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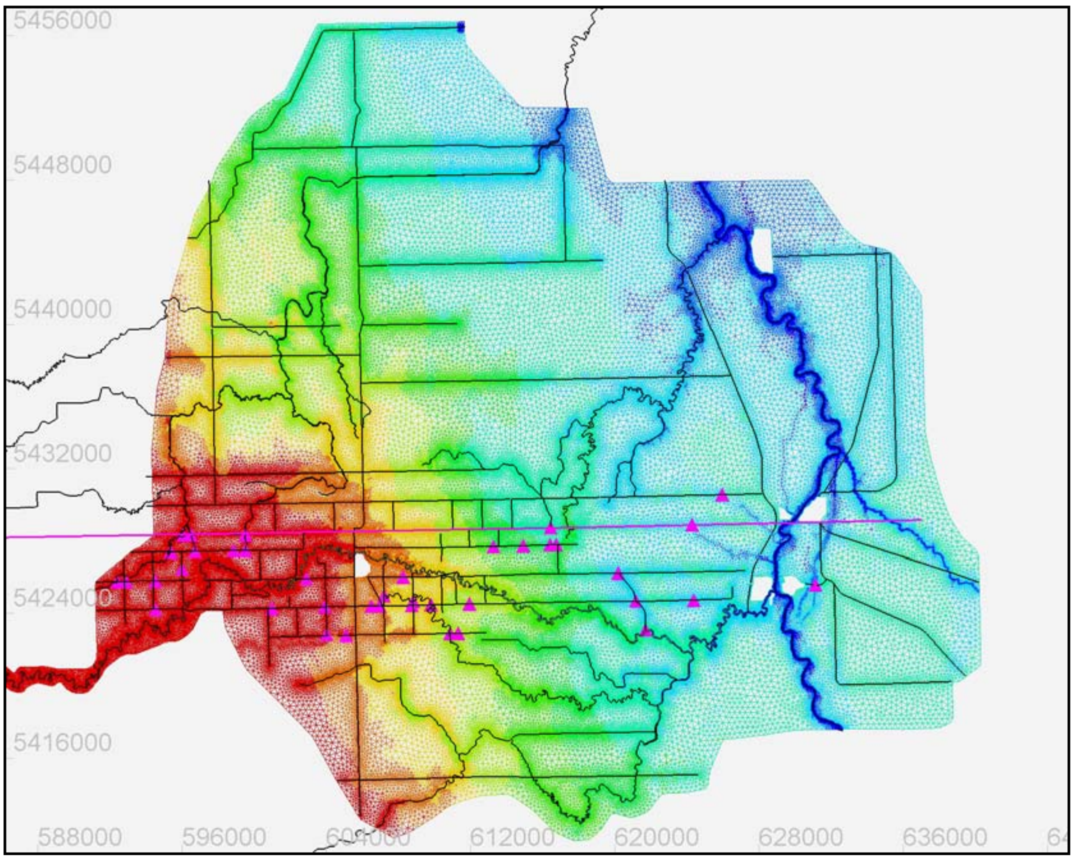
Simulation of Flood Scenarios on the Lower Pembina River Flood Plains with the 2D Hydrodynamic Model



Controlled Technical Report CHC-CTR-106

June 2010

National Research Council Canada
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Table of Content

List of Tables

List of Figures

Simulation of Flood Scenarios on the Lower Pembina River Flood Plains with the 2D Hydrodynamic Model

1. Introduction

The Pembina River Basin Advisory Board, the Pembina County Water Resource District, the Red River Basin Commission (RRBC) and the International Red River Board have for several years examined ways to minimize flood damages from overflows in the lower Pembina River Basin downstream of Walhalla.

To this purpose, an initial two-dimensional numerical model was prepared in an attempt to simulate the flood propagation of the Pembina River more accurately than the existing one-dimensional models. The two-dimensional model was developed as outlined in the July, 2009, Canadian Hydraulics Centre's report entitled "Preparation of a two-dimensional Hydrodynamic Model of the Lower Pembina River Flood Plains" [Reference 1].

This 2009 2D model, utilizing the Telemac-2D software, showed that during a flood, road overtopping and water storage within the road network could be simulated well, because of its ability to represent the two-dimensional aspects of the topography and of the water passages. Although not all regions were perfectly modelled, mainly because of its limited extent both North and South, comparison with aerial photos taken during the 2006 flood showed very good agreement.

The International Joint Commission decided to retain the model and improve it by extending it geographically and by including more infrastructures such as roads and culverts. With this new model, the simulation of floods with various configurations of roads and drains, including the simulation in "natural conditions" without raised roads, will be possible.

This report first describes the modifications to the model, its calibration and its verification. Then it presents several scenarios that were simulated, representing changes in the infrastructure, including road removal, and the associated consequences in terms of the flooding extent of the Pembina River.

2. The Telemac-2D model – Blue Kenue

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 element techniques, and is used by more than 200 organisations around the world.

As of January 2nd, 2010, Telemac 2D software is available as freeware on the Internet.

The pre- and post-processor for Telemac is Blue Kenue, a software developed by the Canadian Hydraulics Centre.

3. Preparation of the new model

The reader is encouraged to read first Reference 1 that describes in more detail the original model.

The new model is a two dimensional model which aims at representing the landscape and infrastructure over a very large area. Obviously a choice had to be made as to the amount of detail that should be incorporated in the model. Every extra kilometre of road or of water channel meant many additional triangles in the mesh, many additional high density Lidar information, additional time for the definition of these infrastructures and additional computing time, to finally end-up with a heavier model more difficult to handle. A trade-off had to be made between the detail of the results and the main purpose of the model. If a road was thought to have only a minor effect on the results, in the region of concern, it was not included.

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 precise 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 Rivers and flood plains

The Western portion of the model from Walhalla to the Leroy Bridge was kept as before. It described the river main channel with a fine grid, and a band of about 850 m wide which included all the meanders. (See Figure 2)

The numerical description of the Pembina River main channel remained unchanged with a grid size of about 7 m x 20 m. With this grid definition, the main channel is described by a series of cross sections having 7 points, every 20 m along the stream, while the top of the banks are represented by a 20 m grid, giving enough definition to most of the landscape characteristics. An example of the river main channel grid is shown in Fig. 1.

Figure 1 - Grid detail over a Google Earth aerial photo with top of bank lines and Thalweg

The definitions of the Red River (coarser triangles on the order of 50 m) and the Tongue River (grid size of 40 m) remained the same as the original model.

The numerical description of the Aux Marais River was increased from 100 m to 50 m so that the grid represented more precisely the shape of this small river and the model provided a better visualisation of the flow through it.

In the new model special attention was given to the north break-outs, 8 km west of Neche. The grid in this location was refined so as to follow more closely the old meanders and their banks on the north side. This has decreased the amount of flow going north and being accumulated along the border of the old model.

The original model was limited in its geographical extent, causing the water to accumulate at the edges on the model in certain conditions, without being able to drain away into a river or a coulee.

It was extended in two phases. First, because the LiDAR data in the Buffalo region was not readily available, the model was extended towards the south, west and the east, to be able to simulate all scenarios not involving the road along the border and the Manitoba region. In a second phase, the model was extended in the Buffalo drainage area once the Lidar survey had been completed and its data processed.

Model extension south, west and east

In a first phase the model was extended in three directions (Fig. 2)

- towards the west to include a short portion of Hyde Park Coulee,

- towards the south to include the Rosebud Coulee, the Louden Coulee and a large portion of the Tongue River with its bypass and
- towards the east to include the Red River flood plains and the overflows running east of the towns of Pembina and Emerson.

The towns of Neche, Pembina, Emerson and Roseau were simulated with their ring dykes. They are represented in the model as islands, or holes in the computational domain, as shown on Fig. 2. This figure shows in black all the roads, coulees and drains which were represented in the model.

The Hyde Park coulee, Louden coulee, Rosebud coulee and County drain 42 were added to the new model and described with a grid size of 30 m. It is to be noted that this description of the channel does not provide the true conveyance of the coulees, since the channels are assumed to be triangular in shape. This was required because these rivers are very small and would have needed a very large number of small elements to describe them accurately. If needed, a smaller model covering only the local region with a refined grid describing its channel can be prepared in order to get more accurate inundation maps. It is to be noted that the grid size for the coulees will affect only slightly the amount of flow going through them, but it will affect more its spread on each side of their channel and therefore their visual aspect in the inundations figures.

The new model, in its version without the Buffalo northern extension, has in excess of 151 000 nodes and close to 301 000 elements. (The original model had about 110 000 nodes and 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 in which the 2006 LiDAR survey data were provided.

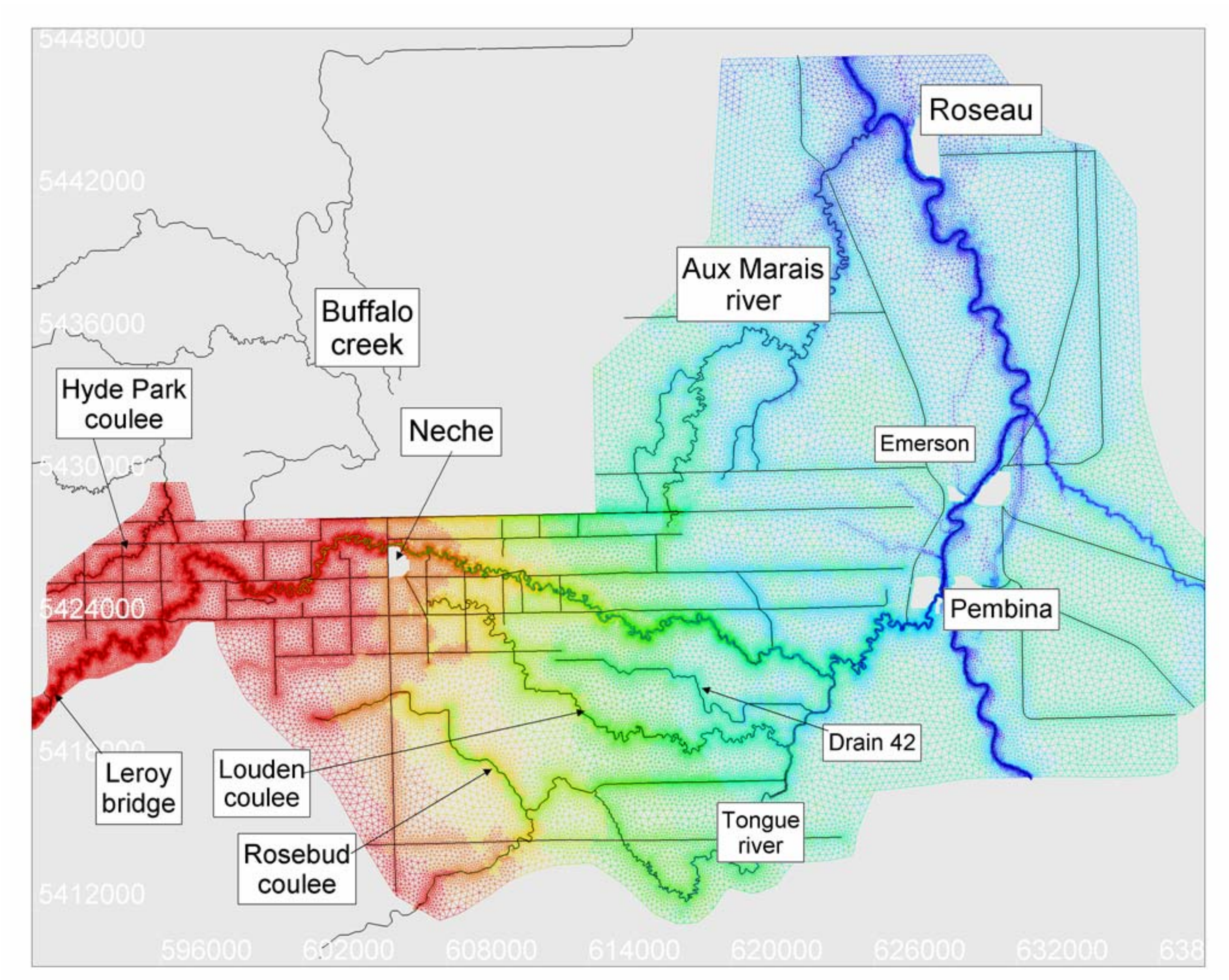


Figure 2 - General layout of extended model without Buffalo creek

Model with the Buffalo creek extension

In order to simulate flood scenarios which allowed waters to flow north to Buffalo Creek, it was necessary to prepare a separate numerical grid which included most of the Buffalo creek drainage system with also a portion of the Hespeler and Rosenheim drains. This extension was possible since LiDAR surveys were conducted over the region in 2007 and in 2009. Figure 3 shows the extent of the full model with, in grey, the original model extent from Ref. 1. It also shows with the magenta triangles the simulated culverts.

The Buffalo creek was simulated with a grid size of 35 m.

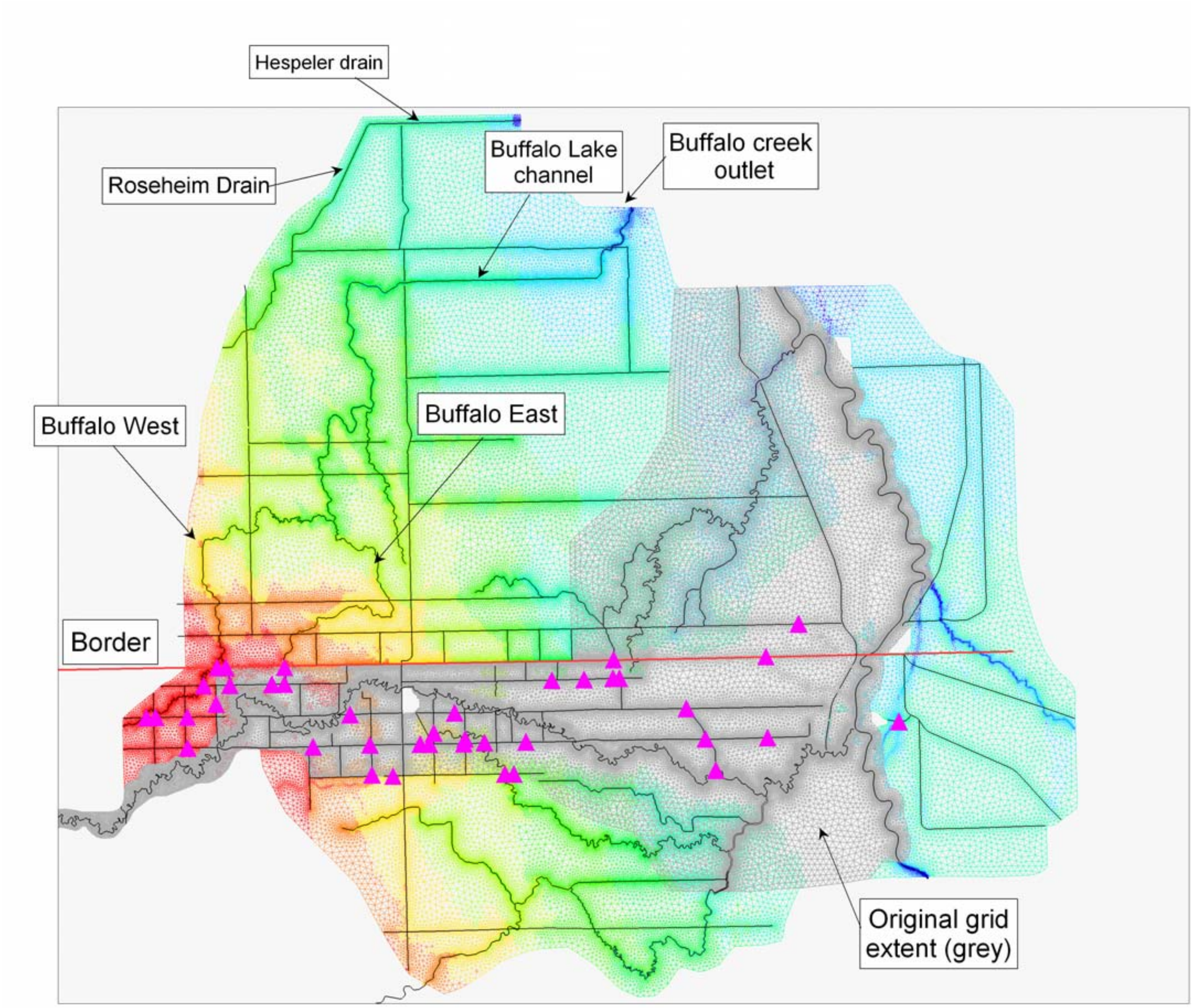


Figure 3 - General layout of fully extended model with Buffalo creek

3.1.2 Roads

Most of the roads around Neche were added to the new model. On the east side of Emerson and Pembina, the major roads and railway track were also included, as shown in Fig. 3. Similarly to the original model, the roads were identified from the LiDAR survey data so that their triangular numerical representation perfectly matched the topography in both location and elevation.

The Buffalo extension model included the major Manitoba provincial roads:

- North-South roads: PR 30, 246, 336, 332, and a number of local roads just north of the border

- East-West roads: PR 201, 14, 243, 421, 524

3.1.3 Drains

Four drains were added to the original model (Fig. 2):

- County drain 42, draining the south portion of the Pembina River into the Tongue River,
- Complete Louden coulee
- Rosebud coulee
- Hyde Park coulee joining the Buffalo West branch

3.2 Model tributaries

Only one tributary of the Pembina River was included, the Tongue River with its bypass, with flows obtained from the USGS gauge at Akra. The split between its natural channel and the Tongue bypass was not modelled in detail.

It is to be noted that 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, 10.7 km upstream from the confluence with the Pembina River and
- prescribed elevations on the Red River, 33 km downstream from the confluence.

The flow in the upstream boundary on the Red River was estimated from its discharge at Emerson to which was subtracted a certain amount approximating the discharge of the Pembina River.

4. The Topography

Several LiDAR surveys were used for defining the land topography. Their coverage is represented in Fig. 4.

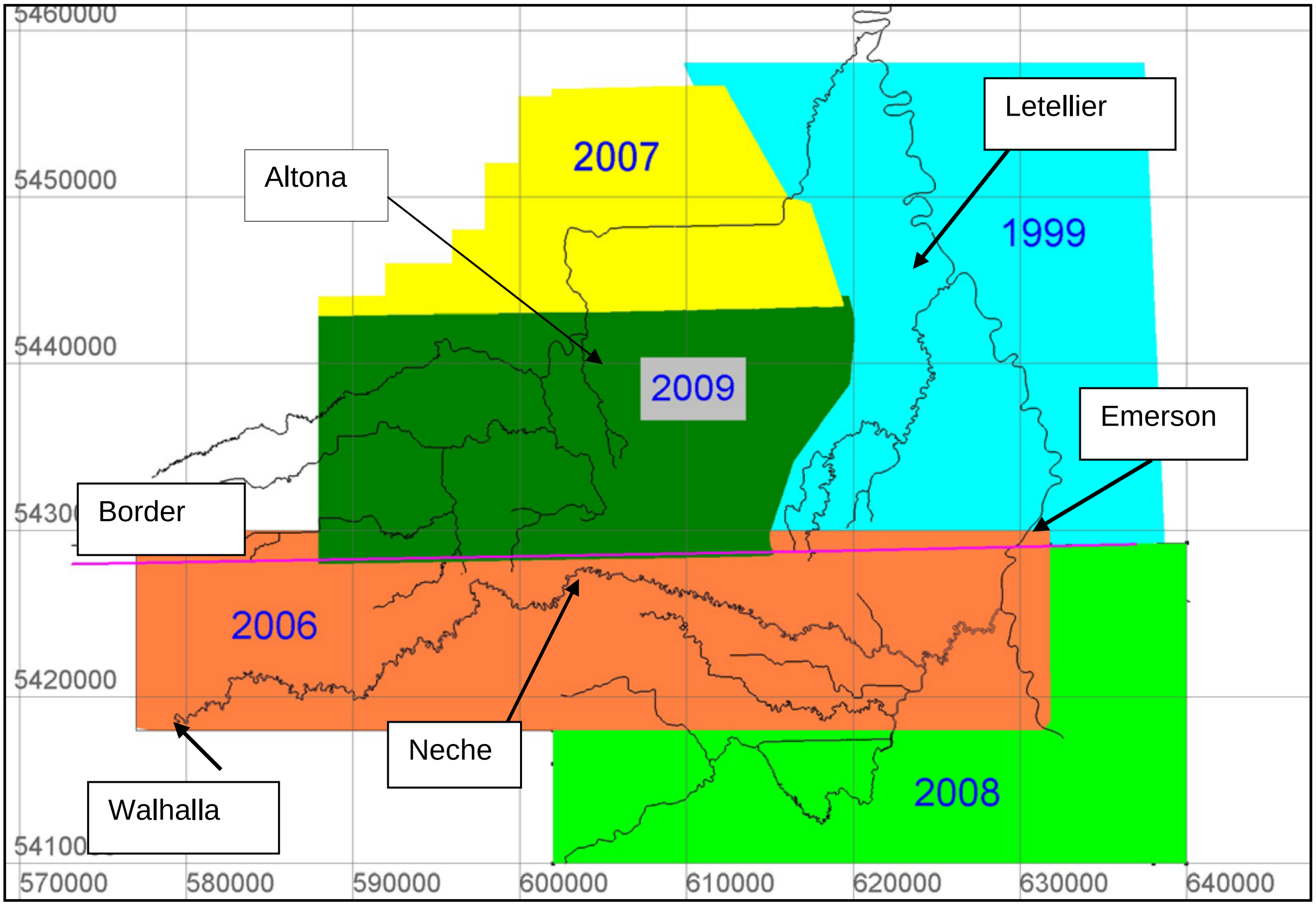


Figure 4 - LiDAR coverage

2006 LiDAR survey – Pembina River

The major portion of the Pembina flood plain was obtained from the 2006 LiDAR survey. This survey, supplied by Agriculture and Agri-Food Canada, was very dense (1 m resolution) and provided all the accuracy required to identify the elevation characteristics of important topographic features. It had been processed so that in most cases, bridges over a channel were "removed" and the elevation of the river under the bridge was shown in the data. The elevations of the wet channels were also included, and were used to obtain elevations of the bottom of the creeks and coulees. An example of this process is indicated in Fig. 5 where a North–South road (in red) is interrupted when it crosses the Louden coulee over a bridge.

