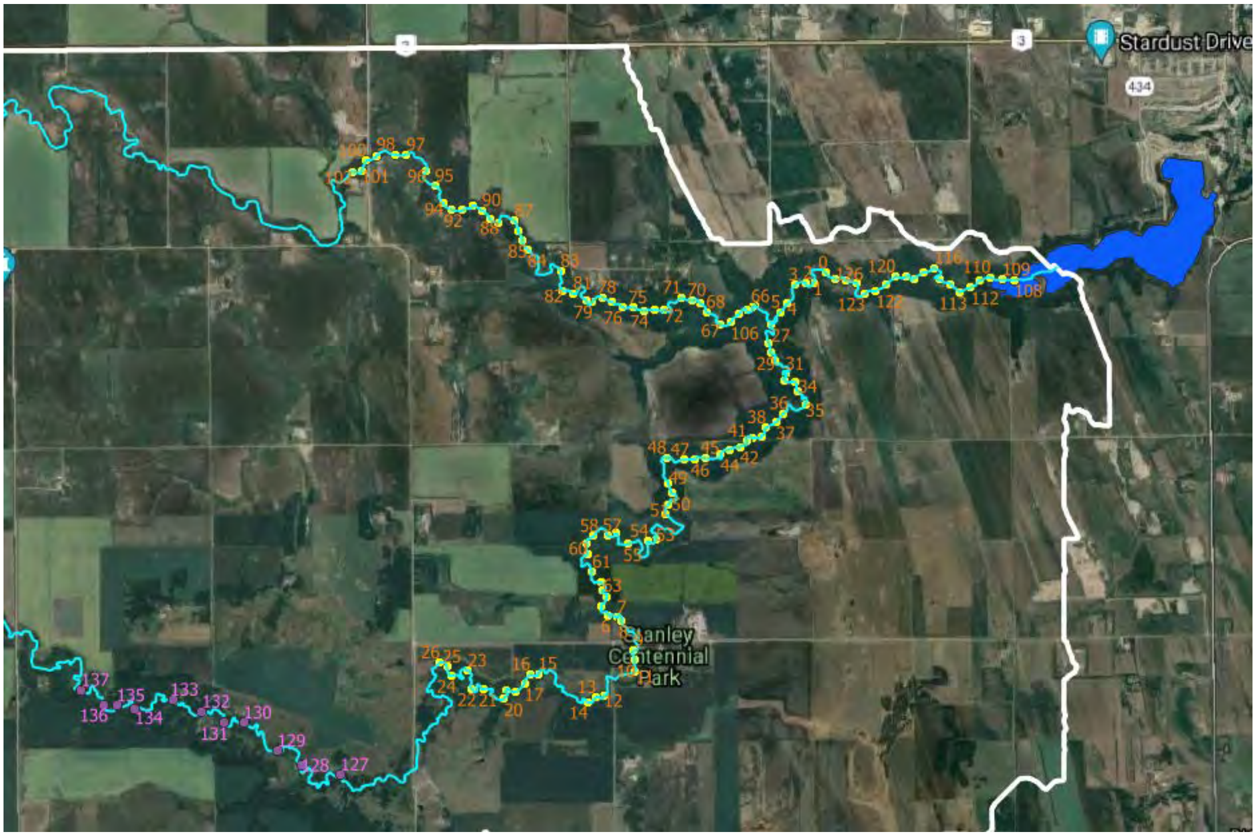

Figure 27 - All storage reservoir sites investigated for cost efficiency.

5.2 Efficiency Metrics

The complete analysis of the storage reservoir sites on the Deadhorse Creek produced a large amount of data which must be filtered down to a small number of select, high-quality sites. To this end, the sites were ranked on the metric of storage efficiency – how many cubic metres of water can be stored in the reservoir per cubic metre of earthworks required for construction. At each location, the water volume was divided by the embankment's volume to determine the storage efficiency, and repeated at every storage reservoir height to generate an efficiency curve. These curves show how the sites compare to each other in efficiency, as well as the optimal storage reservoir height for each location.

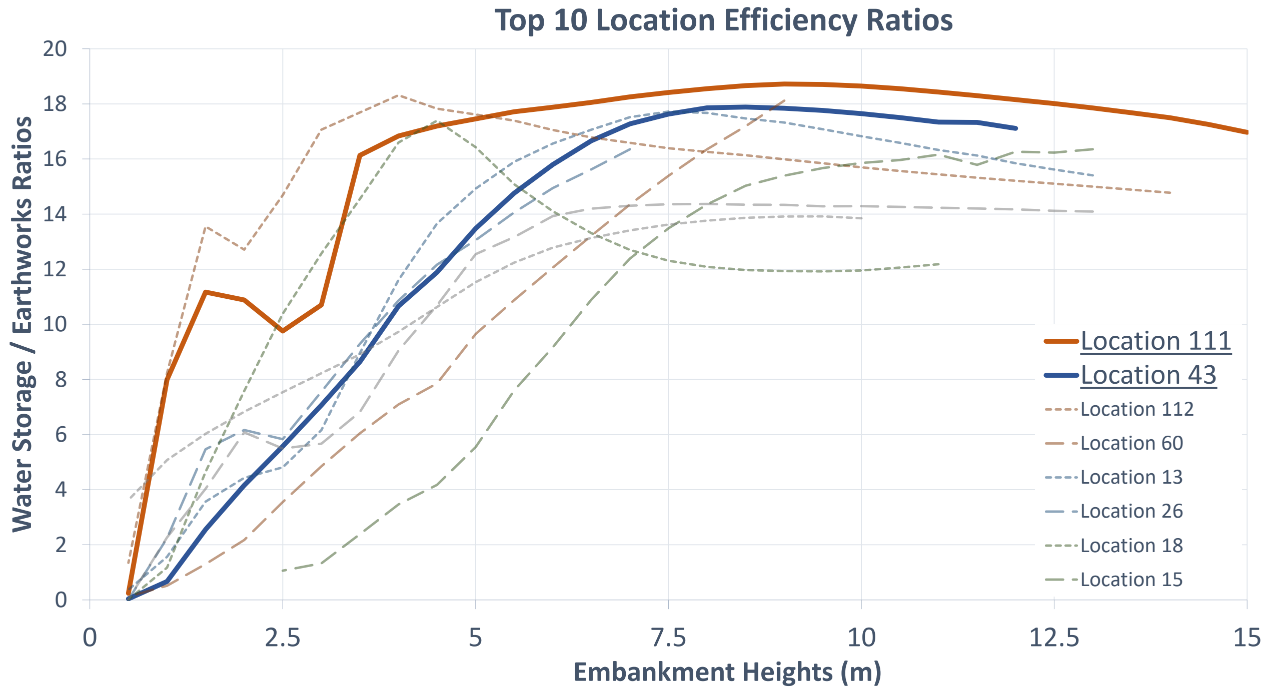

Figure 28 - Efficiency curves for the 10 best performing sites. Sites included in this report are highlighted.

Storage efficiency for the sites furthest upstream areas was almost always significantly lower than for the downstream areas closer to Lake Minnewasta, where the valley is deeper. However, a series of sites were still analyzed in the region closest to the potential Pembina River pipeline, the best of which will remain in consideration due to its ability to easily fill from the pipeline discharge without transmission losses.

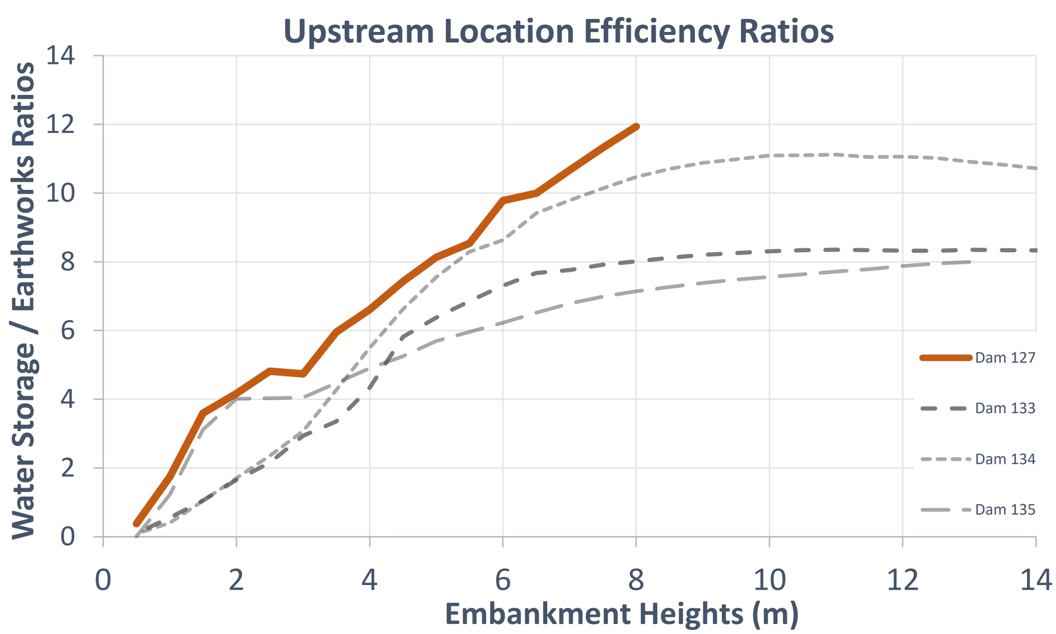

Figure 29 - Efficiency curves of sites nearest to pipeline discharge.

