Preparation of a two-dimensional
Hydrodynamic Model of the
Lower Pembina River Flood Plains

Controlled Technical Report CHC-CTR-093
July 2009
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Preparation of a two-dimensional Hydrodynamic Model of the Lower Pembina River Flood Plains

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Preparation of a two-dimensional Hydrodynamic model of the Lower Pembina River Flood Plains

1. Introduction

The Pembina River Basin Advisory Board and the International Red River Board have been looking for several years at ways to minimize flood damages from the Pembina River overflows.

For this purpose, several one-dimensional numerical models have been prepared in an attempt to model the actual propagation of the flood and try to simulate mitigation measures. These models are becoming more and more complex, trying to simulate the wide spreading of the river’s flow on the flood plain, which are influenced by the complex network of super-elevated roads, dykes, drains, and culverts.

A 2D model is more appropriate to study these kinds of problems since in these models, the local direction of the flow is not assumed, but is calculated everywhere from the local topography of the land, and therefore is a natural consequence of the flow propagation over the terrain.

The International Joint Commission retained the services of the Canadian Hydraulics Centre (CHC) of the National Research Council, to prepare a two-dimensional model using Telemac-2D, a software now freely available from France.

This report describes the preparation of this model and its calibration. Results are also presented for a few hypothetical scenarios where some aspects of infrastructure have been modified. This allows the simulation of hypothetical scenarios, thereby allowing an initial estimation of where the flood waters would be going under such conditions, and what kind of benefits and damages would occur.

2. The Telemac-2D model

The Telemac software is developed by the Laboratoire national d'hydraulique et environnement d'Électricité de France (EDF) in Chatou. It solves the two-dimensional shallow water equation using finite elements techniques. It is used by more than 170 organisations around the world. It is written under the EDF Quality Assurance system that includes the production of a validation document [Hervouet, 2000]. This document conforms to a standard validation system supported by the International Association for Hydraulic Research (IAHR) and includes results of validation studies.

Most of the large rivers and estuaries in Europe are being studied with this software (Loire, Gironde, English Channel, Thames, Severn and Elbe, to name a few), many of these applications being followed by a sediment study. In Canada also, many rivers have been studied with this software such as the Columbia River in BC, the Red River floods, the Outaouais around Ottawa, the St-Lawrence around Cornwall and Montréal, the Manicouagan estuary and recently the St.Clair and Detroit Rivers. Utilities across the country continue to use Telemac as their prime modelling tool.
3. Preparation of the model

3.1 Model grid description

Telemac is a depth-averaged two-dimensional model that requires a grid to discretize the physical system into a set of numerical triangular elements. The grid is unstructured, which means that the size of the elements can vary. A fine grid will allow proper representation in the model of certain details such as the meanders of the river or the elevation of the roads. A coarse grid will not be as accurate in the representation of these details, but will result in a smaller number of elements, needing less computing time.

Each of the 3 nodes of the triangular elements is assigned an elevation corresponding to the bathymetry of the river or the topography of the land, and the water velocity vector and water depth are computed at these nodes. The grid is therefore the discretized numerical representation of the physical river and its adjacent plains.

3.1.1 River and flood plains

The model extends from Walhalla to the town of Pembina along the Pembina River, and from 9.5 km upstream along the Red River, to 33 km downstream along the Red, in order to include the confluence with the Aux Marais River (Fig. 1). This coverage was chosen to study the floods coming from the Pembina River, on its lower flood plains. The inclusion of the Red River is only partial (we cover only a small portion of the right bank of the Red) to allow known boundary conditions at both ends of the Red. As such, the model is not an adequate tool for representing correctly the floods emanating from the Red River.

The flood plains in the western portion of the model, (from Walhalla to about 18 km downstream) were modelled only over a width on the order of 800 m. This would allow the proper setting of the boundary condition at Walhalla without adding numerous grid elements in an area not deemed to be critical. (This area was not covered by the aerial photos taken during the 2006 flood, and as such it was thought that its flooding was not as critical as in the lower section of the river).
The Pembina River main channel was described with a grid size of about 7m x 20 m. The grid size increases to a more regular mesh of 20 m at the top of the banks, then to 150 m in the agricultural fields between roads, and to 300 m away from the roads. With this grid definition, the main channel is described by a cross section having 7 points, every 20 m along the stream, while the top of the banks are described with a 20 m grid, giving enough definition to most of the landscape characteristics.