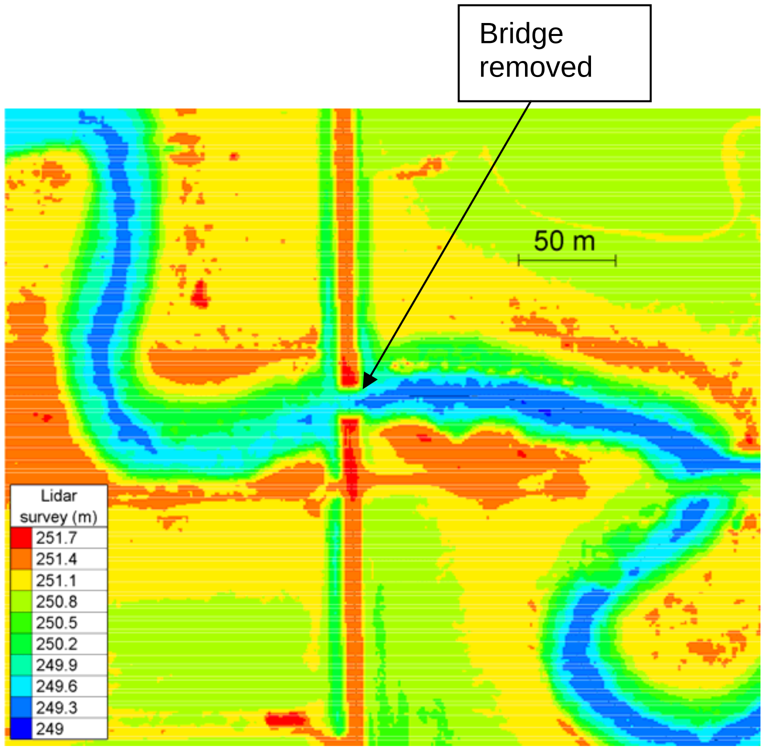


Figure 5 - Sample of the 2006 LiDAR survey at a road–river crossing

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 resolution everywhere except:

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

1999 LiDAR survey – Red River - Aux Marais River

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 (1999 and 2006) 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.

It is to be noted that since the Aux Marais River was described by a 5 m LiDAR grid, the elevation of the bottom of the river channel will not be as accurate as those described by the 1m grid. This may explain why in the following figures in this report, the Aux Marais River shows more flooding than its neighbour, Buffalo Creek.

2008 LiDAR survey – Tongue River

This more recent survey from USGS was used to find the topography of the region south of the 2006 survey, mainly for the definition of the Tongue River and its bypass. In this survey—a slightly coarser set of measurements with an irregular spacing of approximately 1.8 m —the wet portions of coulees and rivers were left blank, and when a road crossed a channel it was also left blank. An example can be found on Fig. 6, showing the crossing of the road over Tongue River at Bathgate. In this case, the river bottom elevation was estimated by lowering the closest available elevation on the banks by 80 cm.

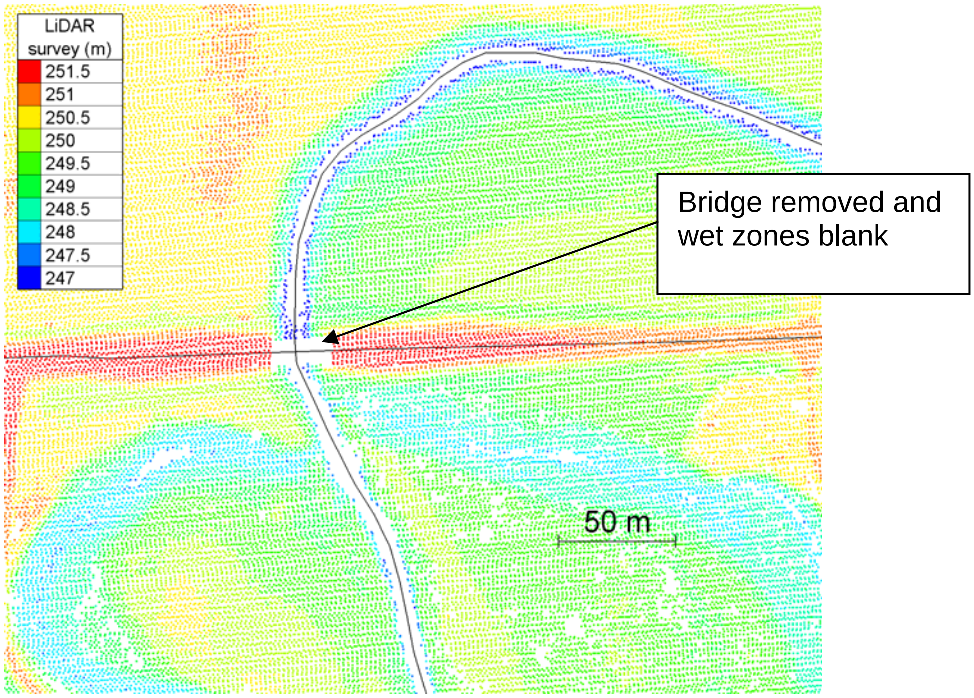


Figure 6 - Sample of the 2008 LiDAR survey at a road–river crossing

2007 LiDAR survey – Hespeler and Rosenheim Drains

This survey provided by MWS has a fine density of 1 m point spacing and was processed to “remove” the bridges, similarly to the 2008 USGS survey. The survey covers the area of Hespeler and Rosenheim drains.

2009 LiDAR survey – Buffalo Creek

This most recent survey was flown on May 23, 2009. The matching with the neighbouring surveys was found very good, with differences in elevation of the order of ±10 cm in most places. Similarly to the 2006 survey, it was processed to remove the bridges over creeks and to provide the creek elevation.

5. The bathymetry of rivers

Pembina River

The same bathymetry as in the original 2008 model was kept, lowering the thalweg of the river (as obtained from the 2006 LiDAR aerial survey) by 1 m (therefore assuming a 1 m depth at the time of the survey) and lowering the elevation by 0.5 m at 7 m away from the thalweg on both sides.

Tongue River

The new model uses the same bathymetry as in the original model. When the LiDAR data was blank, an interpolation was required, followed by a lowering of 80 cm at the thalweg.

Red River

In the fall of 2009, PFRA commissioned a bathymetric survey of the bottom of the Red River to verify the elevations which had been used since the 1950's. Soundings were taken along 5 longitudinal lines, spanning from the Letellier bridge to 10.5 km south of the Pembina river junction. One bathymetric line was taken close to the centre of the river, 2 lines were taken about 20 m away from the centre and 2 more lines were taken close to shore. These latest soundings were used in the final calibration of the model.

Figure 7 shows the previous bathymetries which were used in earlier runs, in comparison with the recent survey. South of the border, data from the NDSWC HECRAS model had been used, while in Manitoba data from the MWS Mike 11 had been used after correction, (the green spikes appeared from the interpolation of the Mike 11 mesh onto the Telemac mesh having a different density). In general the bathymetry defined from the Mike 11 and the HECRAS models is close to the new soundings within 1 m, except in a few places where differences of up to 2 m can be found. These differences will affect the bottom friction coefficients, particularly at low levels.

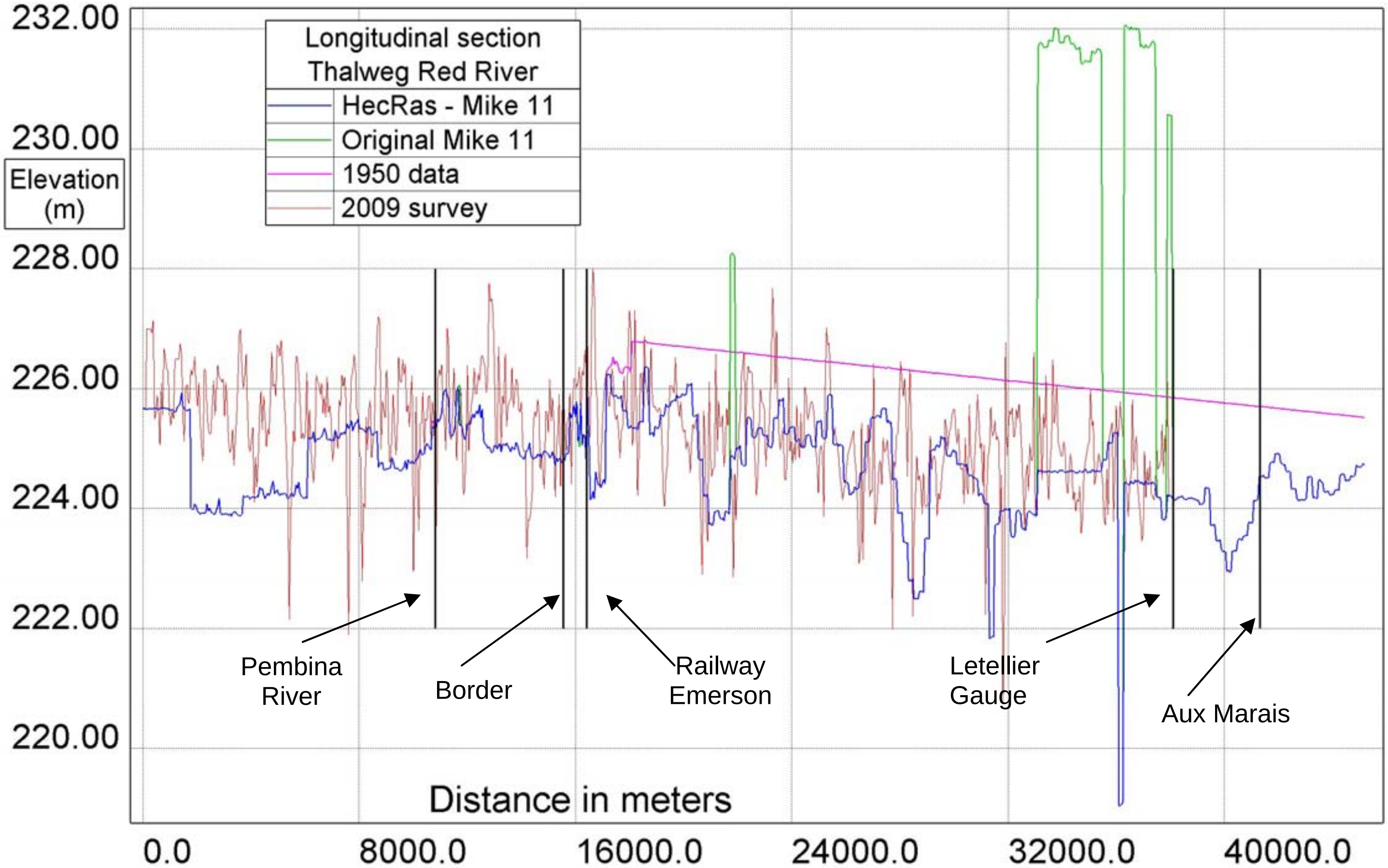


Figure 7 - Comparative longitudinal sections along the Red River
(50 m resolution)

6. Culverts

Houston Engineering [ref. 4] 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, the pipes with size exceeding 2 feet were included. A total of 36 groups of culverts were represented in the model and are listed in Table 1. They are shown on Figure 3.

It is to be noted that in these conditions, the model does not have culvert under Highway 18. The only crossing was a bridge for Rosebud Coulee under Highway 18, 5 km (3.1 miles) south of Neche.

			CULVERTS				
UTM X	UTM Y	Model Ident	Description	Diameter (m)	Number of pipes	length (m)	Culvert Number
596517.9	5428325.1	1	BD_ROAD_DIKE_NO_4E	0.762	1	10.363	1
596152.7	5428310.9	3	BD_ROAD_DIKE_NO_4W	0.6096	1	12.192	2
599530.4	5428370.8	5	BD_ROAD_DIKE_NO_5	0.762	1	7.62	3
616456.1	5428738.4	7	BD_ROAD_DIKE_NO_6	1.083	4	19.126	4
596517.3	5427414.9	9	TWP_ROAD_NO_1	0.9144	2	18.288	5
598899.6	5427393.1	11	TWP_ROAD_NO_4	0.4572	1	15.85	6
599665.8	5427456.4	13	TWP_ROAD_NO_5	0.4572	1	12.802	7
613298.8	5427670.5	15	TWP_ROAD_NO_8	0.772	3	10.668	8
614980.5	5427715.8	17	TWP_ROAD_NO_9	1.5	4	7.315	9
616389.9	5427747.2	19	TWP_ROAD_NO_11	0.6096	1	12.497	10
616713.1	5427751.3	21	TWP_ROAD_NO_15	0.6096	1	11.278	11
621714.4	5423086.7	23	drain_under_HY55_back_to_Pembi_R	1.22	4	10	12
595396.3	5427382.3	25	Hyde_Park_Coulee_Large_box	1	5	5	13
607095.1	5425013.2	27	Louden_coule_across_road	1	3	10	14
608642.5	5424682.5	29	Louden_coule_across_road	1	3	10	15
609810.5	5424506.2	31	Louden_coule_across_road	1	2	10	16
626028.7	5430548.0	33	across_RD_drain_close_to_RED	1	4	10	17
603934.5	5424471.0	35	from_Pembina_County__2	1.07	1	11	18
608276.1	5426079.2	37	from_Pembina_County__3	1.22	2	11	19
602937.5	5425904.1	39	from_Pembina_County__5	1.22	1	11	20
608761.4	5424508.9	41	from_Pembina_County_18	0.91	1	11	21
601006.5	5424364.2	43	from_Pembina_County_94	0.91	1	11	22
606506.3	5424478.5	45	from_Pembina_County_98	0.76	4	11	23
606963.7	5424478.5	47	from_Pembina_County102	1.35	2	11	24
611943.3	5424580.0	49	from_Pembina_County104	1.07	1	11	25
620124.6	5426387.0	51	from_Pembina_County_47	1.07	3	10	26
624415.8	5424660.9	53	from_Pembina_County105	1.22	2	10	27
592911.3	5425744.6	55	from_Pembina_County_68	1.22	1	10	28
594541.6	5424197.4	57	from_Pembina_County_50	0.91	2	10	29
595930.6	5426451.2	59	from_Pembina_County_66	0.61	2	10	30
603998.9	5422849.3	61	from_Pembina_County__1	0.91	1	10	31
594525.9	5425743.8	63	from_Pembina_County__7	0.7	4	10	32
611325.2	5422949.9	65	from_Pembina_County_85	0.91	2	10	33
605026.0	5422829.3	67	my_own_to_go_under_road	1	1	10	34
631117.0	5425493.1	69	culvert_under_171_east_Pembina	5.6	1	25	35
624331.4	5428800.8	71	across_RD_drain_close_to_RED	1	4	10	36

Table 1 - List of groups of culverts represented in the model

7. Bridges

Initially, the thin shape of the bridge piers was represented in the numerical grid so that the model would calculate the hydrodynamics of the flow around the piers automatically. This had required very small elements which made the model run with a very small time step, not compatible with long durations of runs (30 days for a typical flood).

It was therefore decided, instead, to maintain the original channel grid description and represent the losses due to the bridge piers with an increased bottom friction. A total of 15 bridges in the Pembina River and 4 on the Red River were included with this method.

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.

The discharge on the Red River (upstream boundary) was obtained from the estimate at the Emerson gauge, from which 90% of the Pembina River flow at Walhalla, (shifted by 4 days) was subtracted, accounting for the Pembina flow which does not flow into the Red but rather flows north.

During the model calibration, the various friction coefficients including:

- 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 low-flow periods since the main purpose of the model was to look at flood conditions. During the calibration, it has been assumed that the flows estimated by USGS at Walhalla and by WSC at Emerson were correct and did not need adjustment.

It is to be noted that the calibration was carried out with levels. A more complete calibration could have been performed with discharges as well, trying to match the distribution of flow among the various channels. In particular we did not adjust the discharge in the Pembina River main channel since we did not have the necessary information.

Table 2 shows the friction coefficients used. These coefficients are close to those expected from similar rivers. It is to be noted that these coefficients are 2D, (they are applied with a velocity vector with two components) and they include the fact that the continuous fluid has been discretized. Therefore they may not be directly comparable to coefficients found in 1D models.

Region	Strickler friction coefficient
Red River, Letellier to Emerson	26
Red River, Emerson to upstream	31
Red River, top of banks	18
Pembina River, Walhalla to CR 55	39
Pembina River, CR 55 to Neche	42
Pembina River, Neche to Pembina	28
Pembina River, top of banks	15
Flood plain	20
Coulees and drains	30

Table 2 - Bottom friction coefficients (Strickler formulation)

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

During the April 2006 flood, hourly measurements were taken at Neche by USGS. They were compared with the daily average numbers used in the calibration and found not to provide additional information which would help in calibration effort.

Some discrepancies are to be noted:

- **Walhalla levels.** The Walhalla 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, 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 Neche gauge was not functioning during 5-11 April and 24-29 April 2006. A linear interpolation was conducted to fill in these missing data.

Figure 9 shows the calibration levels at Letellier, and at Crossing 6 (see location on Figure 14) which had been measured by Manitoba Water Stewardship for a few days during the 2006 flood. Note that at Border Crossing 6, the top of the culverts are located at about 241.3 m, which is close to 1 m lower than the downstream levels.