5.3 Selected Sites

An objective of this study was to use the automated LiDAR efficiency metrics to find a short list of three top-performing sites. The sites chosen in this report were based on the highest storage efficiency site in each of three key locations. Figure 30 shows a map of each selected location. Site 1 was chosen based on the most efficient site within the far downstream reach near Lake Minnewasta, Site 2 is the most efficient site in the southern fork of the Deadhorse Creek, and Site 3 is the most efficient site in the far upstream reaches near the outlet of the Route 1 pipeline. When the final site is selected, more factors than mathematical efficiency will be taken into consideration such as nearby infrastructure and the desires of local stakeholders, so these selections provides some variety in the location, reservoir size, and topography, while maintaining the best possible efficiency in each region.

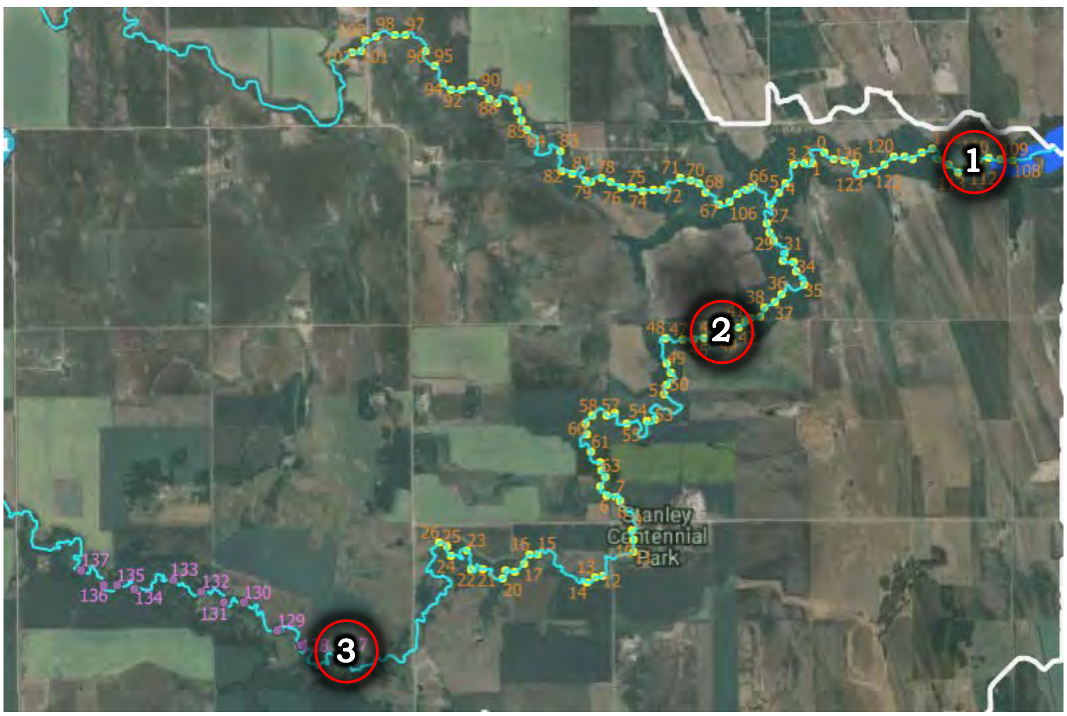

Figure 30 - Locations of top performing studied locations.

5.3.1 Site 1

Site 1 is located immediately upstream of Lake Minnewasta, however is far enough upstream that the maximum reservoir size of Lake Minnewasta does not inundate the new storage reservoir location. This location can provide the largest storage volume due to the depth of the DHC river valley in the area. Figure 31 shows a 3D render of the maximum storage reservoir analyzed height at Site 1 with the maximum reservoir extents.

Figure 31 - Render of full reservoir at Site 1.

The storage and surface area of the reservoir are shown at each studied reservoir height in Figure 32. At the highest reservoir height, Site 1 stores 2.4 million m^3 of water within 0.35 km^2 of reservoir area. This site has a storage efficiency of 17.0. The optimal height of Site 1 is 9.5 metres, which stores 0.84 million m^3 of water within 0.21 km^2 of reservoir area and has a storage efficiency of 18.7.

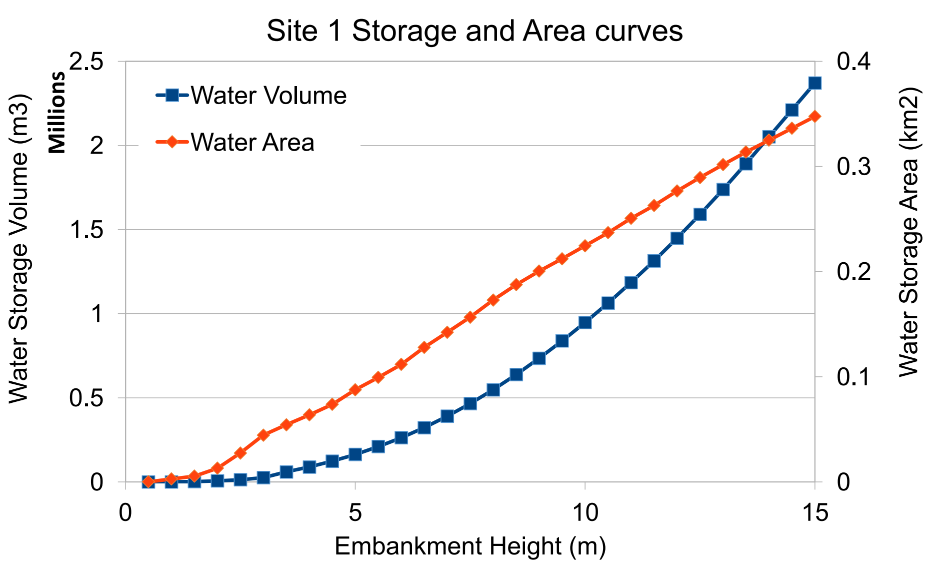

Figure 32 - Storage and Volume curves for Site 1

Based on a notional \$15/m^3 engineered earthworks cost, the construction of the maximum 15 metre embankment will be \$2.1 million. Additional structural and constructability components including spillway, land clearance, outlet works, and dewatering are estimated based on escalated cost values from the same PFRA cross section[5] used for the earthworks estimation.

The non-earthworks reservoir cost components (spillway, outlet works, land clearing and dewatering) are assumed proportional to earthworks costs for all reservoir sites examined in this report. These costs are derived from a detailed cost escalation exercise recently completed for a comparable reservoir project in Southern Manitoba[6], and are included here as illustrative of magnitude until site-specific design and costing can commence. ***Detailed reservoir design and costing was not in the scope of the current project.*** *Non-earthworks cost estimates are therefore reconnaissance-level with an estimated accuracy less than +/- 50% because of the site-specificity required for accurate estimation.*

For Site 1, the non-earthworks reservoir construction costs are estimated at $8.42 million at the optimal dam crest elevation, for a total cost of $15.7 million. The earthworks cost of the optimal 9.5 metre option will be $673,000, while additional structural and constructability costs will likely add up to $2.7 million for a total cost of $3.4 million.

5.3.2 Site 2

Site 2 is located on the southern fork of the Deadhorse Creek, immediately south of Road 11N. This area is advantageous as it contains a narrow bottleneck in the DHC river valley, where a reservoir can be constructed with very minimal earthworks. Additionally, the reservoir site is very close to the existing road, which will provide easy access for construction as well as for any potential lake access. Figure 33 shows the highest reasonable reservoir size for Site 2, with the access at Road 11N visible.

Figure 33 - Render of full reservoir at Site 2.