The thalweg of the river and the top of its banks, right and left, were drawn from the LiDAR survey, by looking at the lowest and the highest survey points along the 122 km long river. The river grid was then aligned along these 3 lines.

The Red River definition is slightly coarser with triangles on the order of 50 m, which is sufficient to define properly the river banks.

The Tongue River is described with a grid size of 40 m to allow a reasonable estimate of the conveyance of that river.

The Aux Marais River grid is only 100 m in size to minimize the number of elements. As such the model will not reproduce accurately the depth of the river, but will provide a good visualisation of the flow through it.

Figure 2 shows a south-west to north-east cross section of the Pembina River through two of its meanders, as represented in the model. It shows the road and the top of the banks, at a higher elevation than the flood plain. This 1650 m long section can be located in Fig. 3. It is about 5 km downstream from Neche.
Figure 2 - Cross section as represented in the model showing land elevation in meters

Figure 3 - Location of cross section on the LiDAR survey
The triangular grid was generated for the most part using Blue Kenue, a pre and post-processor developed by CHC, for Telemac, with many grid details being edited with TRIGRID, a mesh generator available from http://sourceforge.net/projects/trigrid/.

Examples of the grid details are shown in Fig. 4 and 5 with Fig. 6 showing a superposition of the model on a Google Earth picture. The model has in excess of 110 300 nodes and close to 219 000 elements.

The geographic system in which the model was prepared is UTM (Universal Transverse Mercator) zone 14. All levels are referenced to CGVD28 which is the datum to which the LiDAR survey data were provided.

Figure 4 - Detail of mesh describing the top of the banks
Figure 5 - Detail of mesh describing the main channel with part of a remaining dyke

Figure 6 - Mesh detail over a Google Earth photo with top of bank lines and Thalweg
3.1.2 Roads

Only the major roads were specifically prepared in the model. With a grid density of 50 m, they were located from the LiDAR data so that their triangles perfectly matched the terrain elevation. They are shown in Figure 7. Hwy 75 was included in the model but only north of the town of Pembina. It is represented by a coarser density (100 m).

![Figure 7 - Roads and drains represented in the model](image)

3.1.3 Drains

Four drains were represented. They are shown in magenta in Figure 7:

- drain along Canada-United States border,
- two sections of Louden Coulee. The south end of the upper portion is discharging into the lower portion where it will flow into the Tongue River
- county ditch number 11
- a short drain going northwards, 6.2 km west of Neche
3.2 Model tributaries

Only one tributary of the Pembina River was included, the Tongue River, with flows obtained from the USGS gauge at Akra. No local precipitation or local surface water inflow was considered.

3.3 Model prescribed boundaries

The model was run with:

- prescribed flows at the two upstream boundaries: the Pembina River at Walhalla and the Red River, 9.5 km upstream from the confluence with the Pembina River, and
- prescribed elevations on the Red River, 33 km downstream from the confluence.

Initially it was planned to run the model with prescribed levels at both ends of the Red, since level estimates tend to be more accurate than discharge. The Red River boundaries in the model do not correspond to gauging stations, therefore the levels must be obtained from another method. It was thought that these levels could be obtained from an existing 1D model of the Red River from Manitoba Water Stewardship. Unfortunately this model was not reliable, so it was decided instead, to estimate the flow into the Red River from its discharge at Emerson to which was subtracted a certain amount approximating the discharge of the Pembina River. This whole process was part of the calibration, with the aim of obtaining the proper surface elevation at the town of Pembina during the majority of the flood event.

4. The Topography

Most of the topography in the Pembina flood plain was obtained from the 2006 LiDAR survey. The survey, supplied by Agriculture and Agri-Food Canada, was very dense (1 m grid) and provided all the accuracy required to identify the elevation characteristics of the lands.