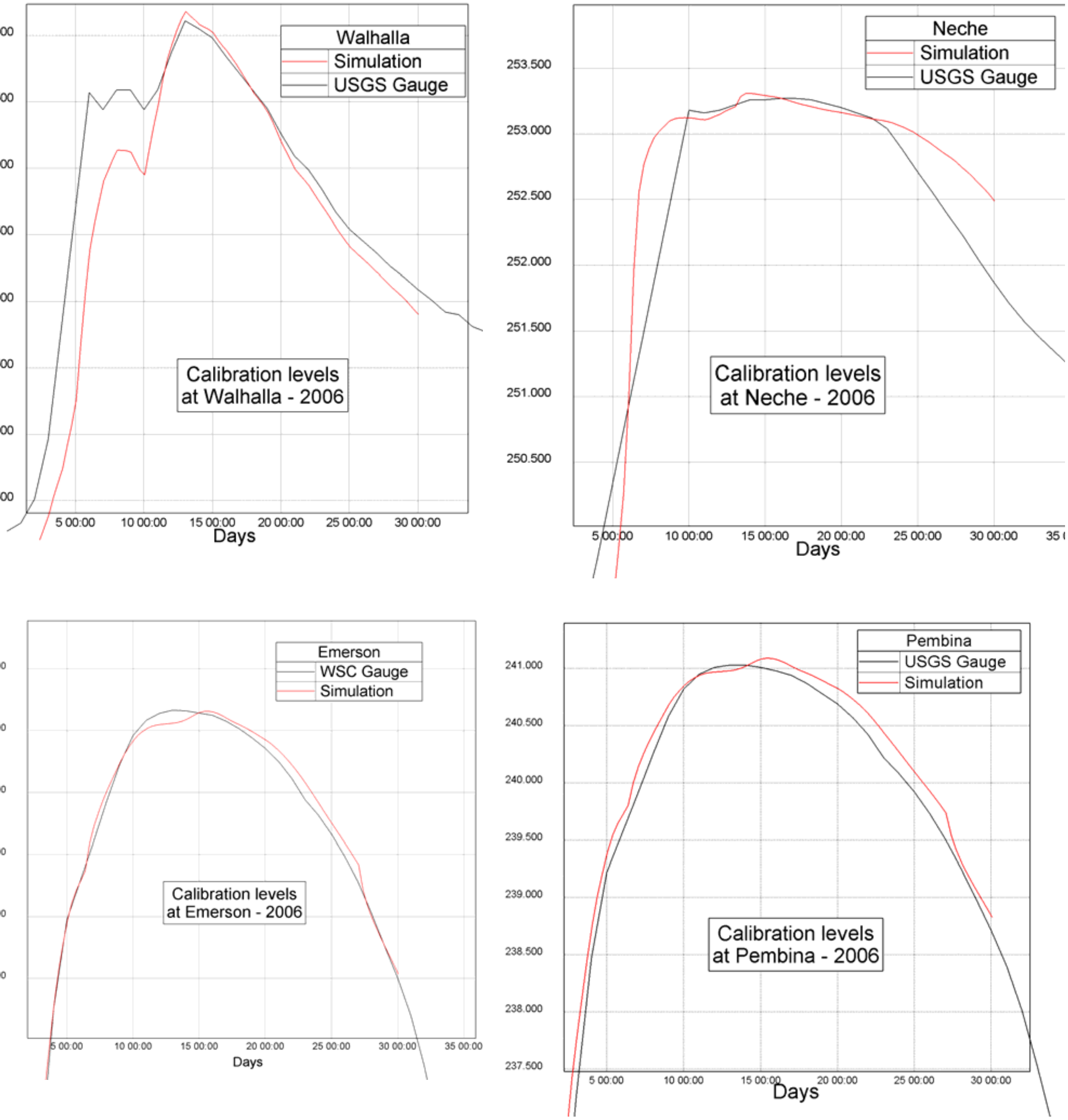


Figure 8 - Calibration water levels (meters) - 2006 flood

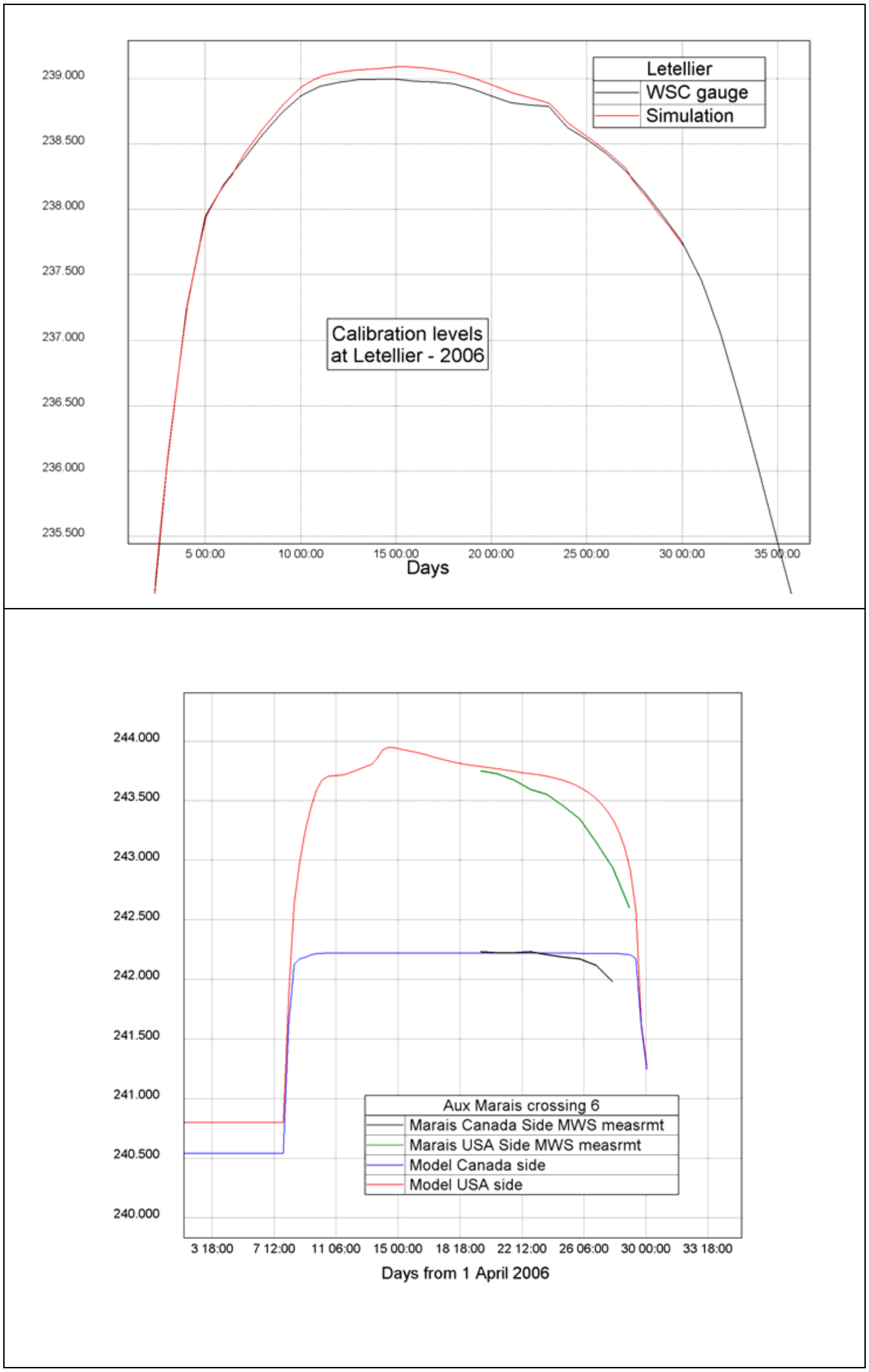


Figure 9 - Calibration water levels (meters) for Letellier and Crossing 6 - 2006 flood

Figure 10 shows the discharge through a north–south section across the entire model at Neche, over Highway 18. It shows that at their peaks,

- 33 m^3/s (1165 cfs) flows in the fields north of Neche, in a west–east direction,
- 133 m^3/s (4697 cfs) flows in the fields south of Neche,
- 185 m^3/s (6533 cfs) flows through the main channel and
- 352 m^3/s (12 431 cfs) is the total maximum flow, which is higher than the estimate from USGS of 306 m^3/s (10 806 cfs), 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 of the Walhalla hygrograph. At the beginning of the flood event, USGS flow estimate at Neche seems to be higher than the flow at Walhalla which indicate that other significant inflows were present, but not modelled.

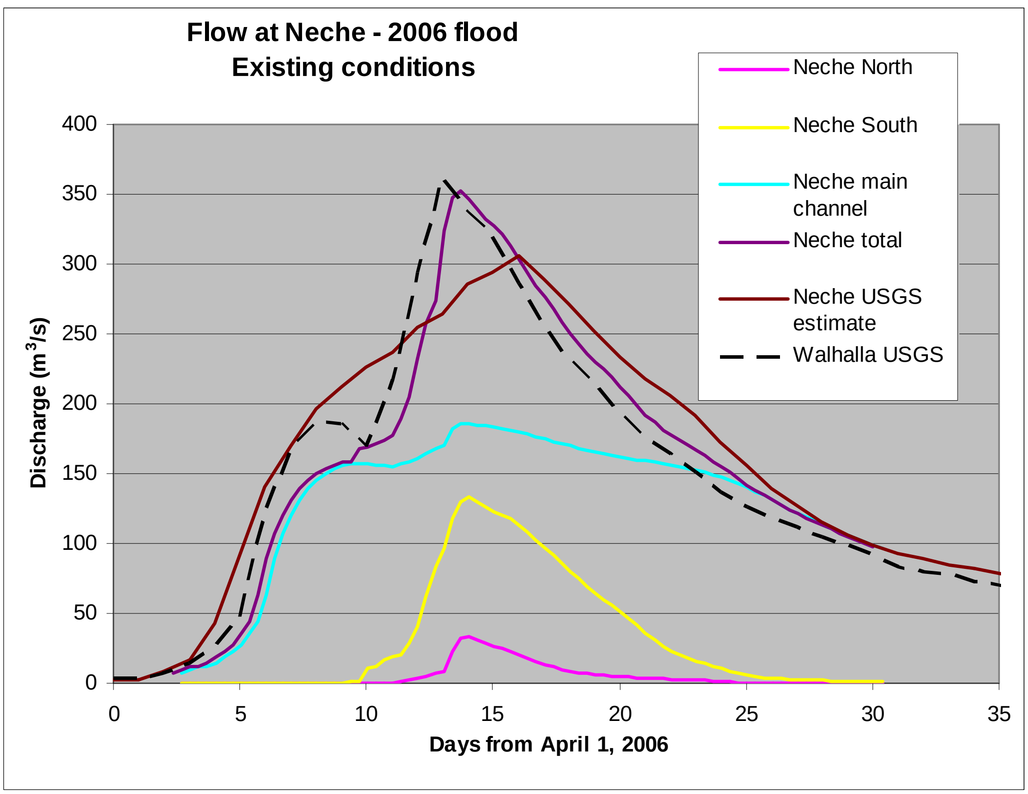


Figure 10 - Discharge at Neche through a north–south section across the whole model—comparison with gauge estimate

Similarly, Fig. 11 shows the flows north and south of the River in sections across the fields located about 8 km downstream from Neche; the section is indicated on Fig. 26. The comparison of Fig. 10

and 11 shows that north breakouts occur downstream from Neche, and that the capacity of the main channel has decreased significantly from what it was at Neche. The total flows remain unchanged.

The flow travelling South of Pembina River in this section, 8 km from Neche, can be broken down, at peak, into:

- Flow in Rosebud Coulee: 29 m^3/s (1024 cfs) (this flow has been measured separately before it joined the Tongue River)
- Flow in Louden Coulee: 10 m^3/s (353 cfs)
- Flow in Tongue River: 14 m^3/s (494 cfs)
- Flow overland between Pembina River and CR 55: 44 m^3/s (1554 cfs)

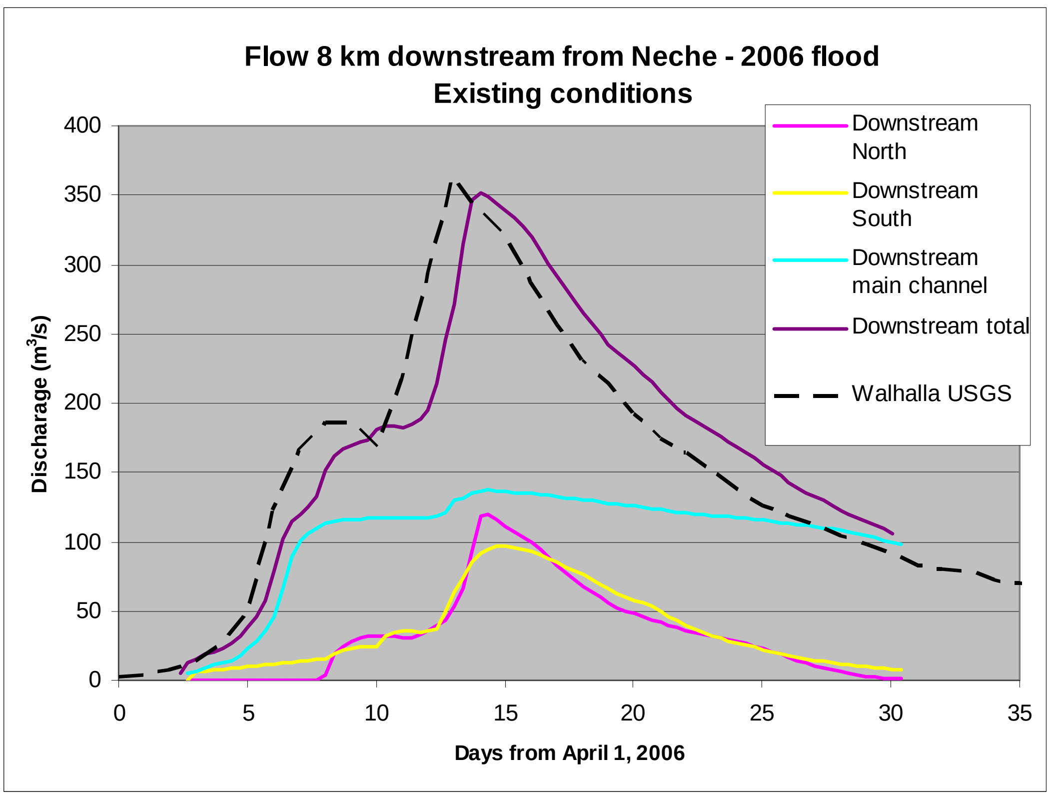


Figure 11 - Discharge 8 km from Neche through a north–south section across the whole model

8.1 Comparison with aerial photos

Aerial photos were taken during the 2006 flood by the North Dakota State Water Commission. They are shown here in four sections and compared with the corresponding flood extents as estimated by the model (Figs. 12 to 15). The photos were taken at dates close to the peak of the flood.

In general, the model reproduces the break-outs and the flood well, considering the fact that this is only a simplified model of a very complex situation, which does not include all the infrastructures and intricacies of the landscapes. In particular:

- the old meanders were not modelled as such with their former banks (this is were the break-outs would initiate),
- not all the roads, culverts and drains were modelled,
- the cross section of the Pembina River main channel was modelled with only seven points which may not be sufficient in some places to describe its conveyance at all depths, and
- the break-outs were not specified as such but were a consequence of the calculated hydrodynamics of the flow, with the prescribed upstream discharge provided to the model.

A close examination between the aerial photos and the model shows some very good similarity but also some discrepancies. For instance:

Some simulated flood extent appears larger than observed. This is due in part to the fact that not all water channels were represented; most roads are aligned with ditches which were not modelled; these ditches carry the water which otherwise is spread by the model over the land. This is particularly true 500 m south of Neche where there is a network of channels and ditches which carry the overflow. These channels were absent from the model and Fig. 13 shows more flood extent than the aerial photo.

In addition, the coulees and drains were represented only by a triangular cross section, instead of the true rectangular channel. As shown in Section 3.1.1 this caused the conveyance of their channels not to be quite accurate. The flow going through the area was reasonably correct, but with a depth slightly different from what it would have been if the true cross sections were represented, therefore providing a different visual aspect in the inundations figures.

There are a few discrepancies between the model results and what actually happened in 2006. For instance, the model still does not reproduce the overtopping of the East West township road just 1 mile east of Neche, the orange circle in Fig. 13. The simulated flood water came 9 cm (3 ½ inches) 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.

The model predicts flooding along the border 2 miles west of Hwy 18, which does not appear on the aerial photos in Fig. 13. This indicates too much break-out flow to the north, west of Hwy 18 at Neche.

In the model, the simulation of the Pembina River bank overflow was based on the bank elevations of the river main channel, discretized every 20 m. The numerical grid was designed so that it followed these banks. Further away from the channel, the grid does not necessarily follow the old meanders and their own banks. On many occasions, the breakouts occur at these old meanders and the flow is then controlled by the elevation of these former banks and not the main channel banks. This was corrected in one case, at the north breakout, 8 km west of Neche where the grid was made to follow more closely the banks of the old meanders, providing a better representation for the breakout and its discharge. Similar improvement could be done at other breakouts. This may explain the breakout and the extra flooding north of Hwy 55 (see Fig 14, orange circle) which does not appear on the corresponding aerial photo.

In spite of these deficiencies, many areas are well simulated (for instance flooding around Horgan Ridge towards Rosebud Coulee in Fig. 13), and it is felt that the present model can be used very effectively to simulate the relative effect of changes in the infrastructure arrangements in the Pembina River flood plain.