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[5] PFRA, 1987. Prairie Farm Rehabilitation Administration Engineering Service. Assiniboine South – Hespeler Area Study. Appendix B Engineering.
[6] Strategic Systems Engineering, 2021. *The Boyne Valley Water Initiative - Treherne Dam Feasibility Study*.

The storage and surface areas of Site 2 are shown in Figure 34. Compared to Site 1 the potential storage volumes are all lower, however also include much smaller flooded areas. The highest reasonable embankment size is 12 metres before the reservoir will begin to interfere with existing road infrastructure. At this height the storage volume is 0.52 million m^3 within an area of 0.12 km^2 and has a storage efficiency of 17.1. The optimal height is 8.5 metres with a storage efficiency of 17.9. At this height the reservoir contains 0.20 million m^3 within an area of .07 km^2.

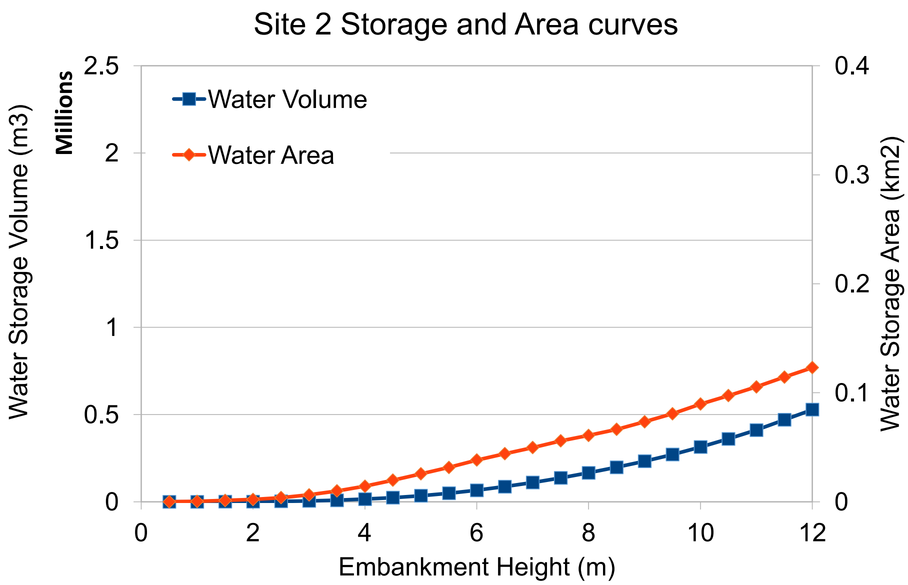


Figure 34 - Storage and Volume curves for Site 2.

Based on the $15/$m^3$ unit earthworks cost, the embankment cost of the maximum 12 metre reservoir at this site will be $463,000. Additional structural and constructability costs for the maximum reservoir size are estimated at $1,860,000 using the same proportionality logic as for Site 1. The estimated total cost is $2,320,000. The earthworks cost of the optimal 8.5 metre reservoir will be $166,000; non-earthworks structural and constructability costs increase estimate total cost to $667,000.

5.3.3 Site 3

Site 3 is chosen within the upstream region of the southern fork of the Deadhorse Creek upstream of Road 35W. This region was chosen for its proximity to the outlet of the Route 1 pipeline to allow for storage of the pumped water during the spring season. The DHC river valley remains fairly deep in this region, whereas further upstream it becomes too shallow for significant storage. Figure 35 shows the 3D render of the Site 3 reservoir site with the maximum possible reservoir. Above this reservoir height adjacent farmland becomes threatened in addition to the inundation of Road 36W.

Figure 35 - Render of full reservoir at Site 3.

Storage and area curves of Site 3 are shown in Figure 36. The maximum reasonable reservoir height for this site is 8 metres. At this height, the reservoir is capable of storing 0.47 million m^3 of water in an area of 0.21 km^2. The maximum height is also the most efficient in this case, and at this reservoir size the storage efficiency of this site is 11.9. Compared to the other sites, Site 3 increases in area much faster than it increases in volume, due to the comparatively flat land. This efficiency is much lower than is found in the other sites, however the site is still shown here as a potential storage site for water discharged by the Route 1 pipeline. Additionally, the constructability of this embankment is more difficult due to being located halfway between the mile roads and surrounded by farmland. This also makes the site less attractive for recreation as there is no direct access to the reservoir from the road.

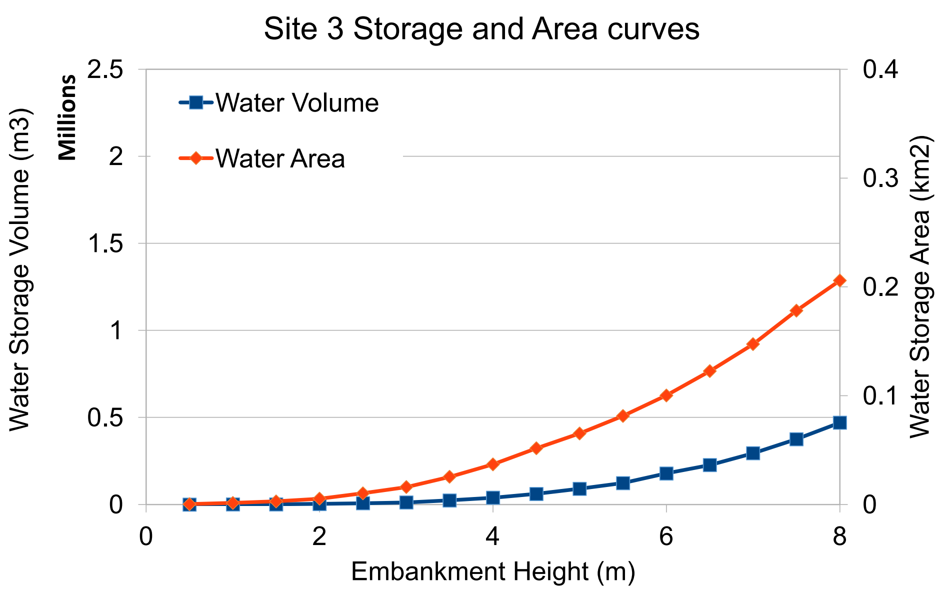


Figure 36 - Storage and Area curves for Site 3.

Using the $15/m^3 unit earthworks cost, the optimal 8 metre reservoir will cost $590,000 for earthworks only. Using the same proportionality logic as for Sites 1 and 2 (scaling relative to embankment size), the non-earthworks reservoir construction costs are estimated at $2,370,000.

5.4 Cost Summary and Cost Caveats

Table 6 provides a total cost summary of each potential project option. This includes the cost of each pipe route, as well as the reservoir options, with earthworks costs, and non-earthworks costs (spillway etc) listed as "Additional Reservoir Costs". Total pipeline cost includes cost of pipe, intake works and outlet structure. Intake works and outlet structure costing was outside the original scope and is adapted from a similar recent study conducted by SSE with input from the MWSB. Non-earthworks reservoir costs were also outside the original scope and are adapted from the same SSE study. Despite these limitations, Route 1 has clearly lower capital cost even with construction of a new reservoir. Moreover, a new reservoir adds climate resilience and operational flexibility – Route 1 is therefore recommended.

Project Option	Route Length (km)	HDPE Volume (m3)	Pipeline Total	Reservoir Volume (m3)	Earthworks Cost	Additional Reservoir Costs	30% Engineering + Contingency	**Total Cost**
Route 1	8.4	198.6	$5,500,000	N/A	N/A	N/A	$1,650,000	**$7,150,000**
Route 1 + Site 1	"	"	$5,500,000	2,400,000	$2,096,000	$8,420,176	$4,804,853	**$20,821,028**
Route 1 + Site 2	"	"	$5,500,000	520,000	$463,000	$1,859,991	$2,346,897	**$10,169,888**
Route 1 + Site 3	"	"	$5,500,000	470,000	$590,000	$2,370,183	$2,538,055	**$10,998,238**
Route 2	24.3	975.4	$19,440,000	N/A	N/A	N/A	$5,832,000	**$25,272,000**

Table 6 - Reservoir Site and Pipe Route comparison – Earthworks and Reservoir costs shown for the maximum feasible storage at that site.

The cost of the Route 1 pipeline shown in Table 6 are slightly lower than those described in the MSWB estimate. This is due to reductions in pipe design sizes and twinned piping. The detailed pipe sizing are shown in Appendices I and II, with cost comparisons to the MSWB estimate discussed further in Appendix III.