To minimize the size of data files and achieve a more manageable data system, while keeping an accurate representation of the topography, the survey points were reduced to a 25 m grid everywhere except:

- along the roads and drains where the full density (1 m) of the data was maintained to preserve the accuracy of their elevations,
- along the Pembina and Tongue Rivers where a density of 2 m was maintained over a width on the order of 140 m.
- along the Red River where a density of 5 m was maintained over a width on the order of 400 m.

This 2006 LiDAR survey did not cover the Red River basin further than one mile north of the border. A previous survey done by the province of Manitoba (1999) was used to get the Red River / Aux Marais River flood plains elevation with a grid of 5 m. A verification was done at the edge of the surveys and they both matched well (within about ±20 cm). This Canadian survey was also reduced to a 25 m grid except for Hwy 75 and the Aux Marais where the initial 5 m grid was maintained.
5. The River Bathymetry

Pembina River
Since a complete description of the river channel was required along all of its length, the bathymetry of the river main channel was obtained from the LiDAR data. This was possible since

- the survey had been done in the fall during very low flow,
- the river banks were dry and
- the survey did provide elevation information even for the wet areas.

For the wet portion of the channel, 1 m was subtracted from the thalweg of the river (assuming therefore a 1 m depth at the time of the aerial survey), and 0.5 m was subtracted at 7 m away from the thalweg on both sides.

Tongue River
The elevation as provided by the LiDAR was maintained for this river.

Red River
Similarly to the Pembina, the LiDAR data were used to describe the shape of the banks. The thalweg of the Red was lowered 2 m from the LiDAR elevation, and 1 m was subtracted at 20 m away from this thalweg on each side.

For the portion of the Red not covered by the 2006 survey, north of Emerson, we could not use the 1999 Manitoba survey since it was blank over the water. The mean slope of the river bed was therefore obtained from a previous study that used 1951 cross-sectional data. These two methods for obtaining the elevation of the bottom of the Red River led to an inaccurate representation of the slope. This concern is addressed in Section 12 of the report.

6. Culverts
Houston Engineering (ref 1) identified and surveyed the culverts along the Border road and the roads about 900 m south of the border. All of these culverts were included in the model. They also provided a separate list of culverts prepared by Pembina County. From this list only the culverts located within the Pembina river flood plain were used. A total of 25 groups of culverts were represented in the model and are listed in Table 1.
### Table 1 - List of groups of culverts represented in the model

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<th>UTM Y</th>
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<th>Number of pipes</th>
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#### 7. Bridges

In a two-dimensional model, bridges must be part of the grid since they direct the flow in certain directions through the restrictions caused by the piers. The bridge characteristics were acquired late in the preparation of the model, when the grid was already generated. Therefore the bridges are not part of the present model. Including them will affect water levels locally, particularly upstream of the piers where some backwater will occur.

#### 8. Model Calibration

The model was calibrated using the 2006 flood (this same flood was also used by UMA (ref 2) in the development of a Mike 11 model), for which a significant amount of data was available. Water levels at Pembina, Neche and Walhalla were obtained from USGS hydrometric gauges. These were provided in the NGVD29 datum and converted to the same datum as the LiDAR survey (CGVD28) by subtracting 4 cm. Levels at Emerson and Letellier were obtained from Water Survey of Canada (WSC) hydrometric gauges.
Discharge data at Walhalla and Neche were available from the USGS, and used in the calibration. The discharge on the Red River (upstream boundary) was obtained from the estimate at the Emerson gauge. It was adjusted (primarily by removing a certain percentage of the flow, equivalent to the Pembina River discharge) so that the levels at Pembina and Emerson would match the actual gauge measurement. This was required because the model does not have the whole Red River flood plains, but only the western portion. At the same time the downstream level on the Red was also adjusted to help in obtaining a good match with the Pembina hydrometric level gauge.

At the initial stage of the calibration, the lowering of the bottom of the Pembina River (1m in the centre, 0.5 m on the sides, performed over the entire length of the river) was also investigated. It is felt that more time may be spent on this aspect of the calibration, by considering individual narrow and wider sections of the river, where the bottom level adjustment should have been different. The lowering of the bottom will affect the levels and therefore model accuracy for overtopping of the banks.