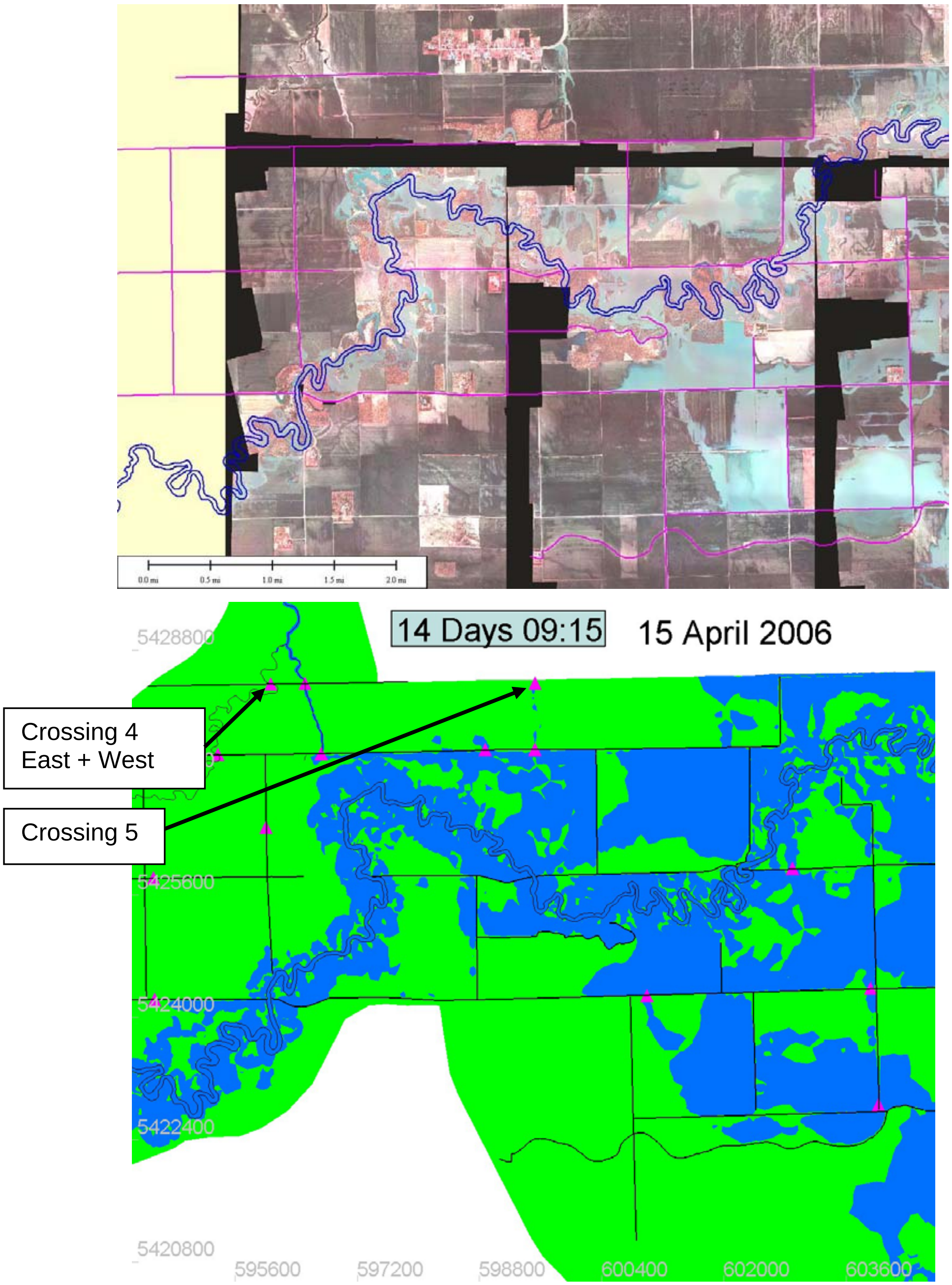


Figure 12 - Comparison of model simulated water extent versus aerial photos 1

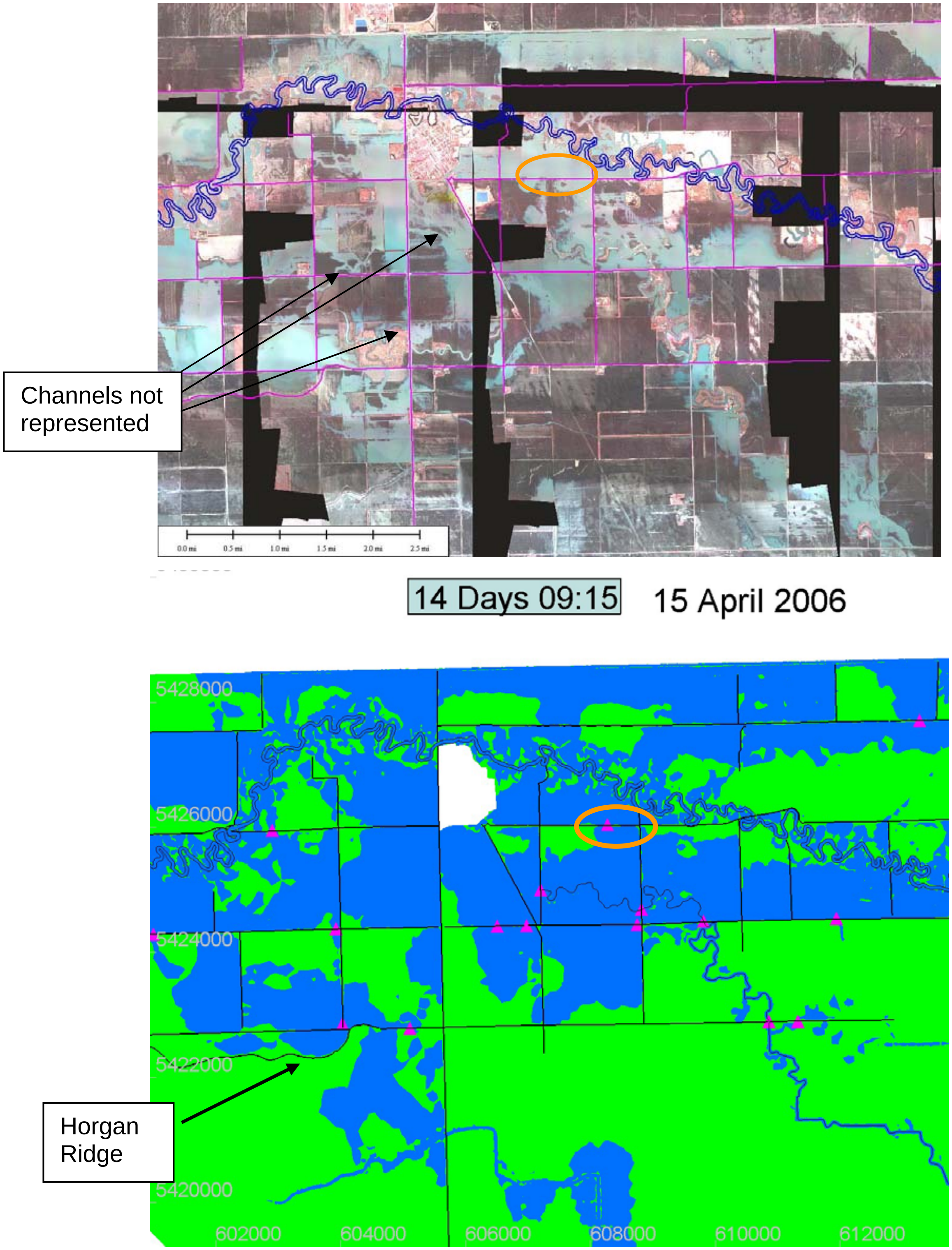


Figure 13 - Comparison of model simulated water extent versus aerial photos 2

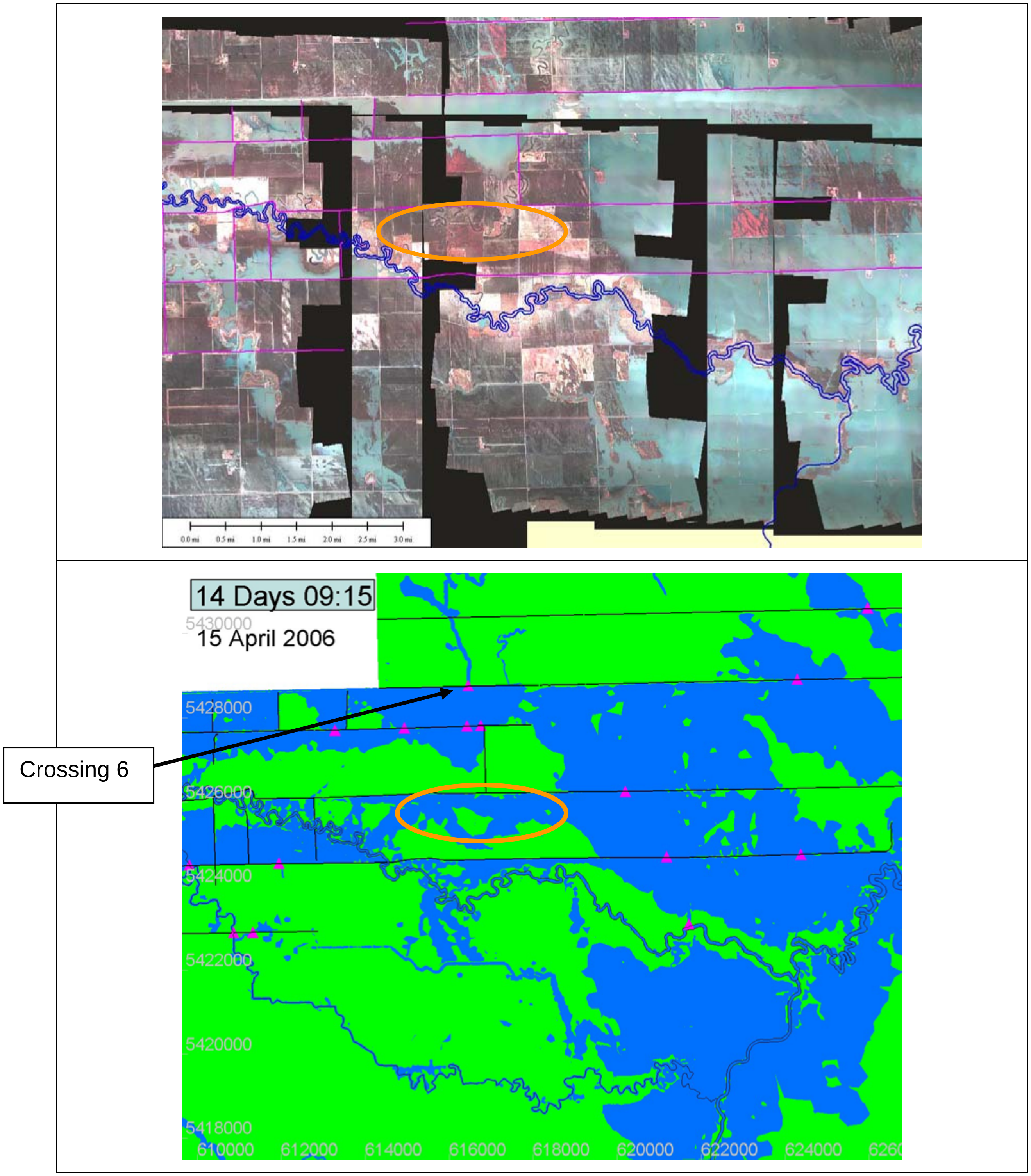


Figure 14 - Comparison of model simulated water extent versus aerial photos 3

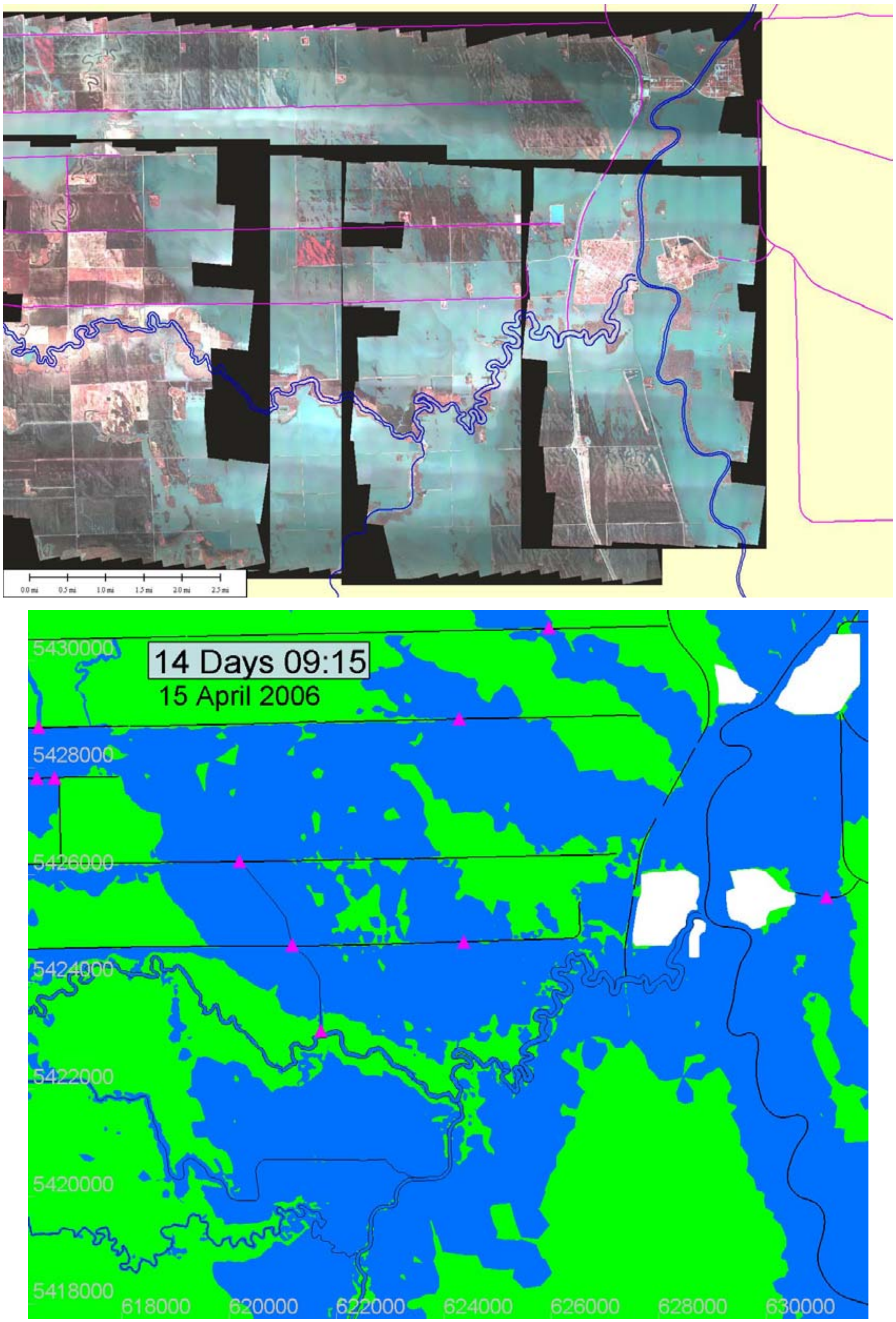


Figure 15 - Comparison of model simulated water extent versus aerial photos 4

9. Model Verification

The recent 2009 flood was chosen for model verification, using the same boundary condition definitions as the calibration period (2006 flood):

- Input flow hygrograph at Walhalla as estimated by USGS gauge in March-April 2009.
- Input flow hygrograph in the upstream boundary on the Red River, derived from the WSC gauge at Emerson, minus 90% of the Pembina discharge, which had been shifted by 4days.
- Water level in the downstream boundary on the Red River, derived from the WSC gauge at Letellier.

During the 2009 spring flood, extensive erosion took place at the Switzer Ridge creating a channel about 30 m wide and between1 and 1.5 m deep (100 feet wide, 3 to 5 feet deep). The site was surveyed by USACE in late January 2010. The data was processed and received in early March 2010, several months after the model was prepared and the calibration-verification performed. The incorporation of the eroded channel in the model, along with its dynamic change in bathymetry, will require modification to the numerical mesh and modification to the model.

The 2009 flood verification was therefore made without the eroded channel. It is felt that this will only affect the water levels locally, by lowering them along the border around border crossing 6, and increasing them further East.

9.1 Verification of levels and flows – 2009 flood

Figures 16 and 17 show the verification levels at Walhalla, Neche, Pembina, Emerson and Letellier. The model reproduces the gauge measurements very well when the flood is close to its peak. On these figures, day 0 corresponds to 1 March 2009. The largest discrepancy was at Emerson, on the order of 20 cm (7.9 inches) one week before the peak.

Figure 18 shows the comparison between the simulated discharge at Neche and its estimate from USGS during the 2009 spring flood.

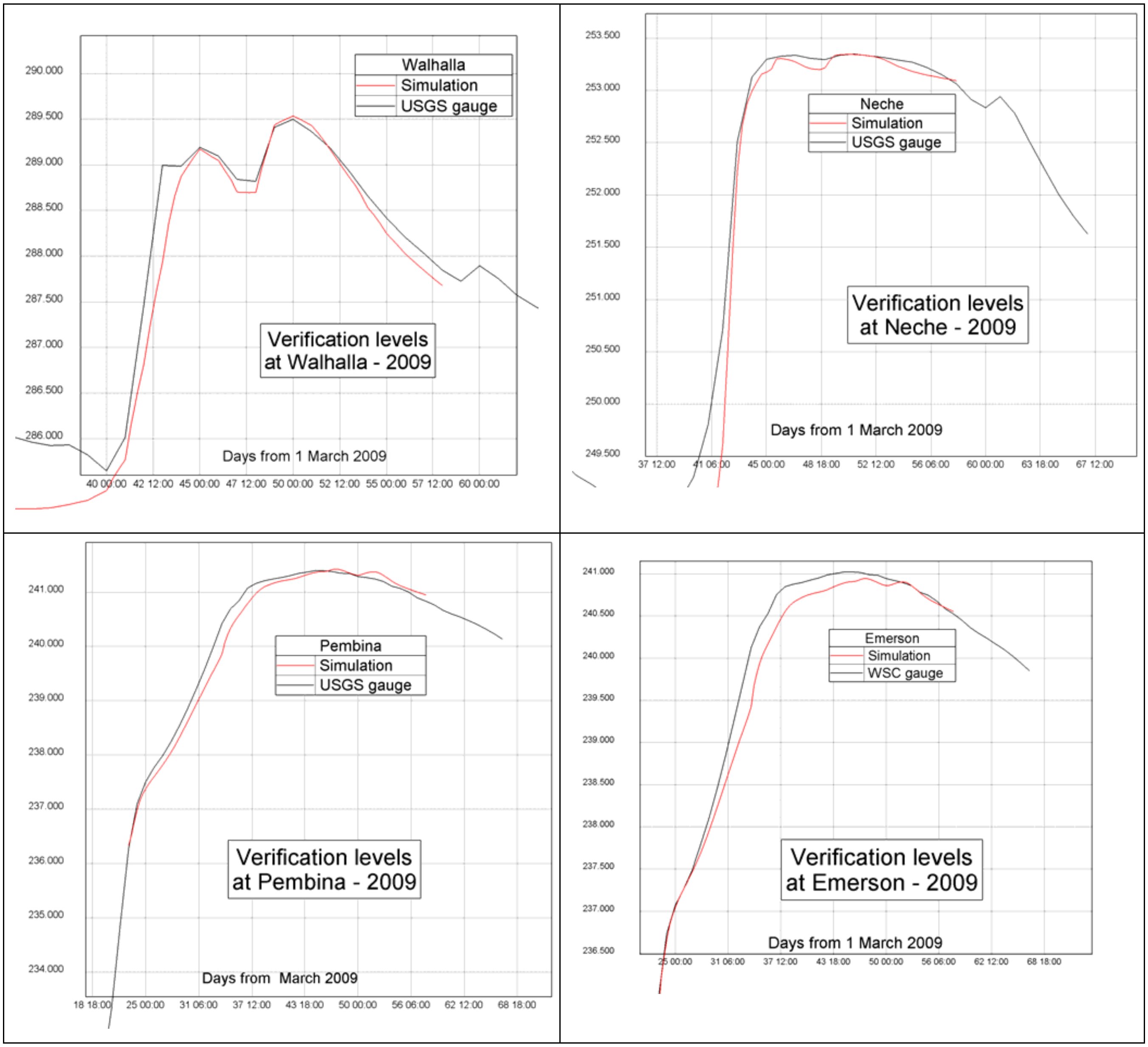


Figure 16 - Verification water levels (meters) – 2009 flood

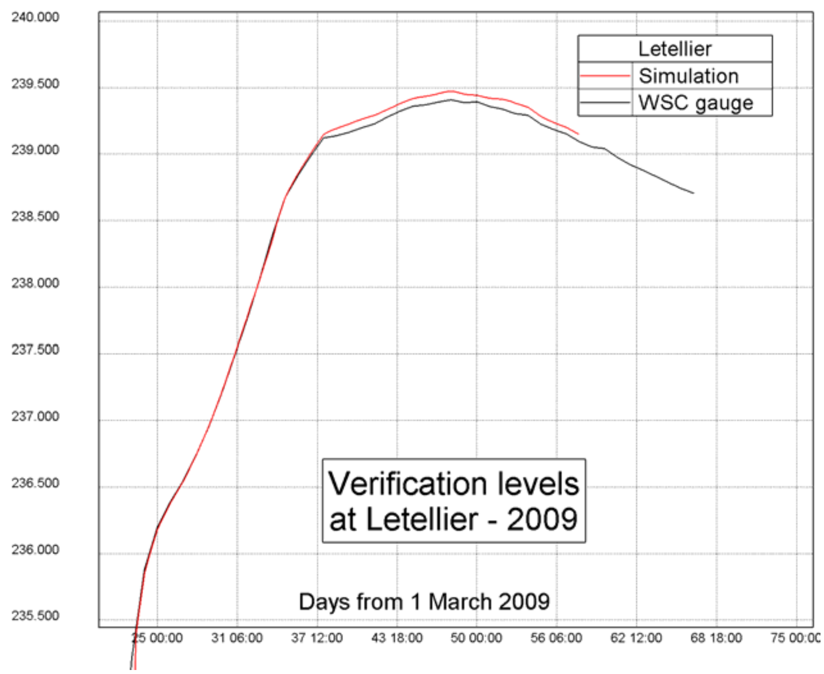


Figure 17 - Verification water levels (meters) at Letellier gauge

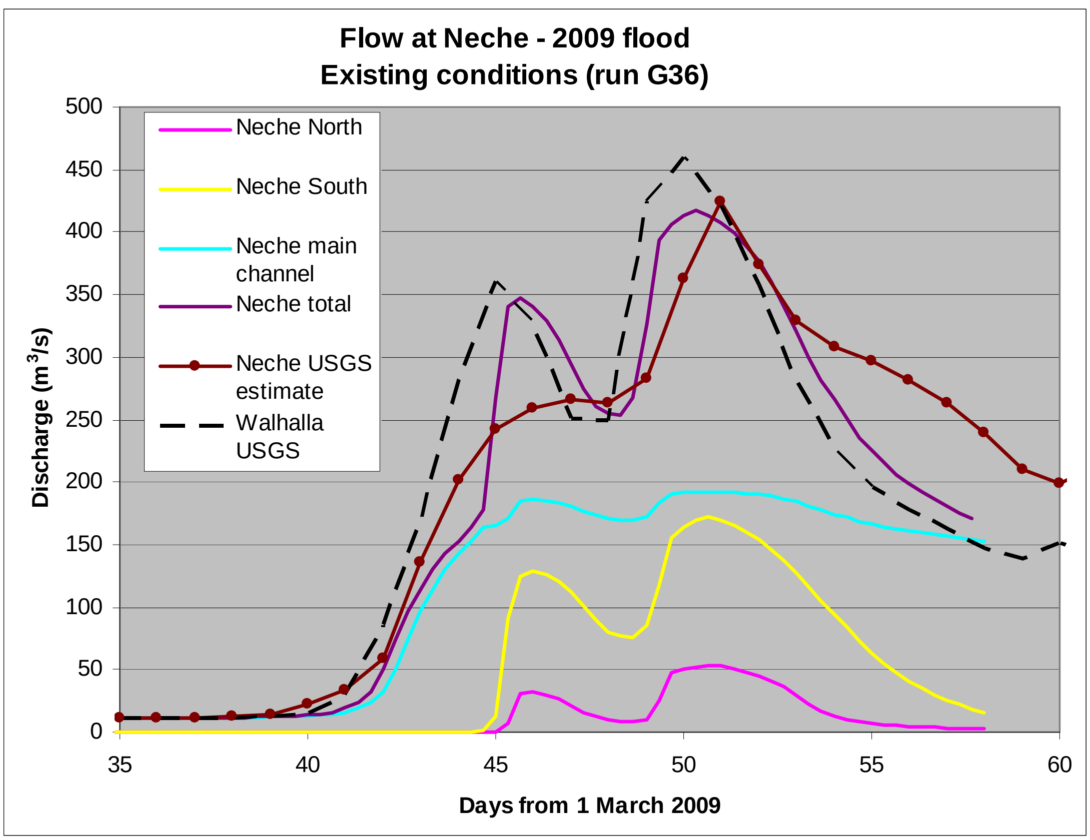


Figure 18 - Discharge at Neche through a north–south section across the whole model—comparison with gauge estimate

9.2 Comparison with aerial photos

The calibrated model results were compared with aerial and satellite images to evaluate flood extent modelling performance. Fig. 19 shows a comparison of the 2009 flood with a RADARSAT photo, while Figs. 20 to 22 compare three photos taken from a helicopter with the corresponding flooding as simulated by the model.

In general, these photos show that the model simulates the actual flood extent very well, and that the water levels are consistent with what was observed during the 2009 flood. A full flood map of the 2009 event is shown on Figure 65.

On Figure 19, flooding west of Highway 75 along the border, is coming from the Red River at Pembina. It eventually crosses the border and flows into the Aux Marais River. A comparison with RADARSAT image shows that the model does not provide enough water to this region (orange circle): This may be due by not having enough flow passages under the border road or under Interstate 29.