6 Conclusions and Recommendations

A hydrologic model of the entire Pembina Watershed was constructed upstream of Windygates, Manitoba using the HEC-HMS modelling system. The Pembina model meets literature-supported statistical performance criteria and was used to analyse Pembina River water supply considering the impact of climate change. The Pembina model indicates that at least 1,500,000 m^3 of water is available to augment Morden water supply at Lake Minnewasta via diversion from the Pembina River even with stringent climate change impacts accounted.

Two pipeline routes were considered for the Pembina diversion. Route 1 was the shortest pipeline route and minimizes trenching costs. After leaving the pipe, the pumped water must flow naturally through Deadhorse Creek tributaries until reaching Lake Minnewasta. Route 2 runs directly to Lake Minnewasta and provides a direct source of water without any risk of transmission losses. However, Route 1 transmission losses are likely to be relatively low for a spring freshet-only pumping schedule, when ground tends to be frozen or saturated.

Strategic Systems Engineering recommends Route 1 given its much lower capital cost and its compatibility with additional Deadhorse Creek storage construction.

The Deadhorse Creek was scouted for efficient storage reservoir sites using a 1 metre LiDAR-derived DEM, with results for the three top performing sites analyzed in this report. Earthworks cost estimation is volume based on 3D DEM modelling for the proposed reservoir sites. Non-earthworks cost estimation (spillway, outlet works, land clearing and de-watering) were adapted from a similar recent Manitoba study and are reconnaissance-level only and will be refined in future study phases. Land acquisition costs are not included. Despite these limitations, some conclusions can be drawn:

Site 1, the largest potential reservoir site and nearest to Lake Minnewasta, provides the most efficient storage to earthworks ratio. This site should be the prioritized for construction if the required land is available for reservoir construction.

Site 2 has similar storage efficiency of Site 1 but a lower storage volume. The site could be preferred if budgetary concerns or recreation co-benefits were prioritized. Site 3 should only be chosen if proximity to the pipeline outlet is prioritized above cost efficiency.

A limitation of either Route 1 or Route 2 is the spring freshet-only pumping schedule. Essentially, the best case that either Route1 or Route 2 can achieve is filling Lake Minnewasta on May 31, when the pumping season ends. The design flow (250 L/s *60 days/year) is based on meeting the estimated incremental flow required for Morden's projected population growth (40 L/s * 365 days/year). The design flow does not account for decreasing Lake

Minnewasta firm yield due to climate change (~estimated at ~20% reduction), nor for evaporation losses or downstream infiltration losses from a balancing reservoir constructed upstream of Lake Minnewasta as considered in this study.

Recommended next phases of study are a re-estimation of the Pembina diversion design flow for two scenarios:

1. The volume required to fill Lake Minnewasta in two months from its expected April 1 level accounting for runoff from the DHC watershed with the impact of climate change assessed.
2. The volume required to fill Lake Minnewasta as in (1) and fill a balancing reservoir to provide additional reliability.

Both design flow scenarios require a systems model of the diversion with reservoir behaviour modelled and utilizing the hydrologic models of the Pembina Watershed and the Deadhorse Creek with climate change impacts. Our current Deadhorse Creek hydrologic model will be refined in the next phase to model inflows to Lake Minnewasta on a daily time step.

The systems model will also be required for licensing and regulatory approvals. Infrastructure Canada funding eligibility requires that the project proponent demonstrate that climate change impacts are adequately considered to prove resilient design and minimized environmental impact. The systems model of the diversion + Lake Minnewasta + new reservoir system will be used for:

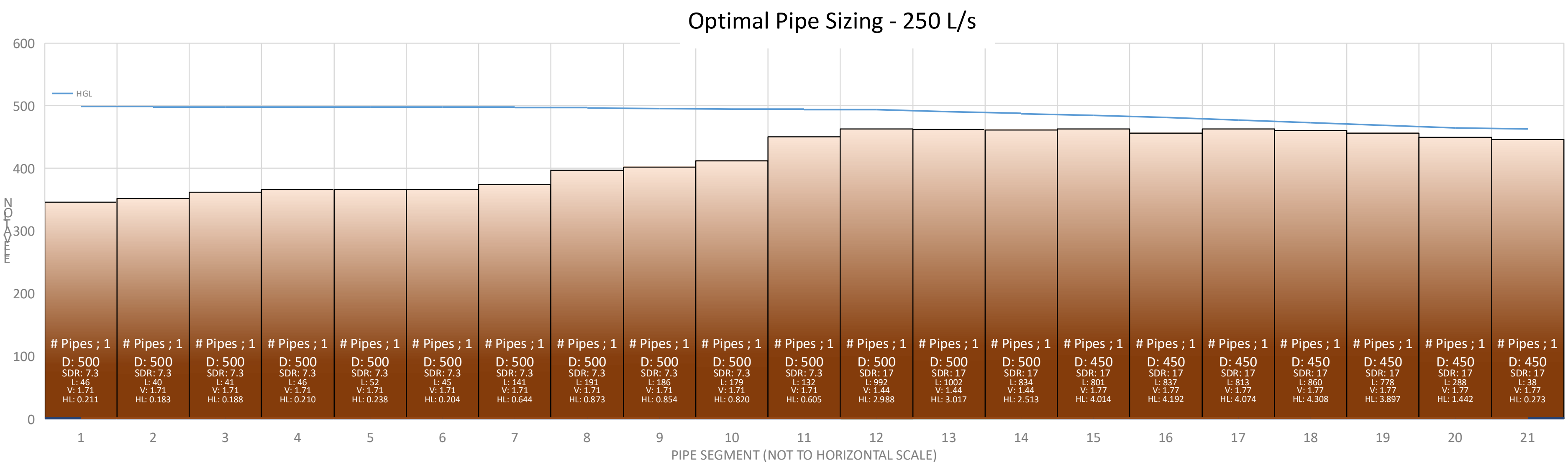
- A refined estimation of the required design flow (with and without a new reservoir),
- the optimal capacity of new reservoir capacity, and
- a return-on-investment calculation based on the economic value of new water supply for the City of Morden.

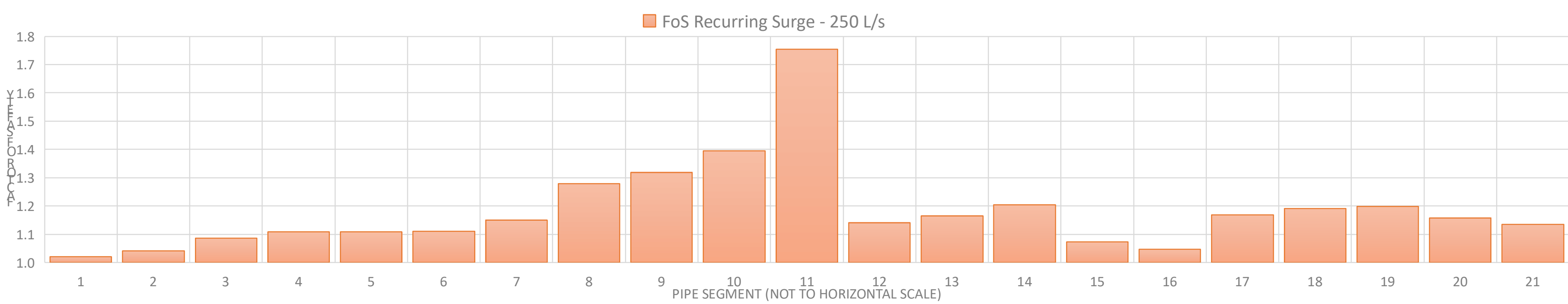
Strategic Systems Engineering recommends that a proposal to Infrastructure Canada for the Route 1 pipeline use a design flow that supports filling a new reservoir to "future-proof" this investment.

Upon refined estimate of the design flow, the next phase of pipeline design requires defining several specifications for the pipeline. These include intake screens, pump house design, thrust and expansion protection, and energy dissipation. Based on availability of pipe sizes from local contractors, some adjustments to pipe sizing may also be required in further design phases in cases where construction logistics must supersede size optimization.