During the model calibration, the various friction coefficients

- in the main channel,
- at the top of the banks (usually full of trees) and
- the flood plains,

were adjusted so that simulated levels closely matched measurements at the peak of the flood. During low flow periods, the bottom friction coefficients were kept the same as during peak flood, which explains the difference between simulated and observed levels (Figure 8). No attempt was made to adjust the coefficients during these periods since the main purpose of the model was to look at flood conditions. It is to be noted that during the calibration, it has been assumed that the flows estimated by USGS at Walhalla were correct and did not need adjustment.

Figure 8 shows the calibration levels at Walhalla, Neche, Pembina and Emerson. The model reproduces very well the gauge measurements when the flood is close to its peak. In these figures, day 0 corresponds to 1st April 2006.

Some discrepancies are to be noted:

- Walhalla levels. The gauge was not functioning during 5-6 April 2006 (day 4-5 in the simulation). The 0.5 m difference during day 6 to 10, may come from a local effect such as ice. Separate runs were performed with a level boundary (therefore forcing the model to reproduce the measured levels at Walhalla and to let it calculate the flow required). In this case the same kind of discrepancy in the flows was noted.

- Neche levels. The gauge was not functioning during 5-11 April and 24-29 April 2006. A linear interpolation was done for these missing data.
Figure 8 - Calibration water levels (meters) - 2006 flood
Figure 9 shows the discharge through a north-south section across the entire model at Neche. It shows that at their peaks,

- 80 m$^3$/s flows in the fields north of Neche, in a west-east direction
- 74 m$^3$/s flows in the fields south of Neche
- 181 m$^3$/s flows through the main channel
- 339 m$^3$/s total flow max, which is close to the estimate from USGS at 306 m$^3$/s, but the USGS estimated the peak 2 days later than the model. Also, the model flow hygrograph shows a narrower peak, with a shape similar to the peak at Walhalla.

Figure 9 - Discharge at Neche through a north-south section across the whole model – comparison with gauge estimate
8.1 Comparison with photos

Aerial photos were taken during the 2006 flood by North Dakota State Water Commission. They are shown here in four sections and compared with the corresponding flood extents as estimated by the model (fig 10 to 13). The photos were taken at dates close to the peak of the flood.

In general the model reproduces very well the break-outs and the flood extent.

It is to be noted that some simulated flood extent was larger than observed, in particular:

- around the County ditch # 42 (the line on Fig 13 just south of the Pembina River, going into the Tongue River). This drain was not specifically modelled and therefore caries the flows with a smaller depth, causing the water to spread more.

- Same remark for the Louden Coulee, South-West of Neche, Figure 11.

- The accumulation of water close to the border dike/road in the area near Hyde Park Coulee/Crossing 4 and 4A. (Top left corner of fig. 10, about 6 miles west of Neche). There may be two explanations for this. The flow over the road going north was not modelled at this model boundary; only the small capacity culvert under it was modelled. Also, the Hyde Park Coulee was not represented in the model. The excess water that normally would be carried north into the Buffalo system through this coulee, now was stored at the edge of the model.

Figure 14 shows an aerial photo of flooding around the Swietzer ridge which is well simulated by the model. Figure 15 shows a road overtopping reproduced by the model.

There are a few discrepancies between the model results and what actually happened in 2006. More time should be spent to try to explain them. For instance the model does not reproduce the overtopping of the East West township road just 1 mile East of Neche (the orange circle in Fig 11), although the simulated flood water came 12 cm below the road elevation, and therefore could not overtop it. Note that the flooding seen on the south side of the road comes from the culvert.
Figure 10 - Comparison of model simulated water extent versus aerial photos 1
Figure 11 - Comparison of model simulated water extent versus aerial photos 2
Figure 12 - Comparison of model simulated water extent versus aerial photos 3
Figure 13 - Comparison of model simulated water extent versus aerial photos 4
Swietzer Ridge with triangular flood storage at Aux Marais river inlet (top left corner of photo) (compare with figure 13)

Overflow 1 mile east of Neche over East-West county road 1/2 mile south of border (see black circle figure 11)

Figure 14 - Swietzer ridge

Figure 15 - County road flooding
9. Model Verification

An initial verification was started with the 1997 flood, but it soon appeared that this was not practical since gauges at Neche and Walhalla were not functioning during the flood, and the topography of the river banks was quite different from what it is today since there were dykes along the river that were removed in 2000-2003, therefore not shown in the 2006 LiDAR.