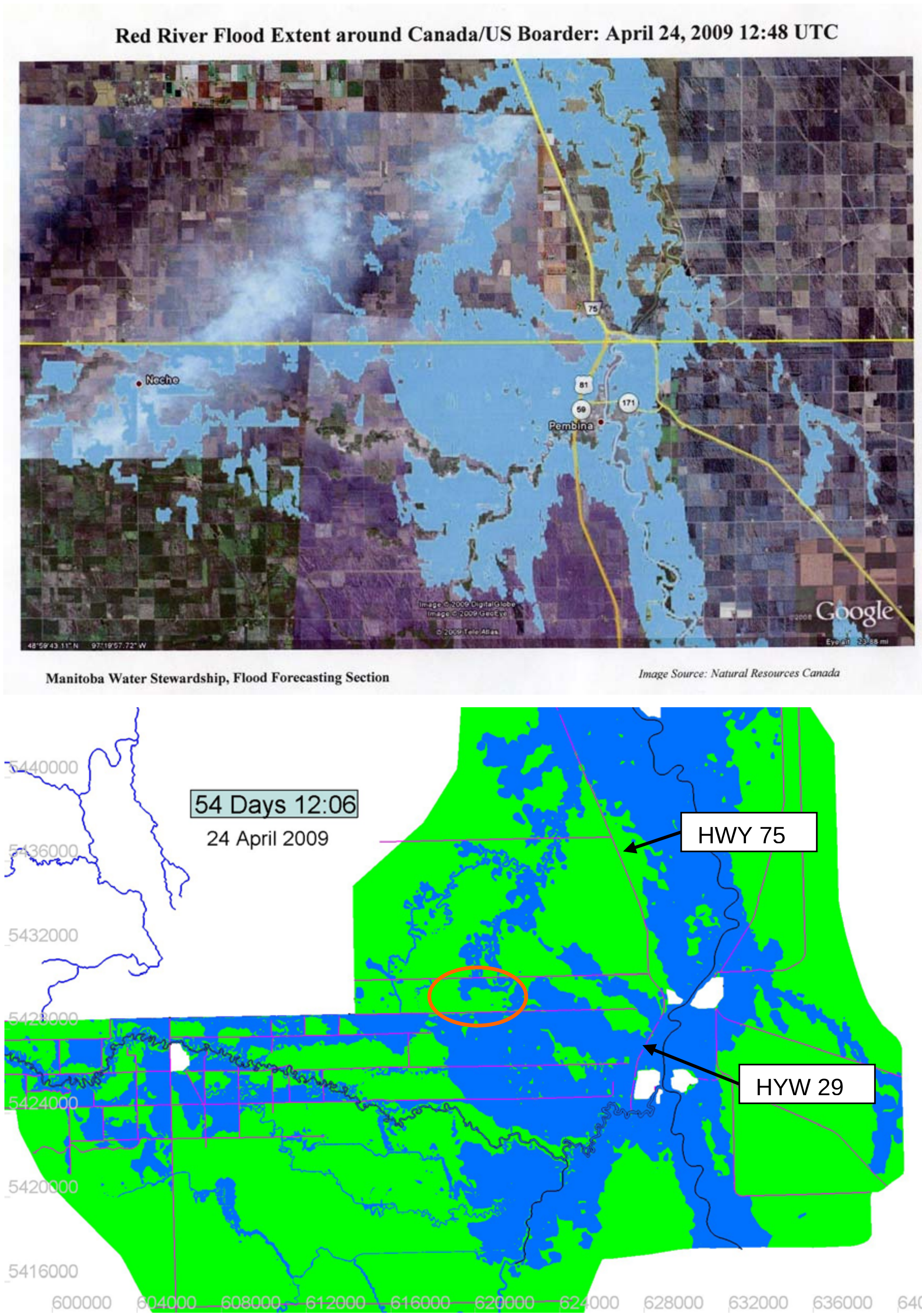


Figure 19 - Flood extent comparison with RADARSAT—24 April 2009

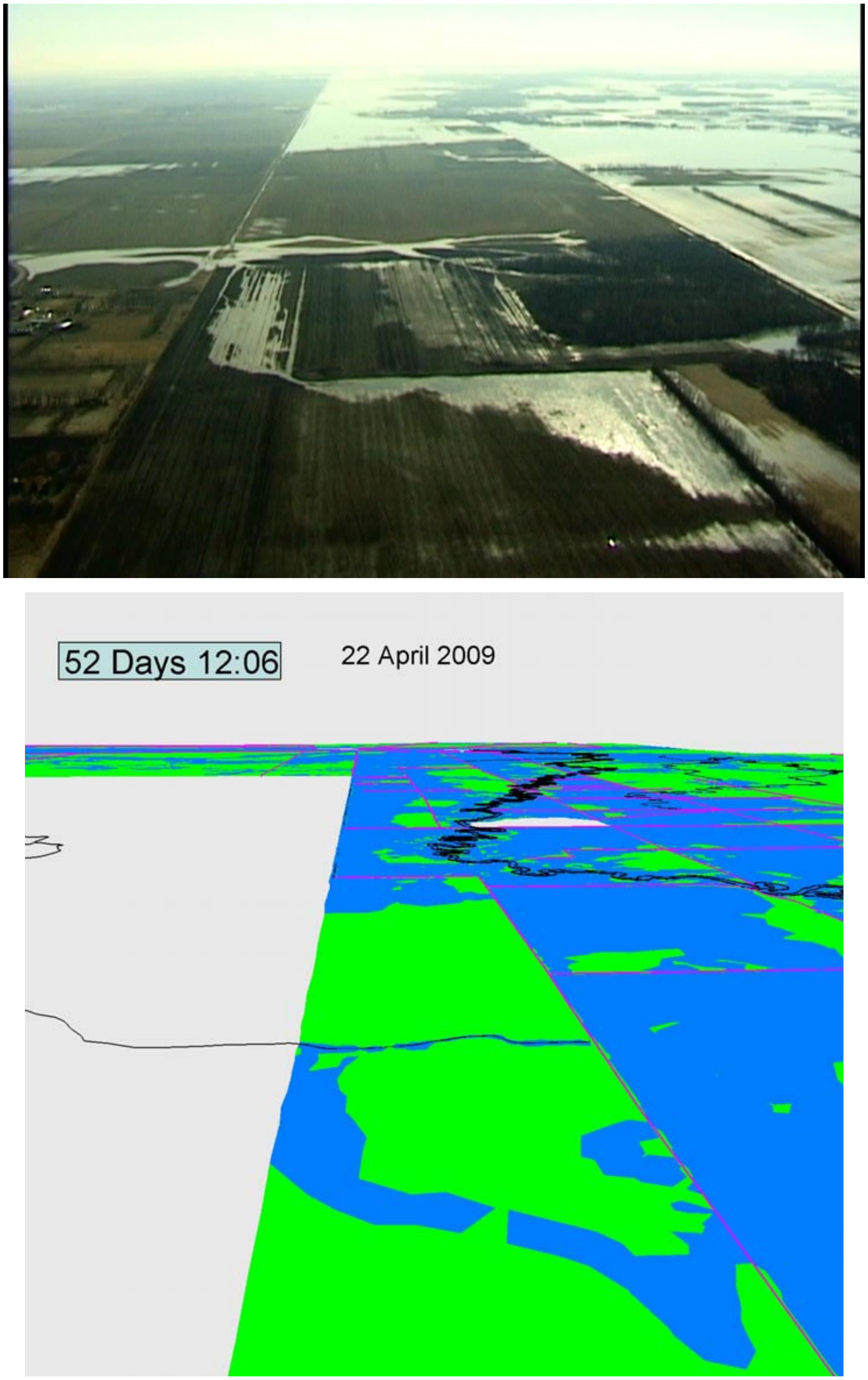


Figure 20 - Flooding around crossing number 5 - 2009 spring flood

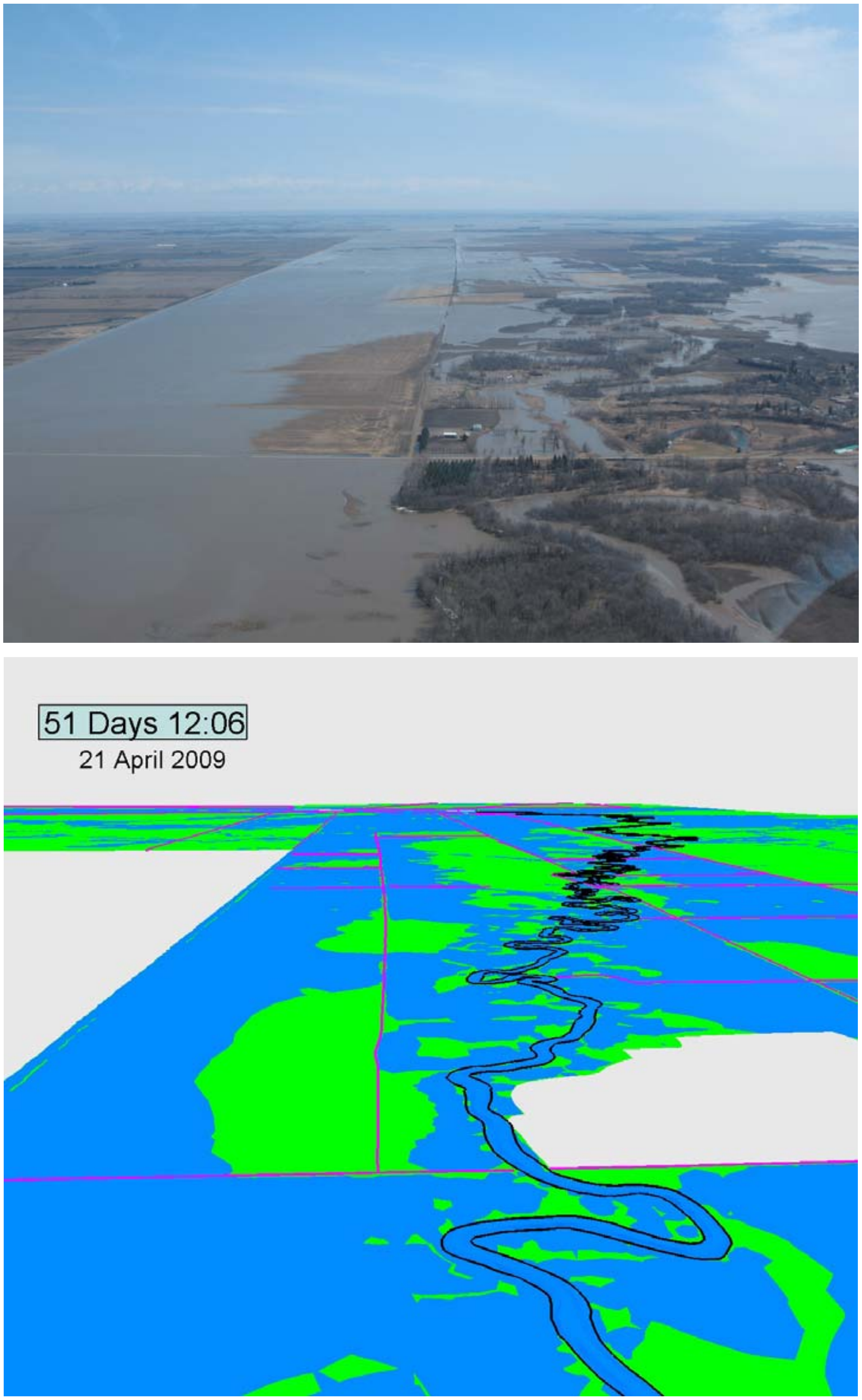


Figure 21 - Flooding east of Hwy 18, north of Neche

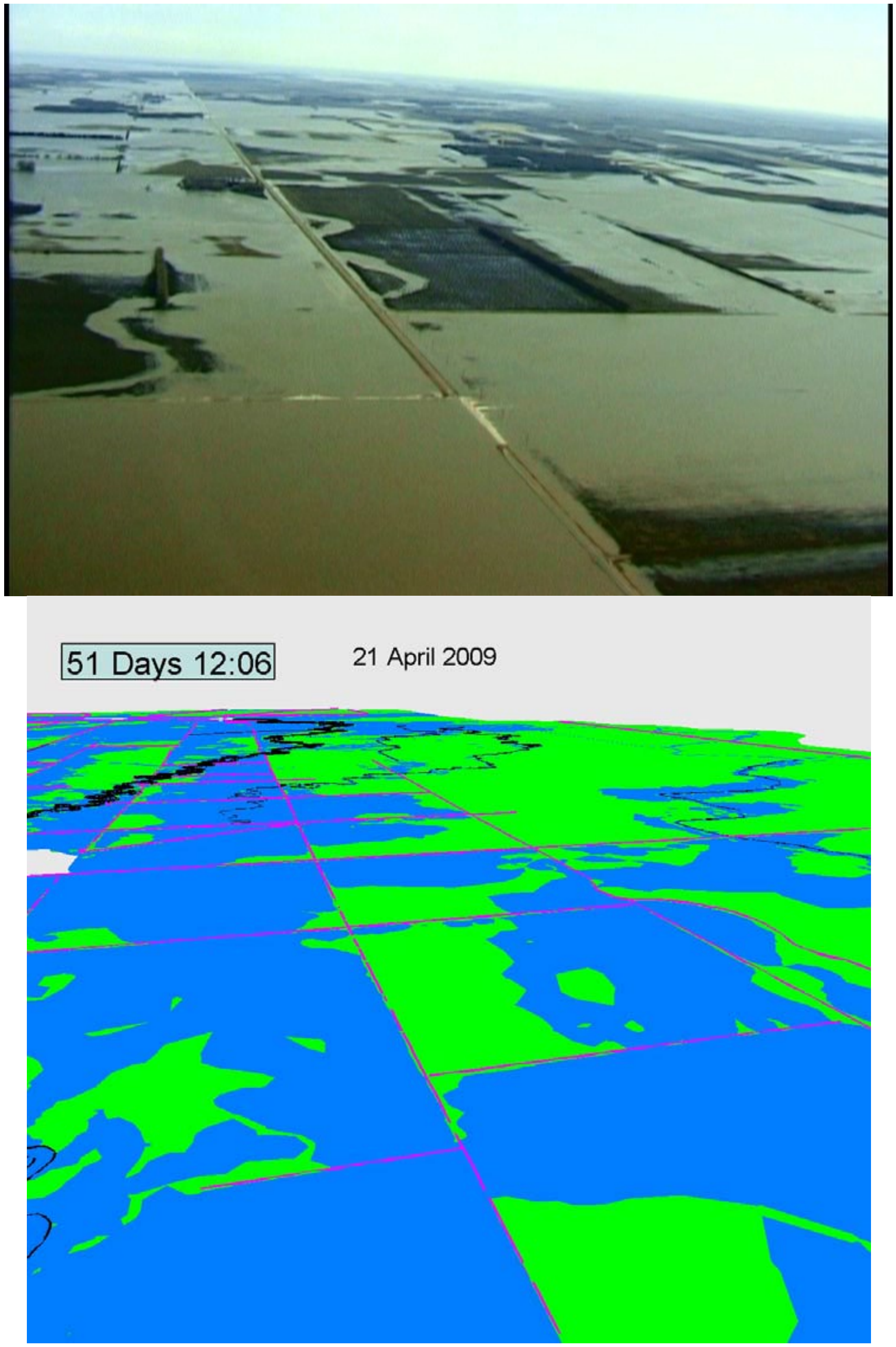


Figure 22 - Flooding along CR 55, south of Neche

10. Red River East overflow

The new model included some of the major roads and railway tracks, east of Pembina and Emerson, although only the bridge under Hwy 200 at Emerson and Hwy 171 at Pembina were modelled with some detail; their widths were known but the river bathymetry underneath was not known. The flow passage under other roads and railway tracks were modelled coarsely.

During the 2006 and 2009 floods, WSC and USGS estimated the east flow breakouts by estimating the flow under the bridges on Hwy 200 and Hwy 171. Tables 3 and 4 show a comparison with the simulated flows. Flows in the Red River main channel are very good, indicating that its conveyance has been well modelled.

In 2006, when the bridge under Hwy 171 was not yet constructed but a large 27 foot wide culvert was built under the road, the model gives good results; the 67.2 % error comes from the difficulty in estimating the flow in the semi-dry culvert.

In 2009 the model shows insufficient flow east of Pembina and excessive flow east of Emerson. This indicates that the discharge at the upstream boundary needs to be reviewed and the west breakout, seen on the RADARSAT photo, needs to be modelled more precisely with its flow passages under the bridges and over the roads. It is felt that the overflow East of Emerson (Table 4) should be going west instead, towards Aux Marais as indicated by the Radarsat image.

In any case it is felt that since the water level at Pembina is reliable, this discrepancy in discharge along the Red River should have negligible effects on the flood simulation in the Pembina flood plain.

Flow at Pembina - 2006									
Date	**Red Main Channel (cfs) USGS**	**Red Main Channel (m3/s) USGS**	**Telemac estimate run G35 (m3/s)**	**delta (%)**		**Q East overflow (cfs) USGS**	**Q East overflow (m3/s) USGS**	**Telemac estimate run G35 (m3/s)**	**delta (%)**
10/04/2006	62,200	1761	1735	-1.5		2640	75	125	67.2
14/04/2006	62,400	1767	1814	2.7		8460	240	214	-10.7

Table 3 - East flow during 2006 event

Pembina Flow - 2009 event									
Date	**Red main channel Pembina (cfs) USGS**	**Red main channel Pembina (m^3/s) USGS**	**Telemac estimate run G36 (m^3/s)**	**delta %**		**Q East overflow Pembina (cfs)**	**Q East overflow Pembina (m^3/s)**	**Telemac estimate run G36 (m^3/s)**	**delta %**
07/04/2009	60,100	1,702	1747	2.7		13,300	377	264	-29.9
11/04/2009	69,700	1,974	1965	-0.4		16,900	479	343	-28.3
18/04/2009	67,100	1,900	2002	5.4		17,700	501	369	-26.4
Emerson Flow - 2009 event									
		Red main channel Emerson WSC (m^3/s)	**Telemac estimate run G36 (m^3/s)**	**delta %**			**Q East overflow Emerson WSC (m^3/s)**	**Telemac estimate run G36 (m^3/s)**	**delta %**
07-Apr		1847	1716	-7.1			111	237	113.5
09-Apr		2081	1871	-10.1			159	293	84.3
11-Apr		2076	1927	-7.2			177	304	71.8
16-Apr		2145	2084	-2.8			203	324	59.6
22-Apr		2054	2013	-2.0			162	316	95.1

Table 4 - East flow during 2009 event

11. Comparison of the Telemac model with previous existing models

Telemac model was compared with two one-dimensional models which were prepared to simulate the floods in the Pembina River lower flood plains, and which have been documented.

UMA Engineering Ltd prepared a Mike 11 model in 2008, (Ref. 2). It used an existing Mike 11 model developed by MWS, with additional details provided by a HEC-RAS model developed by NDSWC. The UMA model was georeferenced and extended north, across the border road towards the Aux Marais drainage area. (See Fig. 23). For the topography of the lower flood plains, the model used the same 2006 LiDAR data as used in the Telemac models, but assumed that the cross sections of the flood plain were sloping down towards the main river channel instead of sloping away from it. Calibration of the model was therefore quite challenging.

Figure 5: Pembina River MIKE 11 Model Floodplain Connectivity

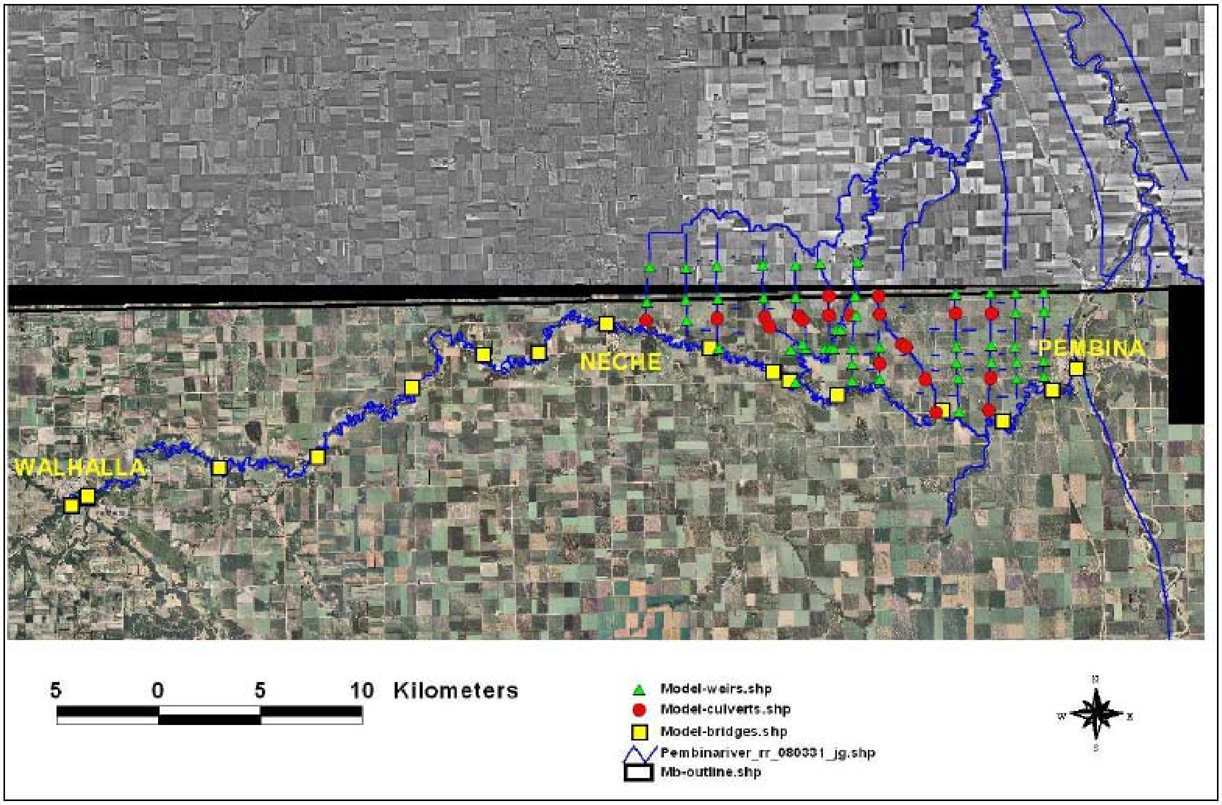


Figure 23 - UMA Mike 11 model connectivity (from Ref. 2)