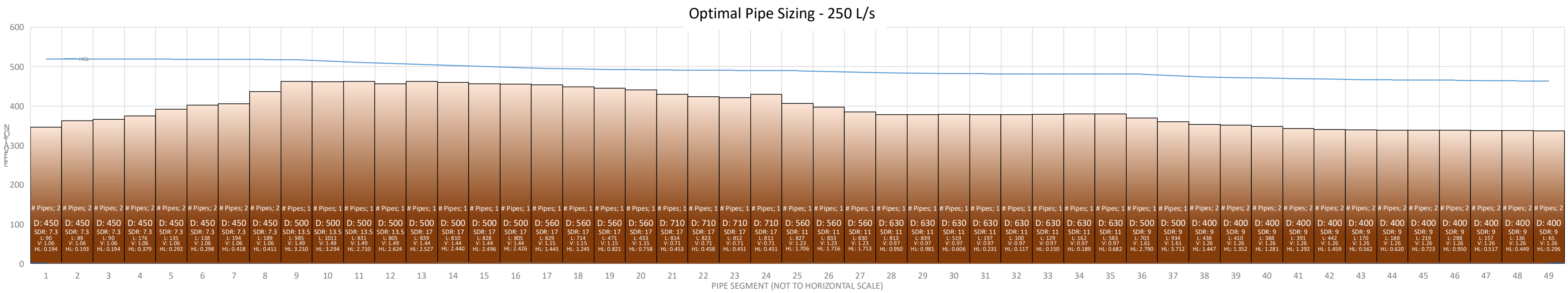
Future phases of reservoir design will include alignment, primary and secondary spillway designs, erosion protection, as well as flood mapping, flood surge analysis, and geotechnical analysis, which will refine the estimated costs used in this report.

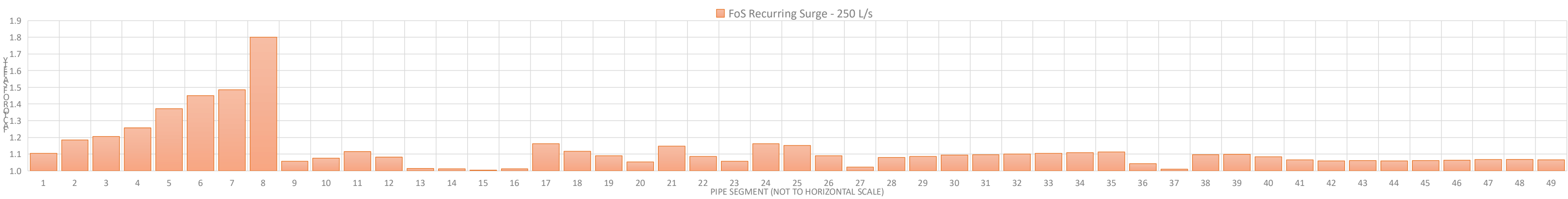
Appendix I: Route 1 Pipeline





Appendix II: Route 2 Pipeline





Appendix III: Cost Data

Costs for this report were estimated based on comparisons between cost-estimates from multiple sources.

THE MANITOBA WATER SERVICES BOARD

City of Morden - Deadhorse Creek Supply Pipeline

Component	Quantity	Unit	Unit Price	Total
Pressure Pipeline				
i) 500mm ø HDPE DR9 (Twinned section)	600	Lin. m	$ 515.00	$ 309,000.00
ii) 600mm ø HDPE DR9	1700	Lin. m	$ 730.00	$ 1,241,000.00
iii) 600mm ø HDPE DR17	6600	Lin. m	$ 420.00	$ 2,772,000.00
Connect to Intake Pumphouse	1	Each	$ 10,000.00	$ 10,000.00
Crossings				
i) Buried Utilities	2	Each	$ 15,000.00	$ 30,000.00
ii) Waterway/Drain	2	Each	$ 25,000.00	$ 50,000.00
Flushout Assemblies	4	Each	$ 45,000.00	$ 180,000.00
Combination Air Valve	2	Each	$ 25,000.00	$ 50,000.00
Intake Works	1	L.S.	$ 1,891,000.00	$ 1,891,000.00
			Sub-Total	$ 6,533,000.00
			Engineering (15%)	$ 979,950.00
			Construction Contingencies (10%)	$ 653,300.00
			Finance & Administration (5%)	$ 326,650.00
			TOTAL ESTIMATED COST	**$ 8,492,900.00**

The above table shows the cost estimate provided by MWSB, including intake works and a somewhat larger twinned pipeline for Route 1. The subtotal cost of the pipeline construction in this estimate is $4.4 million, with additional fixed costs for intake works adding $2.1 million for a sub-total of $6.5 million and total estimated cost (including contingency) of $8.49 million.

Using the generalized volume based cost estimate for pipeline works which was utilized in the main report, the same pipeline design would be estimated to cost approximately $8.57 million, or about 1% higher. The lower cost of the Route 1 pipeline in the main report is due to efficiencies found through using a single, high pressure class pipe, rather than twinned lower pressure pipes. Should the design flow be increased beyond 250 L/s however, twinned pipes would be necessary regardless.

	Pipe	$	$/m3
From jdb projects	D: 630 - SDR: 11	$ 434	$ 8,022
	D: 900 - SDR: 11	$ 827	$ 7,490
	D: 900 - SDR: 13.5	$ 725	$ 7,988
	D: 600 - SDR: 17	$ 311	$ 9,633
	D: 900 - SDR: 17	$ 590	$ 8,122
	D: 1200 - SDR: 17	$ 1,160	$ 8,982
	D: 710 - SDR: 21	$ 374	$ 10,161
	D: 900 - SDR: 21	$ 569	$ 9,620
	D: 1200 - SDR: 21	$ 985	$ 9,368
	D: 710 - SDR: 26	$ 293	$ 9,809
	D: 900 - SDR: 26	$ 485	$ 10,105
	D: 1400 - SDR: 26	$ 1,085	$ 9,342
	D: 250 - SDR: 32.5	$ 69	$ 23,199
	D: 355 - SDR: 32.5	$ 91	$ 15,173
	D: 400 - SDR: 32.5	$ 106	$ 13,921
	D: 500 - SDR: 32.5	$ 160	$ 13,449
	D: 560 - SDR: 32.5	$ 164	$ 10,989
	D: 630 - SDR: 32.5	$ 236	$ 12,495
	D: 800 - SDR: 32.5	$ 341	$ 11,196
	D: 850 - SDR: 32.5	$ 388	$ 11,285
From MWSB	D: 450 - SDR: 17	$ 190	$ 10,462
	D: 500 - SDR: 17	$ 239	$ 10,660
	D: 600 - SDR: 17	$ 515	$ 15,951
	D: 600 - SDR: 9	$ 730	$ 12,302
	D: 500 - SDR: 9	$ 420	$ 10,192
		Average	Escalated
	jdb Projects	$11,018	$ 16,526
	MWSB	$11,913	

The table shown here lists the aggregated pipe costing data that was used to form the volume-based cost estimates shown in this report. The pipe sizes quoted by Accurate HD for the Treherne dam project (conducted by jbd project engineering[7]) are shown in white and result in an average volumetric pipe cost of $11,018/m^3. The pipe cost estimates performed by MWSB are shown in green and result in an average cost of $11,913/m^3. As the jdb project engineering costing was done before the COVID-19 pandemic and its resulting material shortages, these costs were escalated by a 50% factor based on trends in the average cost of HDPE since 2019.

The value used in this report, $16,526/m^3, is slightly higher than the highest cost pipeline estimated by MWSB, and is also expected to be an overestimation. However prices could continue to increase in the time between this report and the beginning of construction.

[7] jdb projects engineering, 2019, Assiniboine River System: Pre-Design and Cost Estimate

Appendix 5: North Region Climate Adaptation Case Study: East Interlake Hydrographic Analysis

STRATEGIC SYSTEMS ENGINEERING INC.

DRAFT - East Interlake Hydrographic Analysis

Project Title	East Interlake Hydrographic Analysis
Client	Armand Belanger, Manager, East Interlake Watershed District Steve Strang, Manager, Red River Basin Commssion
Authors	Hank Venema, PhD PEng. Senior Engineer Matt Sebesteny, B.Env. Lead Geospatial Analyst Ryan Spies, M.Sc. Senior Developer Patrick Lee, B.Sc. Software Applications Developer
Context	In a recent scoping exercise, Strategic Systems Engineering (SSE) demonstrated that EIWD's investment in culvert inventory collection over the past ten years plus the 1m resolution LiDAR are essential for accurate baseline hydrography required to design a retention storage network. SSE and EIWD believe that the entire hydro-conditioned Netley-Grassmere-Willow DEM should be batch-processed to ensure flowpath and watershed delineation accuracy. SSE will adapt its hydrographic processing model to process this large domain (approximately 5 billion cells). At the client's request, we will include the Shoal Lake Watershed, and process the entire Netley-Grassmere-Willow-Shoal Lake domain as shown in Figure 1. The computational effort required will be subsidized by SSE's National Research Council-funded project on high performance computing for climate resilience analytics and natural infrastructure systems design.
Summary	This report will examine the findings of the processing model [Hank edit please]

Domain	The domain includes the southern portion of the East Interlake Watershed District, as well as the southeastern portion of the West Interlake Watershed District (shoal lakes portion). This main areas of the domain are the relatively high up shoal lakes, the higher limestone plateau area – with limited agriculture, the midland agricultural area and the lowlands to the east, which generally have the best suited soil for agriculture.