The 2005 summer flood was chosen instead for model verification, with the following boundary conditions:

- Input flow hygrograph at Walhalla as estimated by USGS gauge
- Input flow hygrograph in the upstream boundary on the Red River, derived from the WSC gauge at Emerson
- Water level in the downstream boundary on the Red River, derived from the USGS gauge at Pembina

Overflow due to ice jam, 7 April. The model shows overtopping at same location 4 days later due to volume of water only. (See figure 10)

Figure 16 - County road flooding
Figure 17 - Verification water levels (meters) - 2005 summer flood
Figure 17 shows the verification levels at Walhalla, Neche, Pembina and Emerson. The model reproduces very well the gauge measurements at Neche and Walhalla, when the flood is close to its peak. The match is not as good for the Red River water levels. Because of its smaller depth, the less accurate bathymetry of the Red has a more pronounced effect on the simulated levels, which show a larger difference with the gauge measurements. The need for the verification of the Red River bathymetry used in the model is clear.

On these figures, day 0 corresponds to 1st June 2005.

Figure 18 shows the discharges at Walhalla and at Neche during the 2005 summer flood.

Figure 18 - Discharge at Neche through a north-south section across the whole model
10. **Flood Scenarios simulations**

We will now look at four scenarios in an attempt to change the propagation of the flood, and understand better where the water is going and why. Ultimately, this approach will lead to a better understanding of the impact of topography and human intervention on the propagation of flooding on the landscape. It is also possible that with this enhanced knowledge, scenarios could be considered that could lead to reductions in flood damages. A two dimensional model is perfectly suited for this kind of investigation since no assumption is made at the onset of the model, on the direction of the flow.

These scenarios were simulated with a model with limited geographical extent, and also a limited number of roads and culverts. Because of this, the results of the scenarios simulations must be considered with caution as not providing the exact representation of what would happen. Model improvements are discussed in Sections 11 and 12.

Nevertheless, we feel strongly that the testing of these scenarios was a very useful exercise so that the stake holders can get a sense for what would be happening.

10.1 **Slope of flood plains**

Before we present the scenarios it is important to notice the shape of the land. Figure 19 shows three cross sections, about 5 km long, which indicate that the flood plains are lower than the top of the banks of the river. Therefore any water overtopping the banks will want to move away from the river either in a northern direction or in a southern direction, as well as an eastern direction.
Figure 19 - LiDAR representation of the lower flood plains, with three across-fields sections; Sections are from south to north; Land elevation in meters.
10.2 Existing situation

Figure 20 shows the flood extent during the 2006 flood in its existing configuration. This same flood will be used for testing the four scenarios.

In this configuration the flow distribution on each side of the river, through a north-south section at Neche, is:

- max flow north of Pembina River: 80 m³/s;
- max flow south of Pembina River: 74 m³/s;
- max flow through Pembina River main channel: 181 m³/s;
- total max flow: 339 m³/s
- max overflow into Aux Marais watershed 10 m³/s (through 4 culverts)

(Note that the maximum of the flow in each area does not necessarily occur at the same time)

10.3 Scenario 1: Remove all roads

In this case we assume all roads have been “flattened”, or a very large number of large culverts allow free passage of all water (Figure 21). The flow distribution on each side of the river at Neche is now:

- max flow north of Pembina river: 123 m³/s
- max flow in Aux Marais river: 130 m³/s
- max flow south of Pembina river: 61 m³/s
- flow through Pembina main channel: 157 m³/s
- total max flow: 338 m³/s

The water tends to accumulate at the edges of the model away from the Pembina river main stem. It follows the natural slope of the plains. In the north-south cross-section at Neche the maximum flow in the south remains essentially unchanged while there is more water in the north.

If the model was extended to the North, it is expected that the flood would flow into the drainage systems of the Aux Marais River and the Buffalo creek.