In 2000, Water Management Consultants, (Ref. 3). had prepared a Mike 11 model which assumed several straight channels, or branches, (about 1 mile wide), in a west–east direction, bounded by the major west–east roads. These channels were crossing through the main channel (about 600 m wide) representing the Pembina River. To account for the two-dimensional nature of the observed flow, the channels in the model were connected together by links where water could cross-over from one channel to the other. The hydraulic characteristic of these links were defined manually. (Fig. 24)

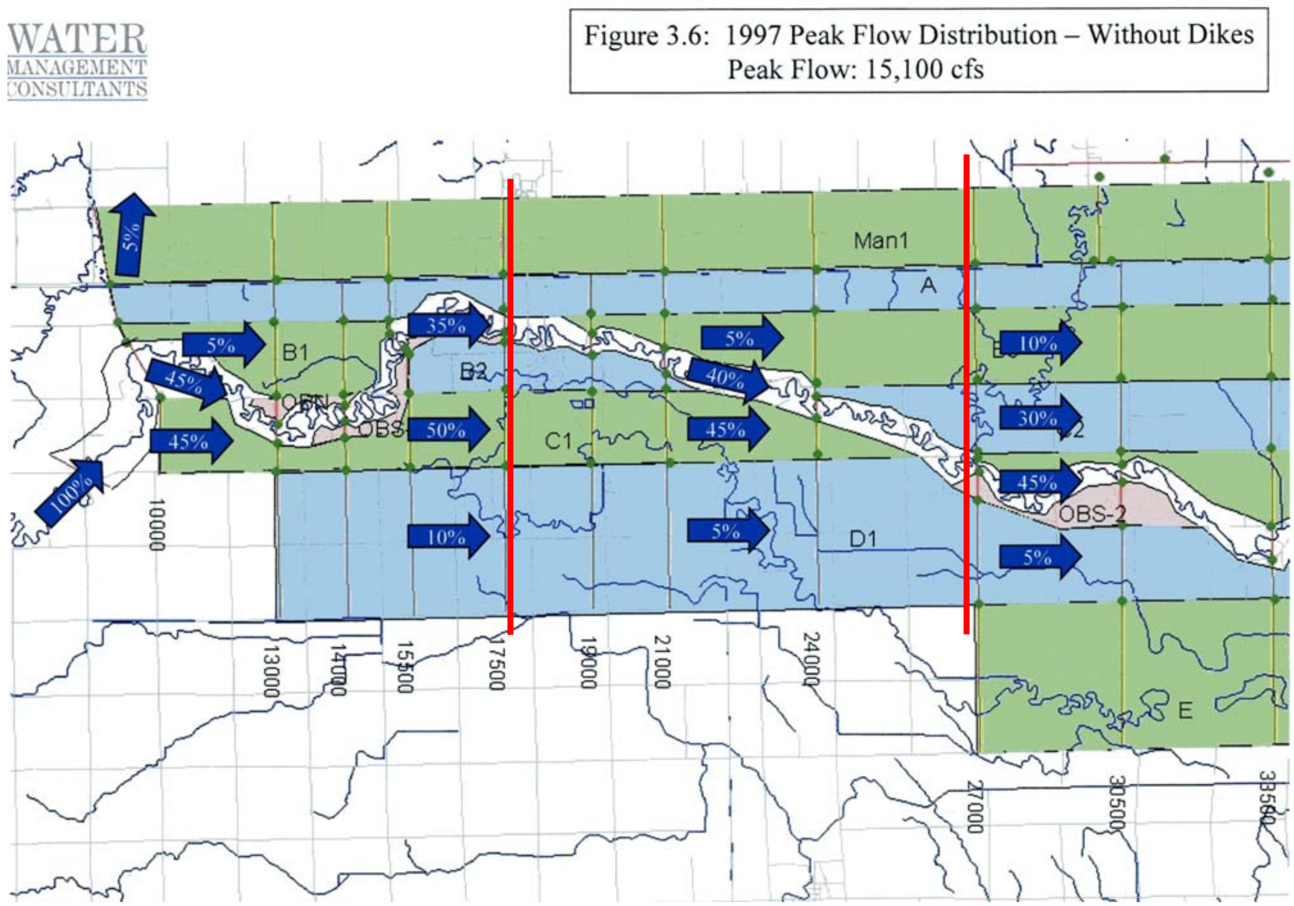


Figure 24 - Water Management Consultants model simulation (from Ref. 3)

Initially the topography was to be defined from several 1998 partial surveys using different technologies, (LiDAR, Differential Global Positioning System and Inferometric Synthetic Aperture Radar). These surveys were combined, but in places their accuracy was not precise enough for the purposes of the study. Further information was obtained from a 1980 USACE HEC 2 model, from GPS data for road crests and from contours from USGS topographic maps.

Calibration of the model was based on level comparison with gauge records at Neche during the 1997 flood. It was suspected that the simulated discharge at each of the links had been adjusted in the model until they matched observed behaviours of the flow during the 1997 flood.

Table 5 shows a comparison of the discharge through the various branches of the Mike 11 model with the corresponding Telemac results. The sections are shown as the two red lines in figure 24. Note that the 2D results were obtained during the peak of the flood on April 15, 2006, (362 m^3/s, (12 784 cfs)) while the 1D model was based on a simulation of the 1997 flood with the agricultural dykes along the Pembina River removed (427 m^3/s (15 079 cfs)).

It is very difficult to compare one model with the other since they are based on totally different assumptions. One could calibrate very well a 1 D model if the modeller knew in advance where the breakouts would occur, where the water would flow and which road would be overtopped. This model would not give the right answer if the infrastructure was changed or the upstream flow was changed.

	Hwy 18 at Neche		**9 km east of Neche**	
Branch	**Mike 11 (1997)**	**Telemac (2006)**	**Mike 11 (1997)**	**Telemac (2006)**
Main channel	35%	51%	45%	49%
A	0%	9%	0%	19%
B	0%	0%	10%	6%
C	50%	27%	30%	9%
D	10%	0%	5%	0%
E		8%		2%
South of E				11%

Table 5 - Flow distribution relative to peak flow, across two sections in the lower Pembina flood plains during a major flood event

12. Flood scenarios simulations

Several scenarios were simulated in an attempt to alter the propagation of the flood, and understand better where the water is going and why. They were chosen after discussion with the Pembina River Basin Advisory Board (PRBAB), the Pembina River County Water Resources District, the Red River Basin Commission (RRBC) and the International Red River Board (IRRB).

The scenarios where the area of interest was only the lower Pembina flood plain were simulated with the small model, extended only to the south but not covering the Buffalo drainage. The other scenarios were run with the complete model. Except for the last Scenario 11, they were all run with the 2006 flood hydrograph.

The following scenarios were simulated.

- Existing conditions
- Scenario 1: Set-back dykes
- Scenario 2A: Floodway discharging into Red River at Pembina
- Scenario 2B: Floodway discharging into Aux Marais River
- Scenario 3: Natural conditions
- Scenario 4: Removal of short road located half mile south of border
- Scenario 5: Existing conditions with removal of County Road 55
- Scenario 6: Existing conditions with removal of the border road
- Scenario 7: Existing conditions with removal of the border road and County Road 55
- Scenario 8A: Five diversions with a total capacity of 63 m^3/s (2225 cfs)
- Scenario 8B: Five diversions with a total capacity of 126 m^3/s (4450 cfs)
- Scenario 8C: Five diversions with a capacity of 63 m^3/s (2225 cfs), assuming widening of Rosebud and Louden Coulees
- Scenario 8D: Five diversions with a capacity of 126 m^3/s (4450 cfs), assuming widening of Rosebud and Louden Coulees
- Scenario 9: Three diversions into Buffalo and Aux Marais with a total capacity of 63 m^3/s
- Scenario 10: Five diversions (63 m^3/s, (2225 cfs)) with lowering of County Road 55
- Scenario 11: 2009 Flood - Five diversions (63 m^3/s (2225 cfs)) with lowering of County Road 55

Because of the large number of maps, the figures describing the flood scenarios are included at the end of this report.

12.1 Slope of flood plains

Before presenting the scenarios it is important to revisit the nature of the region's topography, particularly the configurations of roads and dykes in the Pembina River flood plains. Figure 25 shows three cross-sections, about 5 km (3.1 mile) 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 tend to move away from the river, either in a north-east direction or in a south-east direction.

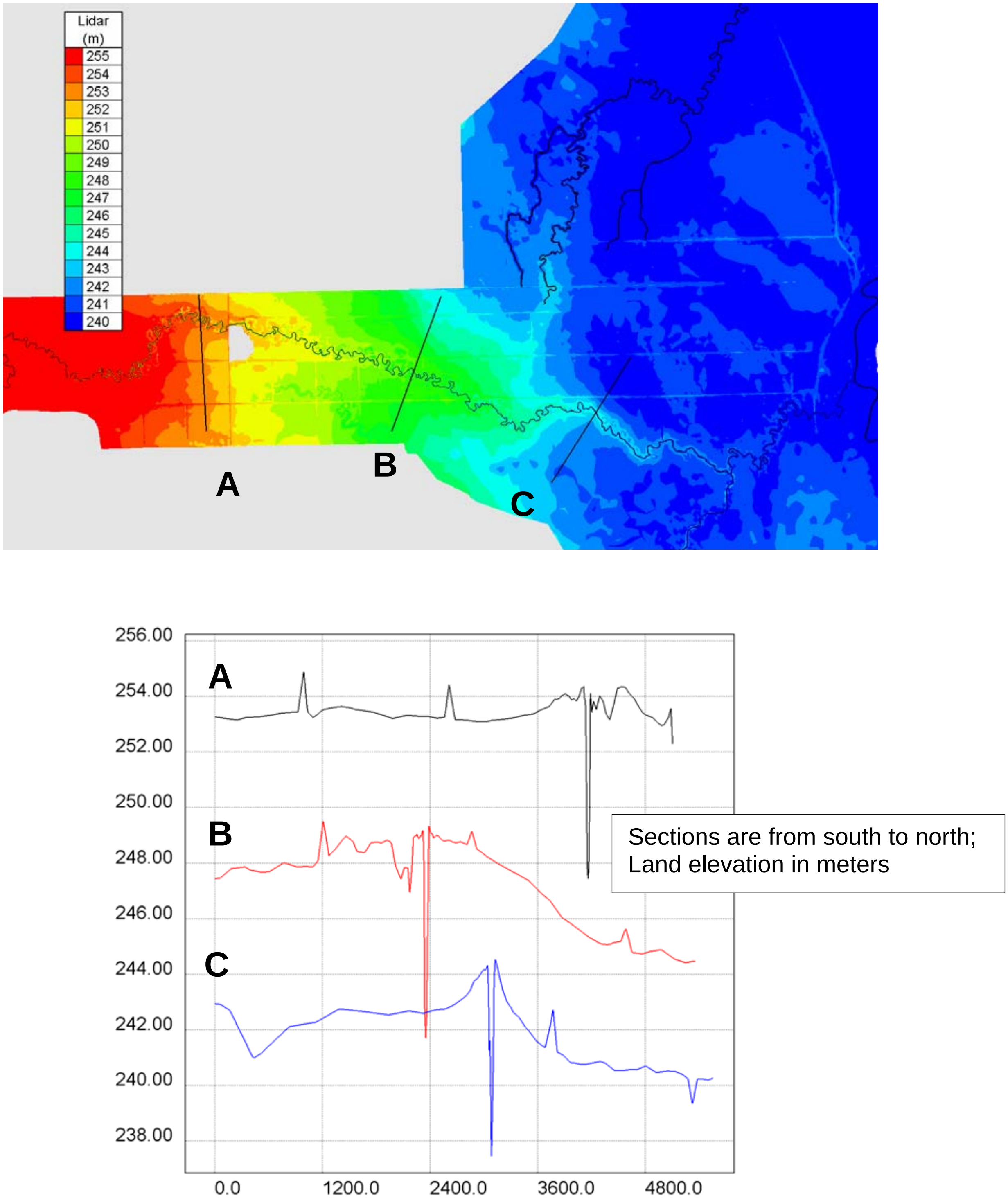


Figure 25 - LiDAR representation of the lower flood plains, with three across-fields sections

12.2 Existing configuration

Figure 26 shows the flood extent during the 2006 flood with the existing infrastructure. It is similar to Fig. 12 to 15.

The same 2006 flood will be used for testing all the various scenarios except 11.

Note that in this configuration the flow distributions across Highway 18 and across a section located 8 km downstream from Neche are shown on Figures 10 and 11.

12.3 Scenario 1: Set-back dykes

Scenario 1 assumes that the river would be contained by a set of dykes, with a width of about 850 m, enough to contain all the meanders. At the Tongue confluence, the south dyke turns south to reach the Tongue bypass, following it for 2 km. On the north side, it ties in with the Interstate 29.

Fig. 27 shows the maximum extent of the flood, in which it can be seen the Pembina flood plain is kept dry, including the Switzer ridge and its east depression. Flooding due to the Red River remains about the same.

Because all the Pembina waters are concentrated in a smaller portion of the Red River valley, the peak level at Pembina on the Red River is higher by 8 cm (3.1 inches) compared to existing conditions.

Figure 28 shows the maximum depth along the toe of the dykes as a function of the distance going from upstream to downstream. Most of the apparent oscillations in the depth come from the roads and depressions in the topography; but some of them come from the dynamic effects during the propagation of the flood wave across the meanders. Figure 28 therefore represents the height of the dykes containing the 2006 flood, without any free board.

12.4 Scenario 2A: Floodway discharging into Red River at Pembina

In Scenario 2A a “floodway” is simulated that is designed to carry a given amount of water from about 8 km upstream from Neche to the Red River. It was running just south of the border. The floodway was not represented physically using a numerical grid, but rather it was modelled as a sink-source combination with the water removed from the Pembina River and reintroduced into the Red River. The berm on the south side of the floodway, preventing the flood water from moving north towards the border was modelled, and new culverts, similar to border crossing 6, were modelled to allow flood waters to move under the Floodway, into the Aux Marais river. Similarly, the culverts for border crossing 5 (see location on Figure 12) were also relocated. A single siphon was also provided to allow flood waters from the Red to flow north across the border road under the floodway (see Figure 29).

The floodway capacity of 57 m^3/s (2000 cfs) was chosen as suggested by USACE in a 1983 study report (Ref. 5). The 85 m^3/s (3000 cfs) capacity was chosen to increase the effectiveness of the floodway.

Figs. 29 and 30 show the flood extent close to its peak during a 2006 flood event with the floodway having 2000 and 3000 cfs capacity, respectively. Both figures show that flooding is still extensive with only minor differences between the two floodway capacities.

We have compared on Figure 31 the maxima of flood levels between the existing conditions and a floodway discharging 85 m^3/s (3000 cfs). Note that these peaks do not necessarily occur at the same time over the whole region. Generally, the floodway has the effect of lowering water levels across the

Pembina flood plains by 5 to 25 cm (2 to 10 inches). An example of this lowering is shown on Fig. 32 for a sample location north of HWY 55. This location, shown on Fig. 29, is situated on the bottom of the photo in Fig. 22.

Fig. 32 indicates that with the floodway, not only would the peak water levels decrease, but also that the duration of the flooding would be reduced by several days. This was expected since the peak discharge of the river was reduced (from 362 to 305 m^3/s), along with a reduction of the peak water levels, but keeping the same duration of the hydrograph. Therefore the time at which the water would start breaking out of the river banks was delayed, and the flooding of the fields was consequently delayed. Similarly, the volume of water carried by the river was reduced, therefore the amount of flood water stored in the fields was reduced, and the time required for them to drain was shorter. The same kind of reduction of flooding duration can be expected when controlled diversions are put in place instead of the floodway.

On the Red River at the border, where the floodway outlet is located, these changes have the effect of moving the peak of the flood ahead by about a day, but the peak water level itself changes only by a few centimetres, as seen on Figure 33.

12.5 Scenario 2B: Floodway discharging into Aux Marais River

In Scenario 2B, the floodway described in Scenario 2A was again simulated but discharged into the Aux Marais, instead of the Red River.

Flood extent in the Pembina plain remains basically identical to Scenario 2A. But, as seen in Fig. 34, flooding in the Aux Marais region increased while the levels in the Red River went down (to be compared with Fig. 31 where the Red River levels did not drop). This figure shows the change in peak levels between this scenario and the existing conditions for an event equivalent to the 2006 flood. Note that these peaks do not occur at the same time across the region.

12.6 Scenario 3: Natural conditions without the border road

In Scenario 3 all roads were set at the elevations of the natural ground, as defined by the LiDAR surveys, about 25 m (82 feet) away from the roads.

Along the border, the road and the drain were set at the elevation of the natural ground as found further away from the road, not to be influenced by any mound or ditch. Along Buffalo Creek, downstream from Altona, the dykes on both sides of Buffalo Lake Channel were also removed. The elevation of the bottom of the rivers and coulees was left unchanged.

For an event equivalent to the 2006 flood, the same break-out along the Pembina River would occur, but the water would flow north and south without being impounded by the roads. Figure 35 and 36 show the flood extent at two different times, while Figure 37 indicates the change in peak levels between this scenario and the existing conditions. On this last figure, the two red spots on the East of the Red River indicate flooding since the roads were lowered on this side of the Red River as well.

In general, because the existing water channels (rivers, creeks and coulees) do not have enough capacity to carry the extra water, the flattening of the roads causes the water to spread over a wide region, but depths remain for their most part shallow (less than 20 cm) . It is also noted that the water breaking-out from the Pembina River cannot travel directly towards these channels, because their natural banks, in some cases, are higher than the plains (for instance the southern West and East branches of the Buffalo creek).

The peak water level at Pembina, on the Red River, dropped by 15 cm (6 inches), due to the fact that in the natural conditions, about 1/3 of the Pembina River discharge now travels towards Letellier and St-Jean-Baptiste instead of Pembina. The Pembina River peak level at Neche dropped by 14 cm (5 ½ inches).

The discharge in the various natural channels is shown in Figure 38, assuming that the 2006 flood hydrograph was injected in Walhalla. The upper graph indicates the individual discharges as a function of time, while the lower graph shows the total discharges going north across the border, south towards Tongue River, and east staying in the Pembina River main channel. The peaks of these three discharges are about the same at 112 m^3/s (3955 cfs).

At the end of the simulated flood which lasted 28 days, the volume of water was divided as follows, relatively to the total volume which entered at Walhalla:

- Flowing along the Pembina River main channel (8 km downstream from Neche): 56 %
- Flowing north across the border towards Aux Marais and Buffalo: 20 %
- Flowing south towards Louden and Rosebud coulees: 23 %

12.7 Scenario 4: Removal of road located half mile south of border

In Scenario 4, the road located ½ mile south of the border and 1 ½ mile west of Highway 18 was lowered. It is shown in the orange circle on Fig. 39.

During the 2006 flood (Fig.12), this road was retaining the floodwaters, therefore keeping the land just north of it dry. The water would eventually either go back to the river further east, or overtop the road and move north. If this road was lowered, the water would accumulate along the border road and most of it would then flow east. Table 6 shows the flows across various locations of the region: more water would flow along the border road, some going West towards Hyde Park coulee, and some going east, while less water would travel towards the South.

Figures 39 and 40 show the flood extent and the change in peak levels between this scenario and the existing conditions for an event equivalent to the 2006 flood.

This scenario does not change the levels held back by CR 55, west of Highway 18, but it lowers them slightly by 5 cm east of Highway 18.

	Existing conditions	**Scenario 4 Road lowered**
Maximum flow into Hyde Park coulee (m^3/s)	2.6	6.8
Maximum flow, north section across Highway 18 at Neche (m^3/s)	33	45
Maximum flow, main channel at Neche (m^3/s)	186	182
Maximum flow, south section across Highway 18 at Neche (m^3/s)	133	114
Maximum flow, north section 8 km downstream from Neche (m^3/s)	120	120
Maximum flow, main channel 8 km downstream from Neche (m^3/s)	137	134
Maximum flow, south section 8 km downstream from Neche (m^3/s)	97	90

Table 6 - Maximum flow comparison during Scenario 4

12.8 Scenario 5: Existing conditions with Removal of County Road 55

A seen on Fig. 26, County Road 55 plays a major role in holding the water. In this Scenario 5, this road was lowered so that it would be at the same elevation as the natural ground.

During a 2006 type flood the water would flow towards Rosebud and Louden coulees in the south, as shown on Fig. 41. There would not be significant changes in water levels north of the Pembina River, except in the zone just north of the second Hwy 55 Bridge, which is now dry since the local breakout did not occur, (orange circle of Fig. 41). Note that this break-out appeared in the model in the existing conditions but did not show in the aerial photos (Fig 14).

The change in peak levels between this scenario and the existing conditions is shown on Fig. 42.

In the model, the Tongue River, after having received the overflows from the Rosebud coulee, north of Bathgate, does not seem to have enough capacity and consequently overflows on the north side towards Louden Coulee (black circle in Fig. 42). This modelled flooding may not be quite accurate since the local roads and railway track have not been represented in this region since they were considered infrastructures far away from the area of concern.

The flow distributions across Highway 18 and across a section 8 km downstream from Neche are indicated in Table 7. It shows a significant transfer of water from the North to the South, 8 km downstream from Neche.