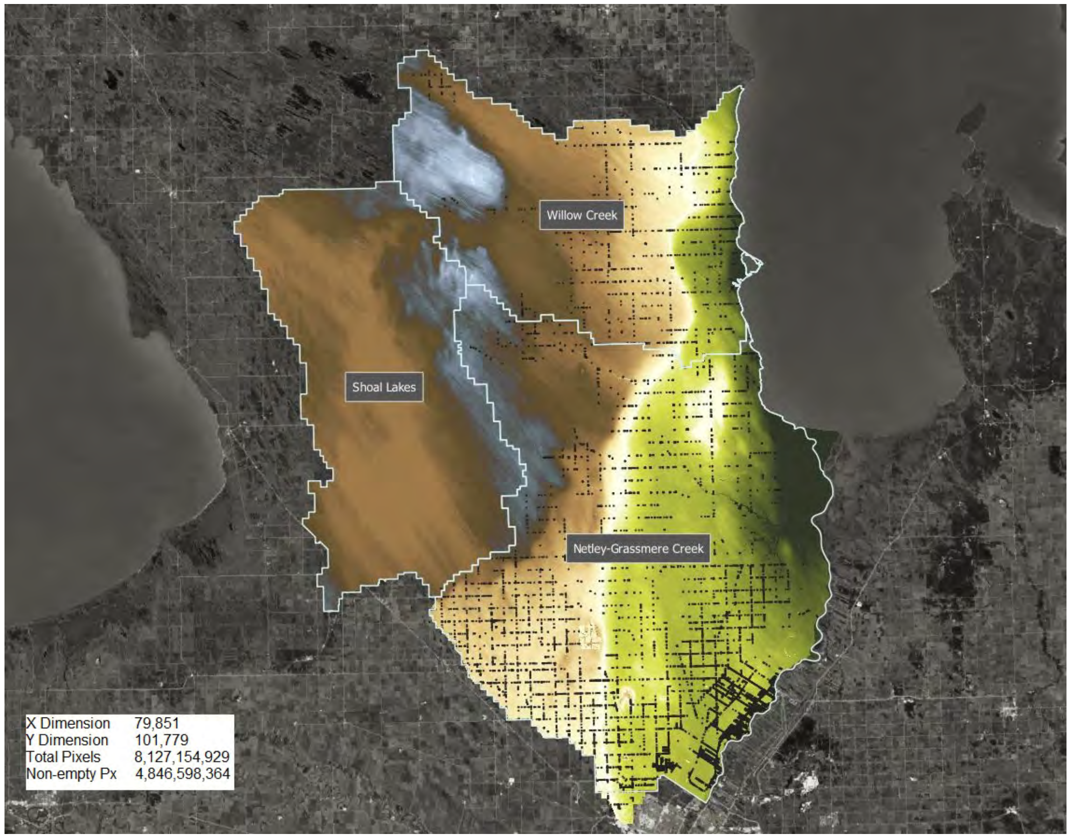
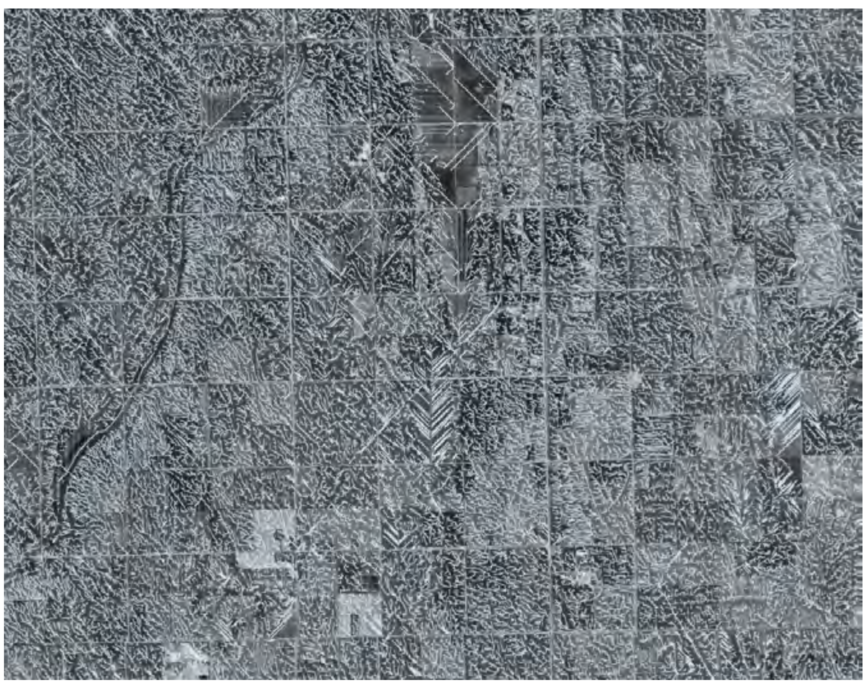
<table>
<tr><td></td><td>


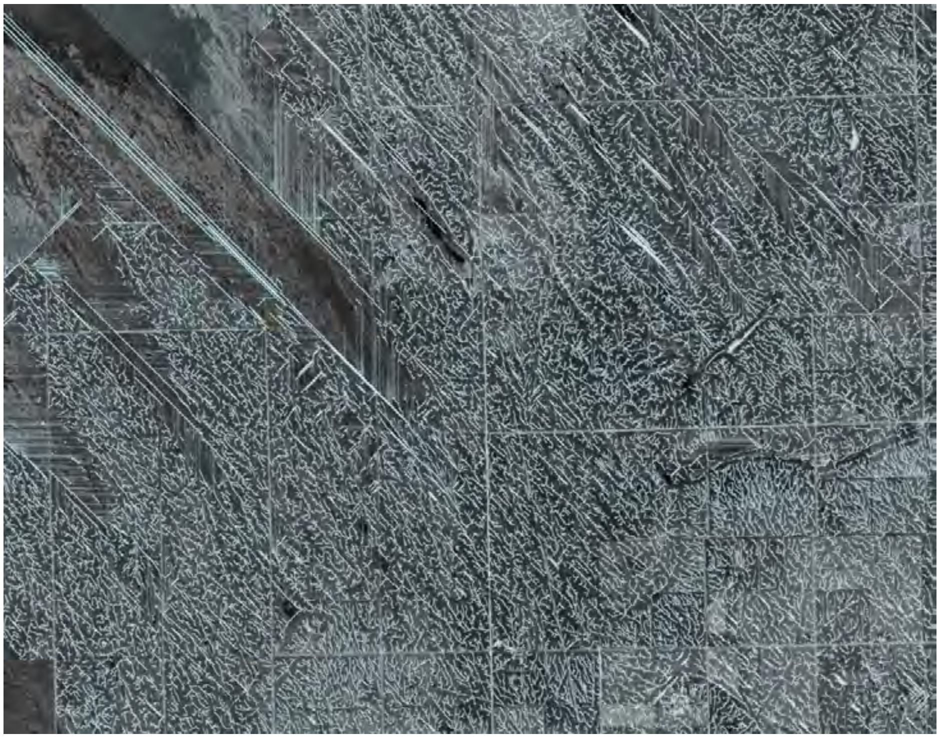
Figure 1: The Digital elevation model domain, shown with the dimensions of the data, along with culvert locations as black dots.

The domain consists of three sub watersheds, as defined by the Canada Water Survey (CWS); Willow Creek, Netley-Grassmere Creek and the Shoal Lakes. Willow Creek drains directly into Lake Winnipeg, Netley-Grassmere drains into Netley marsh (and then Lake Winnipeg) and the Shoal Lakes are less defined.