To the south, the flood would continue until guided by the Rosebud Coulee and Louden coulee toward the Tongue River basin.

This simulation shows that the present model needs to be extended further in both northern and southern directions.
10.4 Scenario 2: Remove all North–South roads

In this case we assume that only the North-South roads have been “flattened” or a very large number of culverts allow free passage of all water from west to east. The maximum flow distribution on each side of the river in a vertical cross-section at Neche is now:

- max flow north of Pembina River: 108 m$^3$/s
- max flow south of Pembina River: 72 m$^3$/s
- flow through Pembina main channel: 155 m$^3$/s
- total max flow 336 m$^3$/s
- max overflow into Aux Marais watershed 10 m$^3$/s

There is not much difference with the existing configuration on the south side of Pembina River, but more water flows north. The Swietzer Ridge is overtopped and major flood occurs east of the ridge (Fig. 22).

The comparison between Figure 21 and 22 shows that County Road 55 plays an important role in preventing the water from moving south.

10.5 Scenario 3: Divert 100 m$^3$/s away from the Pembina main stem

In this scenario we have assumed that two separate channels would divert part of the flow from the Pembina main stem into the Buffalo and the Aux Marais River systems. The actual channels were not modelled, but their effect was modelled: the removal of 50 m$^3$/s in each location A and B and reinjection of 50 m$^3$/s in the Aux Marais (Figure 23). These locations were chosen since they were closest to the border and they were upstream of Neche - therefore lowering levels around this town.

- max flow north of Pembina River: 37 m$^3$/s; (was 80 in existing conditions)
- max flow south of Pembina River: 55 m$^3$/s; (was 74 in existing conditions)
- flow through Pembina River main channel: 141 m$^3$/s; (was 181 in existing conditions)
- total max flow 233 m$^3$/s; (was 339 in existing conditions)
- max overflow into Aux Marais watershed 10 + diversion 50 m$^3$/s; (was 10 in existing conditions)

The maximum discharge at Neche is now reduced by close to 100 m$^3$/s, or about 30% of the maximum flow, which translates into a reduction of the flow over Swietzer ridge, and a reduction of the flood east of the ridge. The model shows more flooding in the Aux Marais system. One could expect also more flooding in the Buffalo system if it was part of the model.
10.6 Scenario 4: Allow water to flow into Aux-Marais River system

In this case the only modification to the landscape is the removal of the road at the upstream end of the Aux Marais River basin. This has the effect of diverting the waters towards the North, while lowering the waters along the border. There is no water flowing over the Swietzer ridge (black circle in Figure 24).

The maximum flow into the Aux Marais watershed is 118 m³/s. The total flow across the model at Neche remains unchanged from the existing situation.

In the Figure, it is to be noted that the flood extent around the Aux Marais River is not accurate since the river main channel has not been accurately represented in the model. But the discharge through the basin is realistic since it is the outlet for the flood waters propagating over all of the upstream landscape infrastructures.

This scenario shows that the portion of the border road just upstream of the Swietzer ridge plays an important role in the extent of the flood.
17 April 2006
Existing situation

Figure 20 - Existing configuration - Flood extent and discharge
Flow at Neche - 2006 - Scenario 1
No roads

17 April 2006
All roads "removed"

Figure 21 - Scenario 1 - Removal of all roads
Flow at Neche 2006 - Scenario 2
Remove all North South roads

Figure 22 - Scenario 2 - Removal of all north-south roads
Flow at Neche 2006 - Scenario 3

17 April 2006
100 m3/s diverted to Buffalo and Aux Marais
(Diversion not shown)

Figure 23 - Scenario 3 - Diversion of flows from Pembina River
Flow at Neche 2006 - Scenario 4
Allow natural flow into Aux Marais

17 April 2006
remove road
north end of
Aux Marais watershed

Figure 24 - Scenario 4 - Removal of Aux Marais River restriction at border
11. Conclusion and recommendations

The floods from the Pembina River can be simulated well with the Telemac two-dimensional model, once all the flow guiding structures such as roads and culverts are properly represented. A comparison between aerial photos taken during the 2006 flood and the overall simulated flood extent is very good.