	Existing conditions	**Scenario 5 CR 55 lowered**
Maximum flow into Hyde Park coulee (m^3/s)	2.6	2.6
Maximum flow, north section, across Highway 18 at Neche (m^3/s)	33	31
Maximum flow, main channel at Neche (m^3/s)	186	185
Maximum flow, south section, across Highway 18 at Neche (m^3/s)	133	134
Maximum flow, north section, 8 km downstream from Neche (m^3/s)	120	85
Maximum flow, main channel, 8 km downstream from Neche (m^3/s)	137	120
Maximum flow, south section, 8 km downstream from Neche (m^3/s)	97	147

Table 7 - Maximum flow comparison during Scenario 5

12.9 Scenario 6: Existing conditions with the removal of the border road

In Scenario 6, the border road and the drain along it were removed, having made the assumption that the material from the road would be used as fill for the drain.

As seen on Figure 43, the removal of the border road allows the water to flow north, but it is then held back by the next obstacles, Road 243 and Road 30.

In the East, Road 243 is eventually overtopped and water flows in a North-East direction. It would be partially held back by the next local roads (assumed less elevated than Road 243 and therefore not modelled) and would flow into the Aux Marais drainage system.

Further East (16 km East of Neche, or 8km West of Pembina) the removal of the border road allows water to flow north, and eventually to reach the Aux Marais system, but only later, at day 17.

In the West, the flow is also held back by PR 30 in Manitoba, the same way as it was held back by Highway 18 in North Dakota. Eventually it overtops PR 243 and flows into the Buffalo system.

Buffalo Creek conveys the increase in flow downstream from Altona without its banks overtopping. The dykes on both side of Buffalo Lake Channel (shown on Fig. 3) keep the flow within the creek itself.

In this simulation the Switzer ridge becomes dry and does not provide water to the area east of it, as shown by the red circle (Fig. 43).

Fig 44 shows that removing the border road only, does not change the water levels held back by CR 55.

The peak water level at Pembina, on the Red River, dropped by only 5 cm, due to the fact that the remaining roads still maintain some of the water within the Pembina flood plain instead of travelling north.

As seen on Fig 45 (top graph), the peak discharges in Louden and Rosebud coulees combined (travelling south of the Pembina River) is still 95 m^3/s (3355 cfs), close to the 102 m^3/s (3602 cfs) found in the natural conditions (Fig. 38). This shows that the removal of the border road alone would have only small effects on the flooding South of the River. The same conclusion can be drawn if we compare the flood extent south of the River in Figure 43, with the extent in existing conditions, Figure 26.

12.10 Scenario 7: Existing conditions without the border road and County Road 55

In Scenario 7 with the combined removal of the border road and CR 55, the impoundments are now created by the north-south roads, including Highway 18, and PR 30, and also by the two east-west roads, ½ mile south of the border and 1 mile north of CR 55. On the Manitoba side, PR 243 is now holding back the water instead of the border road (Fig. 46 and 47).

The major difference between Scenario 7 and Scenario 6 is that the area east of the Switzer Ridge is now completely dry (black circle Fig. 46), because it is not fed by waters running along CR 55. It is felt that this is only a modelling effect since this region was not flooded in 2006.

The increase in water level along the Tongue River at its confluence with the Pembina River is approximately 6 cm.

Similarly to Scenario 6, the peak water level at Pembina, on the Red River, dropped by only 6 cm, because the overflow south of the Pembina River is still reaching the Red River at Pembina through the Tongue River.

A comparison of Figure 48 and 45 (top graph) shows that the south overflow has now increased, and the discharge through the Pembina River main channel has decreased.

12.11 Scenario 8A: Five diversions with a total capacity of 63 m^3/s (2225 cfs)

The flooding along the Pembina River during the 2006 event is due to the fact that its main channel can carry only about 142 m^3/s (5000 cfs), or 43 % of the peak flow which was of the order of 332 m^3/s (11 725 cfs). Therefore more than half of the flow, or about 190 m^3/s (6710 cfs), has to go elsewhere across the floodplains. In the existing configuration, this flow breaks out at various locations along the river, but is contained by the roads, mainly CR 55 and the border road.

In Scenario 8A, some of this extra water which cannot be carried by the main channel was removed from the Pembina River before it overflows, and taken by channels (diversions) to the local natural drains: Hyde Park, Rosebud and Louden coulees, Buffalo creek and Aux Marais River.

Two flow capacities for these diversions were simulated:

- Scenario 8A carrying 1/3 of the excess water: 190/3 = 63 m^3/s (2225 cfs)
- Scenario 8B carrying 2/3 of the excess water: 126 m^3/s (4450 cfs)

The split between the various diversions was based on the peak flows as estimated in the “Natural conditions” Scenario 3 which can be found on Figure 38. They have been adjusted so that equal amounts of flow, at peak, would be diverted North in Manitoba, and South-East in North-Dakota, as shown in Table 8.

Diversion into:	**Peak flow in Natural conditions (m^3/s)**	**% of flow**	**% of flow**	**Diversion flow (m^3/s)**	**Diversion flow (m^3/s)**
	Scenario 3	**Scenario 3**	**Scenario 8**	**Scenario 8A**	**Scenario 8B**
Aux Marais River	39	17	17	11	22
Buffalo Creek East	80	34	18	11.5	23
Buffalo Creek West (Hyde Park)	8	3	14	9	18
Rosebud Coulee	59	25	28	17.4	34.8
Louden Coulee	48	21	22	14.1	28.2
Total	234	100	100	63	126

Table 8 - Scenario 8: Flow distribution in five diversions

All diversions were started upstream of Neche and are shown on Figure 49.

In the model, the channels for these diversions were not represented by the grid, but rather as sink-source combinations with the removal of water from the Pembina River main channel and the introduction of water at the upper end of the coulees. The simulations, therefore, provided information as to how well the natural channels could carry the extra diversion flows, and the corresponding amount of flood reduction in the Pembina flood plains.

Fig. 50 and 51 show the flood extent and the change in peak levels relative to the existing configuration. Several observations can be made:

- In general water level between the border road and CR 55 went down by about 7 cm (2.8 inches);
- Buffalo creek can absorb the extra flow over all its length, without major flooding;
- Aux Marais River shows some flooding but it is not as extensive as when the border road was removed. It is to be noted that in the simulation, the culvert at border crossing 6 was reduced to a discharge of 5 m^3/s (177 cfs) instead of 9.3 m^3/s (328 cfs) (existing conditions) because Aux Marais River was already carrying 11 m^3/s (388 cfs) from the controlled diversion. Aux Marais therefore caries a total of 16 m^3/s (565 cfs) plus some extra runoff.
- At border crossing 6, levels on the US side dropped by 9 cm (3.5 inches), which was not enough to prevent strong flow over the Switzer Ridge
- Rosebud Coulee shows major flooding similar to the previous scenarios
- Flooding along Louden Coulee is reduced
- CR 55 and the border road are still holding back a significant amount of water
- Similar to Scenario 7, the peak water level at Pembina, on the Red River, dropped by 6 cm (2.4 inches).

Figure 52 shows the discharge through the channels where the flow is being diverted. It should be noted that, in this graph, the flow in Louden Coulee includes some of the flow held back by CR 55. This additional flow results from the fact that in this simulation the culverts under the roads were not widened and the coulees were also left with their existing conveyance, therefore there is a significant overflow from the upper end of Louden Coulee which is not carried south but rather held back by CR 55.

In the next Scenarios 8C and 8D, we will assume that these coulees have been widened enough to carry the diverted flows.

12.12 Scenario 8B: Five diversions with a total capacity of 126 m^3/s (4450 cfs)

In this scenario the diversion capacities were doubled compared to Scenario 8A. Fig. 53 and 54 show much reduced flooding between the border road an CR 55 (compared with Fig. 50 or the existing conditions in Fig. 26), but at the expense of more pronounced flooding around Buffalo Creek east branch, Aux Marais and Rosebud Coulee. The flooding along these is due in part by the fact that their channels, in this simulation, were not widened to accept the extra discharge. The west branch of Buffalo Creek seems to be able to carry 18 m^3/s (636 cfs) without flooding its banks.

At border crossing 6, levels on the US side dropped a little (Fig. 55) and the duration of the flood was shortened significantly from 20 days in the existing conditions, to 9 days with the 126 m^3/s (4450 cfs) diversions. This same effect of reduction in the duration of the flood can be found almost everywhere in the floodplain between the border road and CR 55. This is similar to what was noticed with the "floodway" in Fig. 33. Note that Figure 55 shows the water level within the drain along the border. The natural ground would be at around 242.5 m elevation.

12.13 Scenario 8C: Five diversions (63 m^3/s, 2225 cfs) with widened channels

In Scenario 8C it was assumed that Rosebud and Louden Coulees had been widened and their culverts and bridges did not obstruct the extra flows coming from the diversions. This was simulated by ending the diversion flow further downstream, closer to the Tongue River. The diversions inlets and outlets are shown on Fig. 56 with the red triangles.

With the relocation of the diversion outlets, flooding shown south of the Pembina River on Fig. 56 is therefore not due to the diversion flow, but only to the overflow from the Pembina River.

Comparing Fig. 51 and 57 shows the effect of relocating the end of the diversion channel. In Fig. 51 one of the channel discharges at the upstream end of Rosebud Coulee which shows significant flooding, whereas in Fig. 57 it discharges closer to Tongue River which now shows more flooding.

Flooding along Rosebud Coulee still occurs although to a lesser extent than in Fig 50 indicating that this coulee is running at full capacity.

For Louden Coulee, the major difference with Fig. 50 is the water level north of CR 55 which is about 10 cm lower in this simulation.

12.14 Scenario 8D: Five diversions (126 m^3/s, 4450 cfs) with widened channels

Scenario 8D is similar to the previous 8C, except that the total diversion flow was 126 m^3/s (4450 cfs).

Fig. 58 and 59 show the same trends as with smaller diversion flows, but they are more pronounced:

- Water is still stored between the border road and CR 55, and behind Highway 18
- Lower end of Rosebud Coulee as well as the Tongue River show significant flooding, since this is where the diversion outlets are located
- There is a reduced flow over Switzer Ridge resulting from a level drop of about 25 cm (9.8 inches) both east and west of the ridge.
- More flooding around Aux Marais and Buffalo due to the increased diversions into these channels.

12.15 Scenario 9: Three diversions into Buffalo Creek and Aux Marais River

In this scenario only three diversions (see Fig. 60) are implemented to carry water away from the Pembina River main channel, and relocate it as follows:

- to the two branches of Buffalo Creek, north of the border, and
- to the existing drain along the border.

In this simulation it is assumed that this border drain was the same as in the existing conditions with the same depth and width, but the local North-South roads leading to it in North Dakota would be lowered over a length of about 400 m (1312 feet), so that they would allow water to flow along the border without restriction. This change was applied to four local roads and Highway 18.

At crossing 6, the border road was lowered to natural ground level over a distance of 150 m (492 feet) to allow all the flow along the border to be diverted north into Aux Marais River.

The diversion discharges were similar to Scenario 8A, totalling 63 m^3/s:

- Buffalo West branch (Hyde Park Coulee): 20 m^3/s (706 cfs)
- Buffalo East branch : 20 m^3/s (706 cfs)
- Border drain: 23 m^3/s (812 cfs)

In this scenario Aux Marais River carries a peak flow estimated at 69 m^3/s (2437 cfs) corresponding to the 23 m^3/s from the diversion plus the natural overflow coming from the break-outs of the Pembina. This explains the heavy flooding along Aux Marais River. There is no flow over the Switzer Ridge since the border road had been opened (see Fig. 61, 62).

Since most of the Pembina overflow travels in an eastern direction, Buffalo Creek carries only the 40 m^3/s diversion flow through its two separate branches, with some flooding.

12.16 Scenario 10: Five diversions (63 m^3/s) with the lowering of County Road 55

This scenario is a combination of Scenario 8A with 5 diversions and Scenario 5 with the lowering of County Road 55. It was thought that a combination of controlled diversions and lowering of roads would be best for minimizing flooding, by reducing the amount of water being spread over the land and reducing the amount of storage held by the roads. It is to be understood that “lowering of roads” is equivalent to providing large culverts under the road, as often as required, to allow water to travel from one side to the other.

Fig. 63 shows that the water held back by the road is now overloading Louden Coulee and Tongue River (red circles) but at the same time relieving the flooded area north of the Pembina River (black circle). In these conditions the peak flows were estimated at:

- Lauden Coulee: 55 m^3/s (1942 cfs)
- Rosebud Coulee: 80 m^3/s (2825 cfs)
- Buffalo Creek: 21 m^3/s (742 cfs)
- Aux Marais: 18 m^3/s (636 cfs)
- Pembina main channel: 119 m^3/s (4202 cfs)

A comparison of Fig.64 with the corresponding Figure 42 (lowering CR55 without the diversions) shows a net decrease of levels along the border of the order of 10 cm, with a slight increase along the Tongue River.

12.17 Scenario 11: 2009 Flood - Five diversions with the lowering of County Road 55

In Scenario 11, the same conditions were used as with Scenario 10 but the 2009 flood hydrograph was applied at Walhalla instead if the 2006 hydrograph. This hydrograph has a peak flow at Walhalla of 458 m^3/s (16 174 cfs) instead of 362 m^3/s (12 784 cfs). For testing the 2009 flood, Scenario 10 was selected because it seems that a combination of controlled diversions and lowering of roads would be the best approach to minimize flooding. In order to compare scenario 10 and 11, the same topography was used, including the un-eroded Switzer ridge.

Figure 65 shows the 2009 event in the existing conditions and Figure 66 shows the event with the diversion in place and the lowering of County Rd 55. Along the border, flood extents are similar, but depths have been decreased by 5 to 10 cm (2 to 4 inches).

On the south side, Rosebud, Louden Coulee and Tongue River show flooding similar to the 2006 event (compare Fig. 66 with 63).

On the Red River, the changes in peak levels, compared to existing conditions, are negligible (3 cm (1.2 inch) drop at Pembina, 2 cm (0.8 inch) at Emerson).

The efficiency of Scenario 11 seems identical between the 2006 event (Figure 64) and the 2009 event (Figure 67).

13. Conclusions and recommendations

A total of ten scenarios with five variations were simulated in an attempt to understand the flooding process from the Pembina River and try to reduce it through topographic and infrastructure adjustments. None of the scenarios appears to provide full protection for a 2006-type flood since none were able to prevent flooding completely but could only reduce it in some locations, and exacerbate it in others.

If, instead of the large 2006 flood event, a smaller event had been chosen, with a peak flow of the order of 200 m^3/s (7000 cfs), flooding shown on the figures for Scenario 8 would have been minimal and the diversions would have appeared much more effective, since flooding due to break-outs from the Pembina main channel would have been small. But flooding would have still occurred south of the border, at the outlets of the diversions, since the existing drainage network is not designed for these kinds of discharges.

These scenario simulations have shown different aspects of the problem.

- The first scenario with set-back dykes would of course be the most effective since they would hold back all waters and prevent their spreading. If the dykes were far enough from the river, their height would be minimal, but the detailed design of the dyke configuration could be difficult to configure as it crosses the local drains and enclose some of the fields.

- In the present configuration, flooding is held back by a network of roads, mainly CR 55, Highway 18 and the road along the border, and also by smaller roads. The lowering of these roads (Scenarios 4, 5, 6, 7 and 10) would transfer the water from one area of the floodplains to another, therefore lowering water levels where it was stored behind the roads, but increasing water levels and therefore increasing flooding, further downstream on the other side of these roads.

- In Scenarios 2, 8, 9, and 10 the principle of flood mitigation was to divert water by removing it from the Pembina main channel and carry it to another place within the region. These diversions reduce the amount of flooding (the larger the diversion, the larger the flood reduction); but they are only effective if:

    - enough water is removed, otherwise break-outs still occur and their water is still stored behind the elevated roads, and if
    - at the downstream end of the diversions, where the water is taken to, channels have enough capacity to convey the extra flow.

- CR 55 and the border road play a major role in storing the overflows. Between these two roads, water levels are controlled not as much by the amount of flow over the fields but by the elevation of the roads which act as weirs.

- One of the most positive aspects of the simulations relates to the duration of the flooding with diversions in place. With the diversions as tested, break-outs still take place, but with a smaller volume of water being dispersed over the fields providing a much reduced flood duration. In some cases the reduction could be by more than a week.

- The scenarios tested did not affect significantly flood levels along the Tongue River since most of this water was coming from the Red River and not the Pembina River.

- The diversion of water from the Pembina River into Aux Marais generally reduced the levels on the Red River at Pembina by about 5 cm (2 inches). This change occurred at the expense of more flow getting into the Red River from Aux Marais. The present model could not simulate the level change on the Red River because it was located too close to the model boundary.

- In the natural conditions run, the same conclusion as above would apply. Since less water is conveyed through the Pembina River, there would be a lowering of levels at Pembina and Emerson (15 cm (6 inches)), a lesser lowering at Letellier (confluence with Aux Marais River) and no change near the confluence with Buffalo Creek since flows would then be identical with the existing conditions, except for a change in timing.

Recommendations

- Following these simulations it is felt that a combination of controlled diversions and lowering of the roads should be investigated with the model in more detail. The controlled diversions will reduce the amount of water being spread over the fields and the flood duration, while the lowering of the roads will reduce the amount of storage, therefore reduce the flood extent.
- Installing larger culverts under the roads would have the same effect as "lowering" the roads, while having a better control on where the water is travelling. These culverts must discharge into existing drains or new channels, with adequate capacity, so that new flood damages are minimized. These new simulations would be more detailed than the one tested in this study, with roads/culverts being modified at specific locations, rather than in generic terms. In particular it is suggested to simulate the installation of large culverts under Highway 18, the border road and CR 55 with new drains leading to and from them.
- The drains and four main channels, Aux Marais River, Buffalo Creek, Rosebud Coulee and Louden Coulee coulees were represented in the model with a triangular section 60 m across with the centre depth as specified by the Lidar data. The conveyance of these channels should be compared with the flows carried by a rectangular and narrower section. This would help in assessing the true extent of the large flooding found in the Rosebud Coulee and the upstream end of Aux Marais. This comparison could be done numerically with the preparation of a small model and verified, if possible, with a site flow measurement.
- The Aux Marais River was prepared only from a 5m LiDAR grid. It is recommended that the original 1m LiDAR grid be used, if available, so that a better representation of this river could be prepared in the model.
- On the Red River, in order to improve the simulation, the flow passages east of Pembina and Emerson should have a more accurate representation for all the local bridges. The west overflow, the course of which was not represented as such in the model, should also be prepared, since this may have an influence on what is happening on the east side of the Red River.
- If a large amount of water is to be diverted into Buffalo and Aux Marais drainage systems, it is recommended that the model be extended further downstream at least to Morris, to be able to assess the effect of these diversions on the Red River, close to Letellier and St Jean Baptiste.
- We do not think it is necessary to extend the model upstream to the next USGS hydrographic gauge (Drayton) since this would require an extension of the 2D model to the south which would make it unnecessarily large. It is felt that the existing calibrated 1D models should be used to obtain the Telemac upstream flow boundary conditions.

14. Acknowledgment

We would like to thank Gordon Bell from AESB/AAFC and Alf Warkentin from MWS for providing the valuable data required for this project, in particular the Red River bathymetric survey, the flows East of Pembina and Emerson, and all the photos during the 2009 flood.

15. References

[1] *Preparation of a two-dimensional Hydrodynamic Model of the Lower Pembina River Flood Plains,* Canadian Hydraulics Centre, National Research Council, Controlled Technical Report CHC-CTR-093; July 2009

[2] *Development of a Lower Pembina River Mike 11 Model*, UMA Engineering Ltd, June 2008. Prepared for Agriculture & Agri-Food Canada

[3] *Hydrodynamic modelling of the Lower Pembina River,* Water Management Consultants, March 2000; prepared for the International Joint Commission.