A study by KGS in 2010 eluded to the Shoal Lakes as naturally being in a terminal basin, meaning they will not drain out anywhere. However, SSE had identified a probable connection with regard to drainage being possible outside of this basin. Two pathways that are situated about 1.2m above the water level as detected by the LiDAR, drain outside of the area - one being into Lake Manitoba near St. Laurent and the other into the Netley-Grassmere watershed, northeast of Woodlands.
</td></tr>
<tr><td>Hydroconditioning</td><td>Hydro-conditioning is the process of indicating water management features in a watershed to define hydraulic connectivity - how water moves downstream. The process involves correcting for features that LiDAR, which is acquired by sensors aboard an aircraft, cannot</td></tr>
</table>

	capture. These most often comprise the underside of bridges and culverts. The asset data key to completing this process is a regional network of lines representing an inventory of culverts (or other water management features) and their defining characteristics. This hydro-conditioning process utilizes the extensive culvert inventory developed by the EIWD, which is compatible for a rasterization process to imprint, or burn in, the features to a regional Digital Elevation Model (DEM) available from the Manitoba Land Inventory (MLI). This process results in a hydro-conditioned DEM suitable for high-quality flood risk mapping. The EIWD has a comprehensive culvert inventory for the Willow Creek and Netley-Grassmere subwatersheds, but little to no culvert inventory data is available at this time for the Shoal Lakes area.
Wang-Liu and Filling algorithm	In 2006, Wang and Liu published an algorithm for extracting hydrology parameters from a LiDAR-derived DEM[1]. The Wang-Liu approach fills all surface depression features prior to computing the drainage topology for the watershed, which accounts for the real-world “fill and spill” characteristics of prairie potholes for example. SSE first implemented the Wang-Liu algorithm in Python, to take advantage of the open-source geospatial library known as the GDAL (geospatial data abstraction library), which essentially allows GIS processes to take advantage of modern high-performance computing. The algorithm itself is built to examine every pixel of the DEM to detect if a depression is present, and adjusts the elevations accordingly to create a smooth downward slope. The Wang-Liu algorithm repeats the depression filling process until every cell in the DEM is investigated. In the end of the process, we will have a depression less DEM ready for flow topology analysis. Afterwards, a Flow Direction and Flow Accumulation raster from the depression filled version of the DEM can be created. Both flow rasters are generated using the D8 algorithm, that routes flow to only one downslope neighboring cell. From here, we can use the Flow Directions of each DEM pixel to determine how flow is being routed between neighbouring cells. In addition, if a cell does not receive flow from any of its neighbours, then the cell in question is at the most upstream region, which is the process used to define watershed boundaries. Essentially, the algorithm climbs the elevation hierarchy upwards starting at the most upstream cells and continues to calculate flow accumulation as we follow the flow directions. Ergo, this is the underlying logic of the D8 Flow Accumulation algorithm.

	 Figure 2 – The flow paths at the domain scale. It's not possible to see each individual flow path at this zoom level, but this shows that the entire domain has been processed.  Figure 3 – Zooming in towards the center of the domain. Note that some areas have straighter flow lines that appear almost like 'veins in a leaf' – these are 'sink' areas that have

	been filled due to their depressed but flat nature. Most areas however are more hilly, so the pathing follows perpinducular to the contour of the landscape.
	 Figure 4 – Zooming further into the area southeast of East Shoal lake. More detail can be seen here. Note the abundance of straight paths immediatley southeast of the lake, indicating the elevation differences are very small here. The pathing travels in the southeast direction.

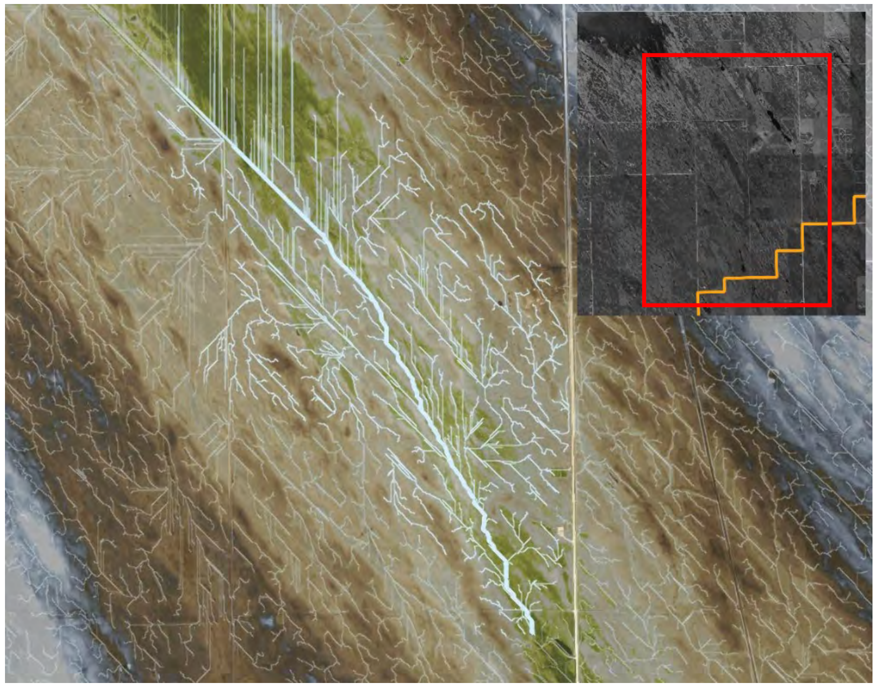


Figure 5 – Zoomed in to the depressed channelized area southeast of East Shoal lake. Pictured here is the underlying DEM, along with the Wang-Liu algorithm output flow paths in blue. The inset map shows the extent in Red, with the Canada Water Survey watershed boundary in orange.

This area is of special interest as it's been expressed that the Shoal lakes may drain through this channel towards the Netley-Wavery watershed, which would cross over the CWS boundary.

In fact, the Wangl-Liu code delineation sees the CWS watershed boundary as not siginificant to prevent flow from the lake into the Netley-Grassmere watershed.

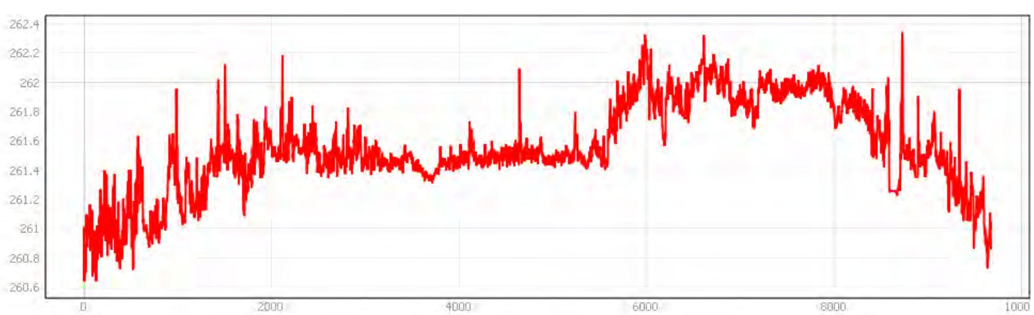


Figure 6 – The profile of the thicker blue line in Figure 5 above. The average vertical noise/error in the LiDAR for this piece is ±20cm, at 95% confidence. The left side of the graph is at the edge of East Shoal lake and the right side of the graph is near PR 322 @ RD 85 N.

	The difference from the Shoal Basin to the CWS subwatershed boundary at peak elevation (at the 6000m mark) is approximately 115 cm.
Shoal Lake drainage recon	The Shoal lakes are in a depression of around 1-3m from all sides and are thought to be in their own terminal basin. Two likely drainage paths have been identified by SSE, one to the northwest of North Shoal lake and one to the southeast of East Shoal lake. Two crossings for provincial roadway split the waterbodies into three sections. It is unknown at this time how many culverts exist under these crossings, as there is no culvert inventory data currently. A ditch network approaches the northwest side of North Shoal lake, but only connects to a marshland that is approximately 110 cm above the lake level – at the time of LiDAR capture, on October 20th, 2015. Ostensibly, under an extreme rainfall event, some water may flow towards this outlet, which would be made easier by a stiff southeast wind. A channelized depression accompanied by marshland can be found southeast of East Shoal lake. Due to the numerous bog and fen sub-depressions and the fact the approximate elevation at the crest of the channel is only 115 cm above the lake level, it could act as a condiut for high waters levels to egress into the Netley – Wavey watershed, provided enough rainfall and a stiff northwest wind.