The model 2006 calibration has been presented to ND State Water Commission and to a flood expert, formally from Manitoba Water Stewardship. Both indicated that the results of the model appeared to fairly accurately represent what occurred during the 2006 flood. They noted many of the local places where the model gave an accurate representation of the 2006 flood, and pointed also to some of the areas where the model was not accurate and needed improvement.

The model has been well calibrated for events close to the peak of the flood, in terms of water levels and flows along the Pembina River. As far as the flood extent is concerned, the model does not reproduce exactly all of the details of what happened in 2006. The two main reasons are the restricted coverage of the model and not all the roads culverts and bridges were represented. One has to remember that this is only the initial development of a model of a very complex physical problem. Uncertainties such as the discharge estimates at Walhalla, or the LiDAR “bare ground” elevations of the banks along the Pembina River, or the numerical grid which may have missed a local levee, will be critical in the simulation results showing or not showing a local overflow.

Only four scenarios were simulated. These scenarios were simulated with a model with limited geographical extent, and also a limited number of roads and culverts. Because of this, the results of the scenarios simulations must be considered with much caution, particularly the visual aspect of the flood extent seen in the animations. This is a new tool brought by the usage of a 2D model which is susceptible to much increased scrutiny over simple graphs from a 1D model.

This preliminary scenarios investigation was to have a feel for what the flood waters would be doing if some of the infrastructures were modified. The four scenarios were rather drastic, in the sense that changes were global (“all” roads were modified), where a better solution might be to modify only certain roads or culverts locally. To do this, more scenarios must be discussed among the stakeholders and simulated with an enhanced model.

The initial extent of the numerical grid was chosen mainly from the aerial photos of the 2006 flood event. It is obvious that this grid needs to be extended further to the north, west and south, if natural conditions without manmade structures such as roads, are to be simulated. This would allow the modelling of the natural flow into the Buffalo system, the Hyde Park coulee and the Louden coulee respectively. Extension to the east would be required in the case where the Red River hydrodynamics would be strongly affected by the modification to the infrastructure close to the confluence of the Red and Pembina Rivers.

It is to be noted that the geographical extension of this model will provide a different model of the Pembina River and its flood plains, which might therefore give different simulation results.

12. Future work

In order to have a better numerical representation of the Pembina River floods, some new aspects of the project must be addressed. They cover the modelling effort that should improve the simulation results and include the acquisition of more data.

- Extend the model north into Buffalo drainage system. This will require the acquisition of additional good topographical data, north of the current model coverage area. This will allow
the proper simulation of flood propagation in the area, in the case of the scenario where the border road/dyke is removed.

- Extend the model west and south into the Hyde Park coulee and the Louden coulee respectively. LiDAR coverage from this area already exists from a 2008 survey.

- The existing model was not designed to simulate the complete hydrodynamics of the Red River. Depending on which scenarios would be simulated on the Pembina River, in particular if a floodway is to discharge excess water into the Red River around Emerson or Pembina, it will be required to extend the model east, to include some of the Red River flood plains, and therefore have a more accurate estimate of the effects of the Red River on the Pembina River and vice versa. Additional LiDAR data already exists for this area of the model extension.

- The bathymetry used for the Red River was derived from old simulation studies on the Canadian side and from the 2006 LiDAR survey on the US side. These two sets of data did not match, causing difficulties during the verification of the model at low flow. It is recommended that more reliable Red River cross sections be obtained from Manitoba Water stewardship (MWS) and from ND State Water Commission over the extent of the Telemac model.

- With this new Red River main channel bathymetry, if the same kind of hydrodynamic modelling problem persists, a new bathymetric survey should be undertaken along the Red River, across the border, over a distance that corresponds to the coverage of the present model.

- With the extended model more scenarios representing different layouts of roads and dykes should be undertaken to reveal the impacts of the existing or potential infrastructure. These scenarios could be characterised from discussions with the stake holders.

- The culvert inventory is quite extensive but lacks some data such as bridges over the coulees and drains. These data should be acquired.

13. Acknowledgment
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14. Reference
1 - Pembina River Study, Structure Crossing Inventory, for International Joint Commission; Houston Engineering Inc. Maple Grove, MN, June 2006

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