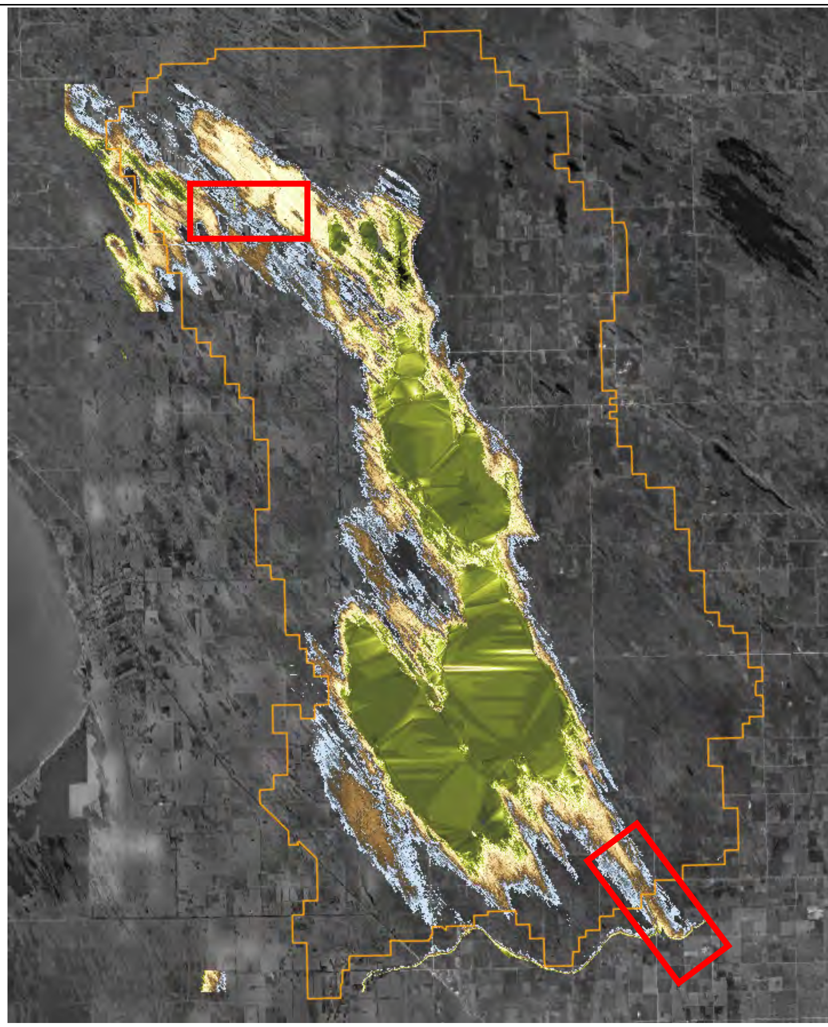
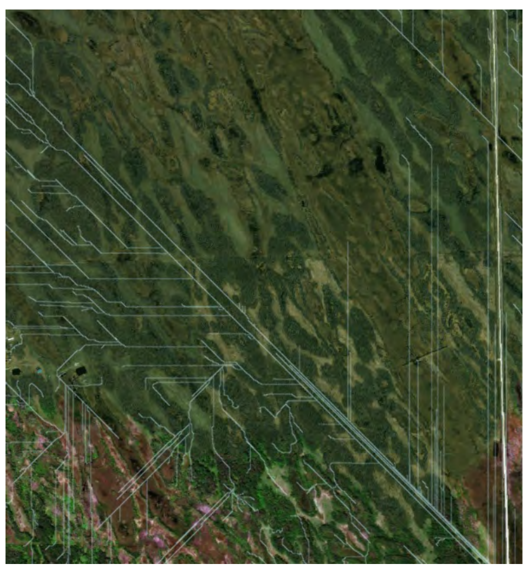


Figure 7 – The Shoal Lakes, with shoreline and basin shown. The color scale has been compressed between 260.4 and 262.8m asl, and masks other elevations out for illustrative pusposes. The two likely outflows are shown in red boxes, where SSE believes a significant, quick precipitation event and some wind may drive some water out of the basin.

This hypothesis is complicated by the fact that there are two road crossings that split the lakes into a southern, central and northern sections, with normal lake levels, being PR 415 and PR 229. It it likely the roads may be overtopped given a severe flooding event, especially the northern road (PR 229), which is less than 80cm in spots relative to the LiDAR lake level.

Because of this, SSE believes it is still possible that wind may have an effect, but more extensive modeling would have to be done to estimate the vertical push-up of water on the leeward side of the lake in conjunction with an extreme rainfall.

	A screen capture of Google street View data for PR 229 shows the lake level in spring of 2012 overtoping the road.  Figure 8 – Google Street view capture of PR 229 meeting North Shoal lake on the east side, in May of 2012 (exact day unknown). The vehicle used for this image capture did not traverse over the section of road cutting across the lake, most likey because it was overtopped and therefore not tenable to travel across it.
Investigation into spillage from East Shoal into Netley-Grassmere	The southeast channellized depression is a linear depression with pockets of bogs and fens, in an almost string like manner extending from East Shoal lake, across the watershed divide and down to PR 322.  Figure 9 – Satelite view, courtesy of Bing, of the channelized depression, shown with the Wang-Liu delineation. Again, the flow pathing is mostly straight here, meaning this area is in

a flat depression so this area was sink-filled – the resulting calculation pushes water southeast.

The first order of reconnaisance work is to test the southeast channelized depression with a medium forcing event of 100mm to examine what divergence from the Canada Watershed Survey boundary there edns up being. A ponding model, called WDPM standing for Wetland DEM Ponding Model was used at a tolerance of 5cm.

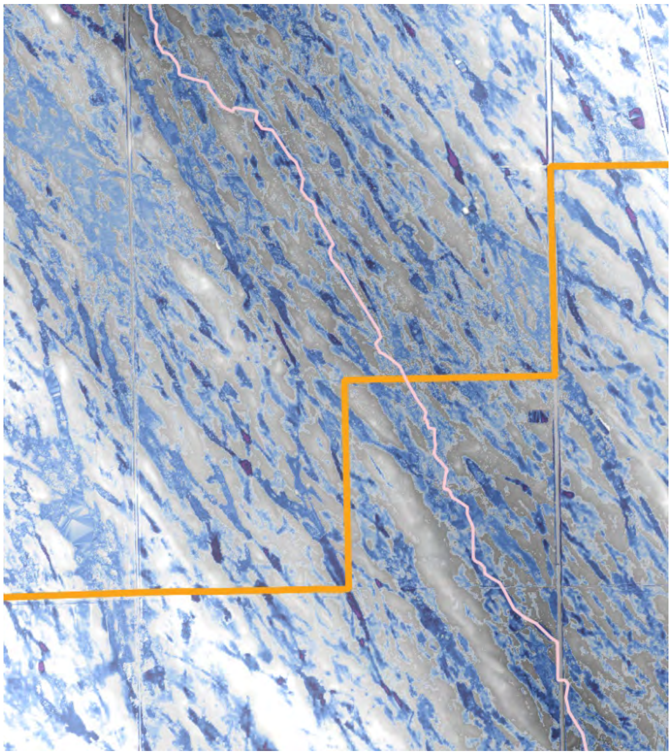


Figure 10 – Results from the 100mm forcing event, in the channel at the divide. The blues show depth, between 0 – transparent, and 60cm – dark blue; and the elevation is shown in greysace with lightness equaling height.

Although WDPM doesn't handle fluvial (river and stream) runoff, these results indicate the area is fairly flat, and the channel gradient to the divide is shallow. This means the liklihood of water flow across the divide is reasonably likely, if enough fills the channel.

Appendix

The following are part of the data package included with this report			
File name	**Data Type**	**Description**	**Attribute(s)**
dem.tif	raster	The hydroconditioned digital elevation model	Elevation in metres
flow_accumulation.tif	raster	Flow accumulation values (upstream catchment area in m2)	Upstream catchment area in sq. metres
flow_direction.tif	raster	Directionally coded raster using the D8 system	Direction code
flow_path.shp	vector, line	Single line feature showing delineated flow paths	• Overland, if the flow drainage area is between 0.5 sq. mile and 0.5 sq. km • In-channel, if the drainage area is over 0.5 sq. km • Drainage area in sq. meters
pour_points.shp	vector, point	Point shapefile showing locations where the flow from each subwatershed polygon empties out of	
subwatersheds.shp	vector, polygon	Polygons showing subwatershed boundaries within the test watershed	Area in sq. **miles**
sink_areas.shp	vector, polygon	polygons of where the dem was filled up to eliminate pothole depressions (sinks) affecting flowpaths	Area in sq. **miles**, volume (m3), elevation (m) , depth (m)
watershedbounds.shp	vector, polygon	A single polygon of the large watershed of the domain	Area in sq. **miles**
tp_mass.tif	raster	Estimated yearly TP mass loss leaving the landscape.	mass in grams/pixel
tp_mass_acc.tif	raster	Estimated yearly TP mass that accumulates from upstream.	mass in grams/pixel
Tn_mass.tif	raster	Estimated yearly TN mass loss leaving the landscape.	mass in grams/pixel
Tn_mass_acc	raster	Estimated yearly TN mass that accumulates from upstream.	mass in grams/pixel