[4] *Pembina River Study, Structure Crossing Inventory*, for International Joint Commission; Houston Engineering Inc. Maple Grove, MN, June 2006

[5] *Pembina River Basin Reconnaissance Study,* Section 905(b) Analysis, (WRDA of 1986); USACE, St Paul District, January 2007; Draft

16. Simulation run identification

Scenario	Run	Geometry file	Description
	G39 2006 I8 2006	G22_2006 I2	Calibration Existing conditions 2006 flood Existing conditions 2006 with full Buffalo grid
	G40 2009 I17 2009	G23_2009 I8	Verification Existing conditions 2009 flood Existing conditions 2009 with full Buffalo grid
1	G21	G14_2006	Set-back dykes 850 m wide
2 A	G24 2000 G28 3000	G18_2006	Floodway discharging into Red R north of Pembina, south of the border Q=2000, 3000 cfs (57, 85 m3/s)
2 B	G29 3000	G18_2006	Floodway discharging into Aux Marais R, Q= 3000 cfs (85 m3/s)
3	I4	I1	Natural conditions South and North
4	G33	G20	Without the east-west road located on the north side of the Pembina River, starting about 1 1/2 mile west of HW #18 (Neche). It is located 1/2 mile south of the border
5	G34	G21	existing conditions with the removal of County Rd #55
6	I6	I3	Existing conditions without the border dyke
7	I7	I4	existing conditions with the combined removal of the Border dike and County Rd. #55
8A 8B 8C 8D	I9 I10 I12 I13	I2	5 diversions (332-142)/3=63 m3/s total capacity 5 diversions (332-142)* 2/3=126 m3/s total capacity 5 diversions 63 m3/s Reinjection Louden Rosebud downstream 5 diversions 126 m3/s Reinjection Louden Rosebud downstream
9	I11	I5	3 diversion into Hyde Park - Buffalo - border ditch 63 m3/s total capacity
10	I15 2006	I6	5 diversions 63 m3/s total capacity with removal of County Rd #55
11	I16 2009	I7	Same as Scenario 10 with 2009 flood

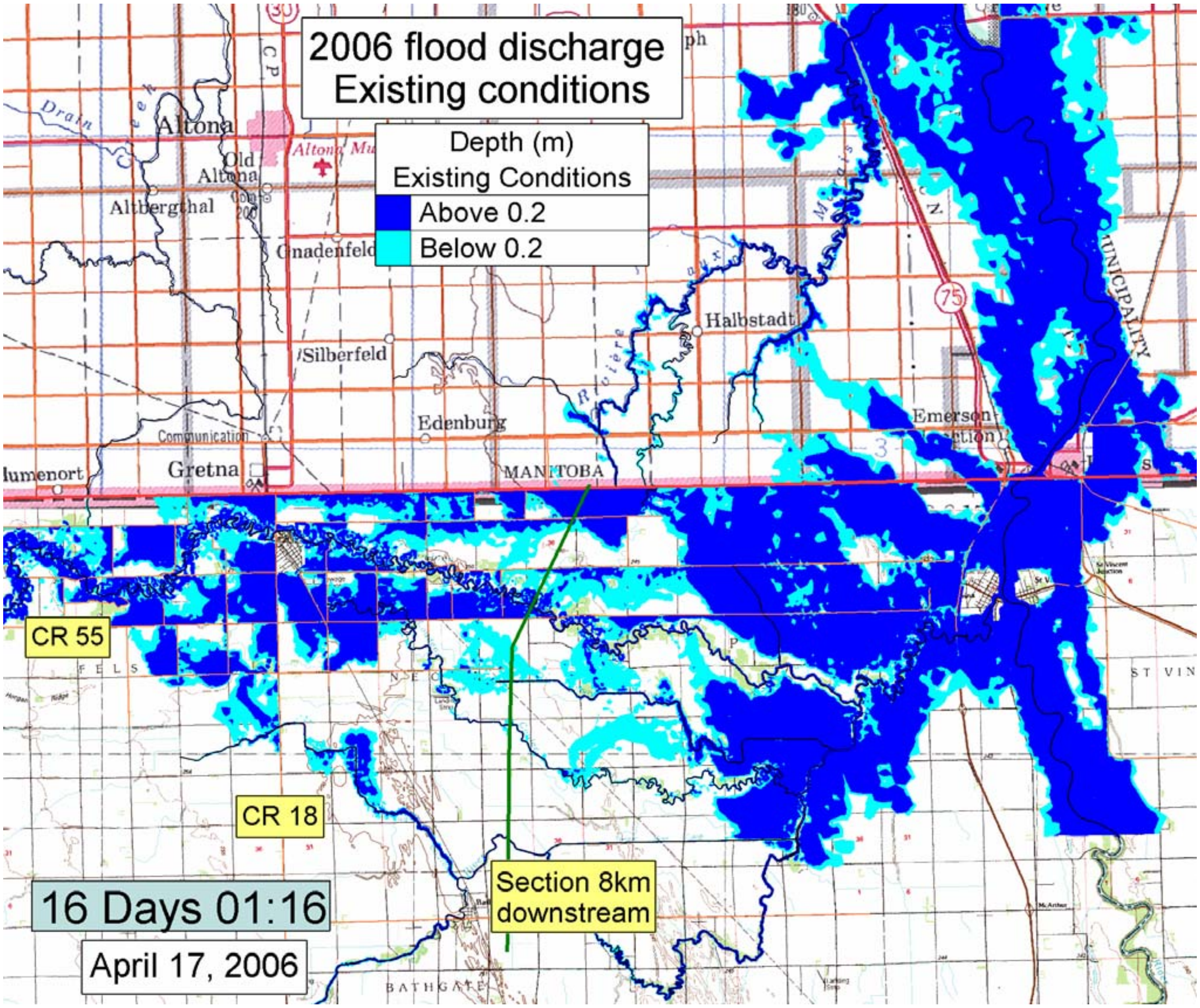


Figure 26 - Flood extent during the 2006 flood (existing conditions)

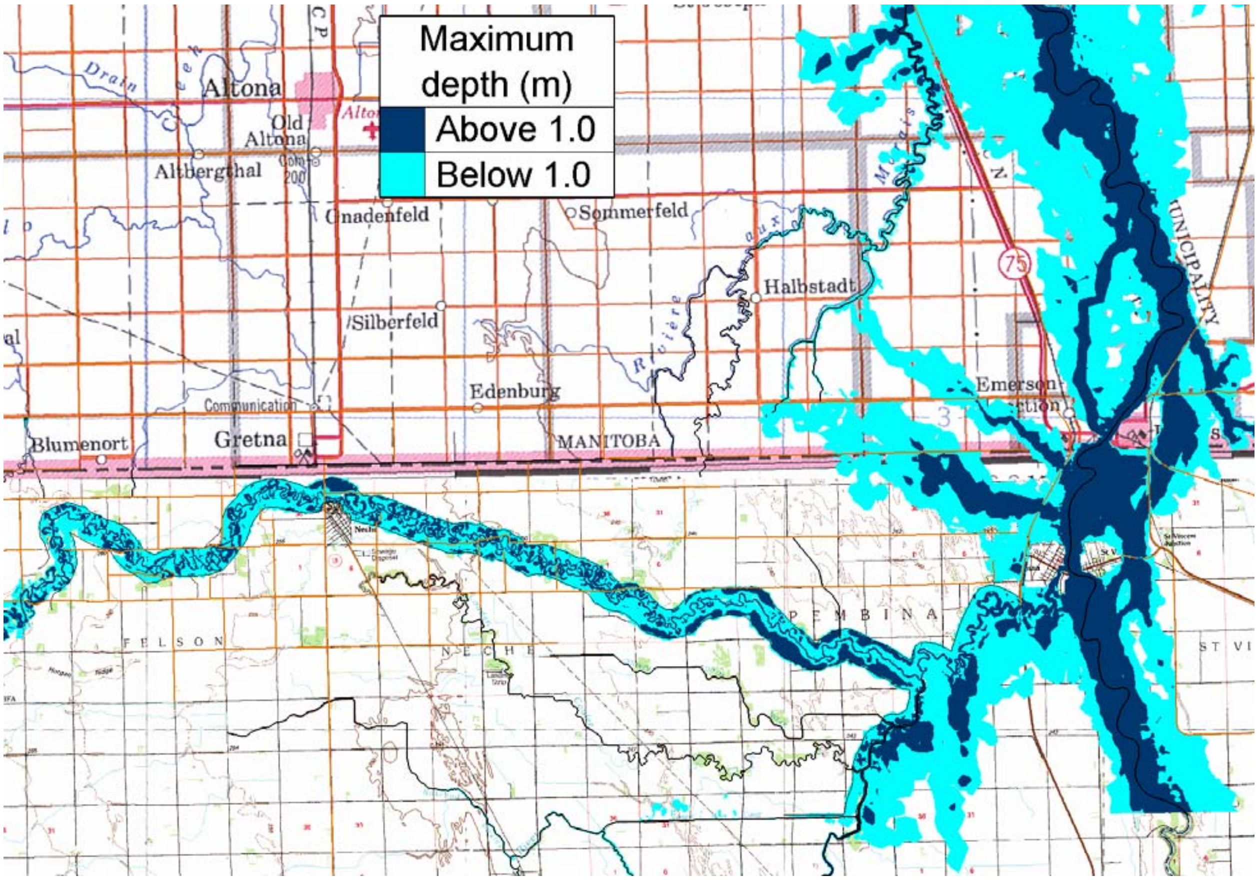


Figure 27 - Scenario 1: Maximum flood extent with set-back dykes

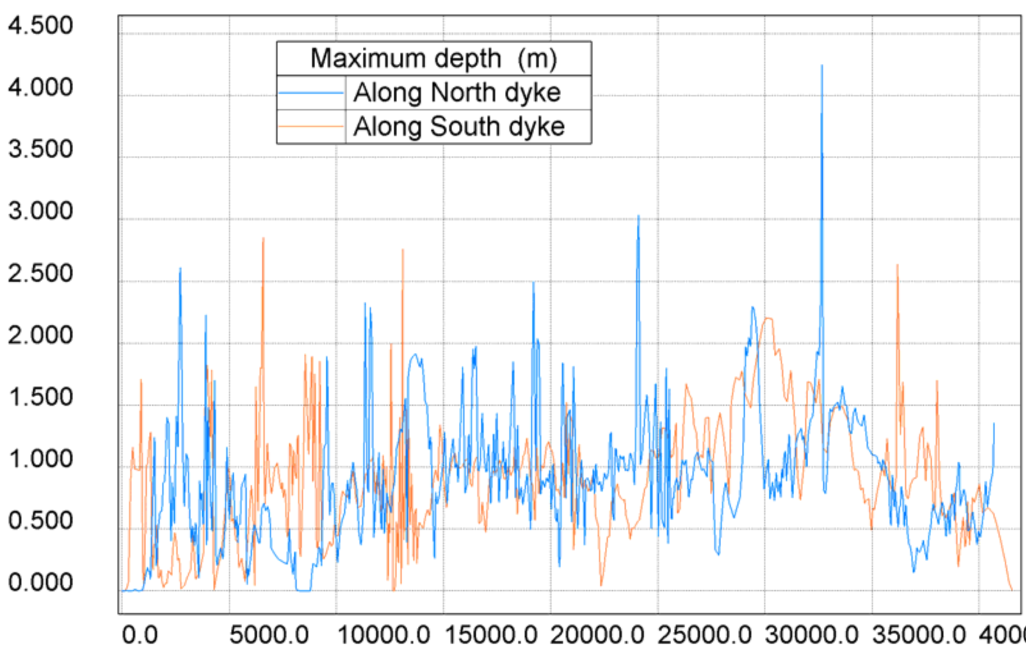


Figure 28 – Scenario 1: Maximum depth along the dykes (meters)

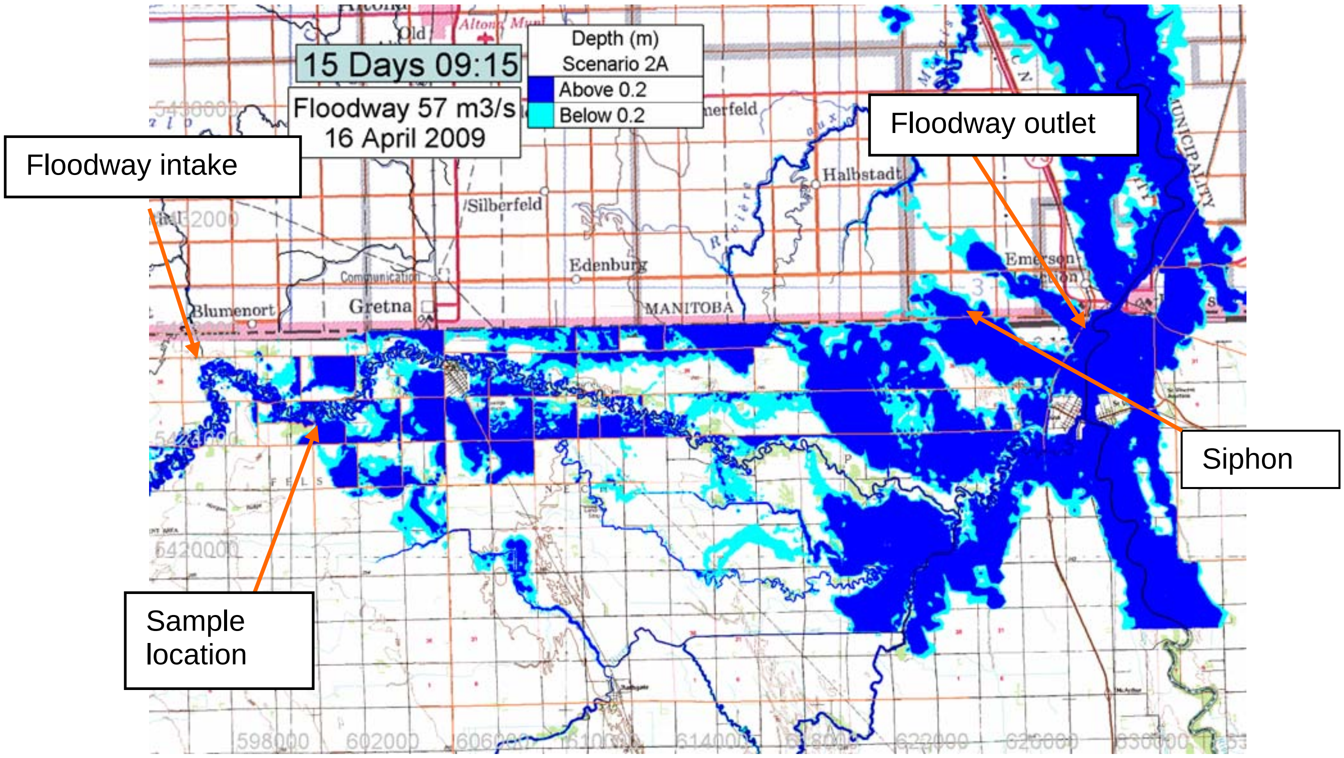


Figure 29 - Scenario 2A: Inundation map with floodway (2000 cfs)

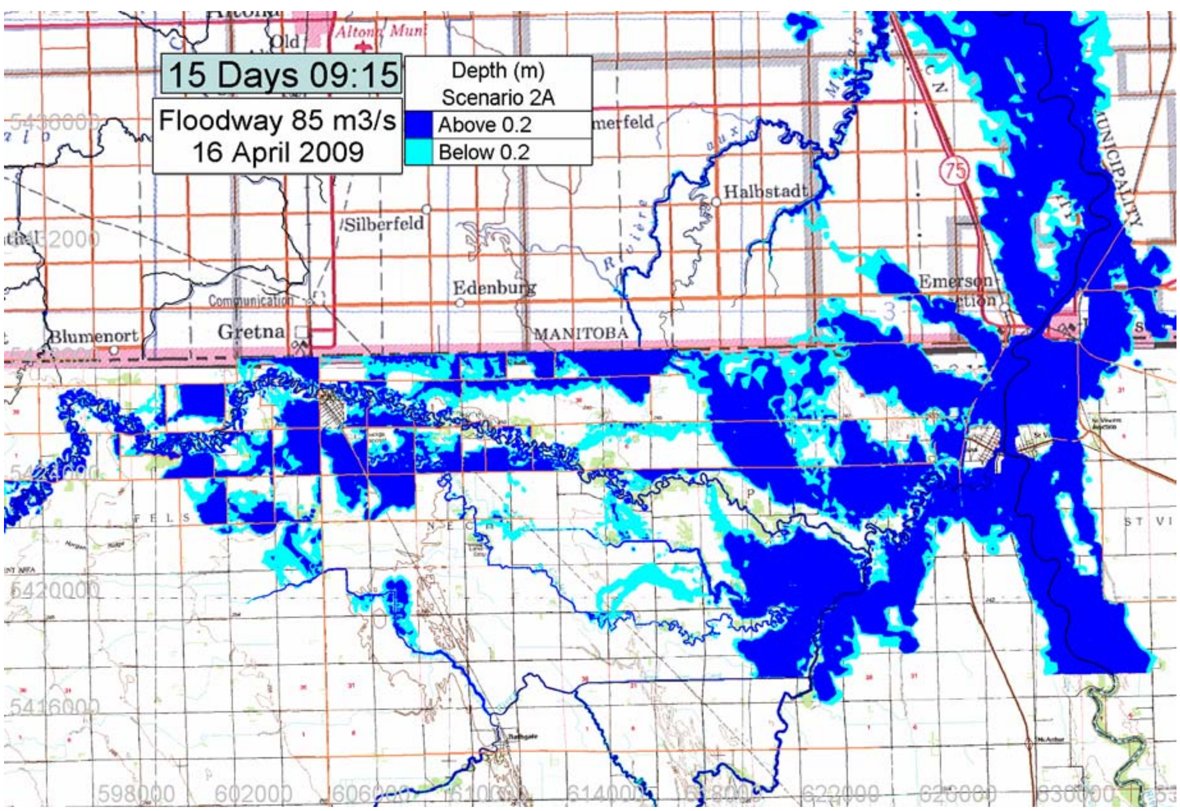


Figure 30 - Scenario 2A: Inundation map with floodway (3000 cfs)

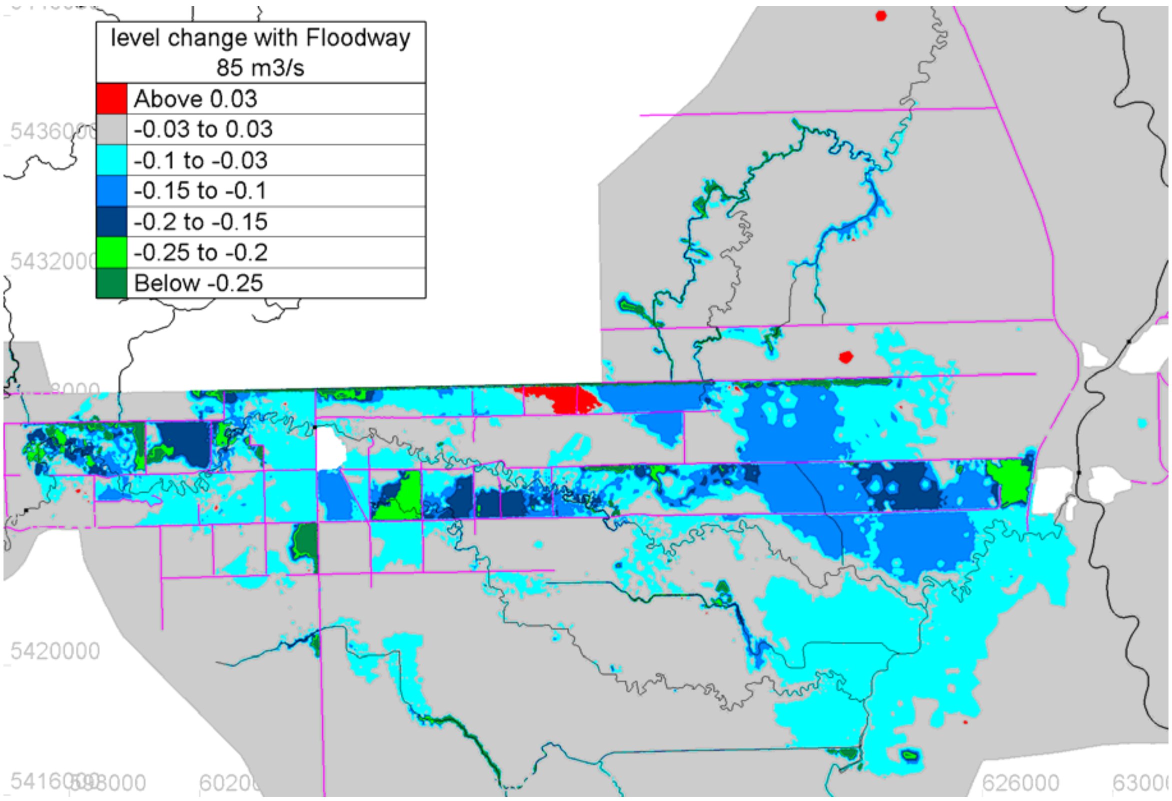


Figure 31 – Scenario 2A: Level drop with a 3000 cfs floodway into Red River

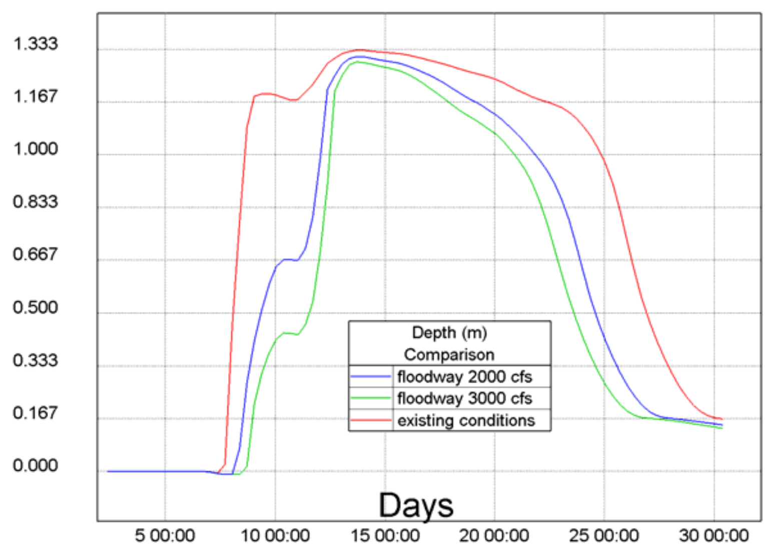


Figure 32 - Scenario 2A: Example of depth variation (meters) with the floodway (location is shown on Fig. 29)

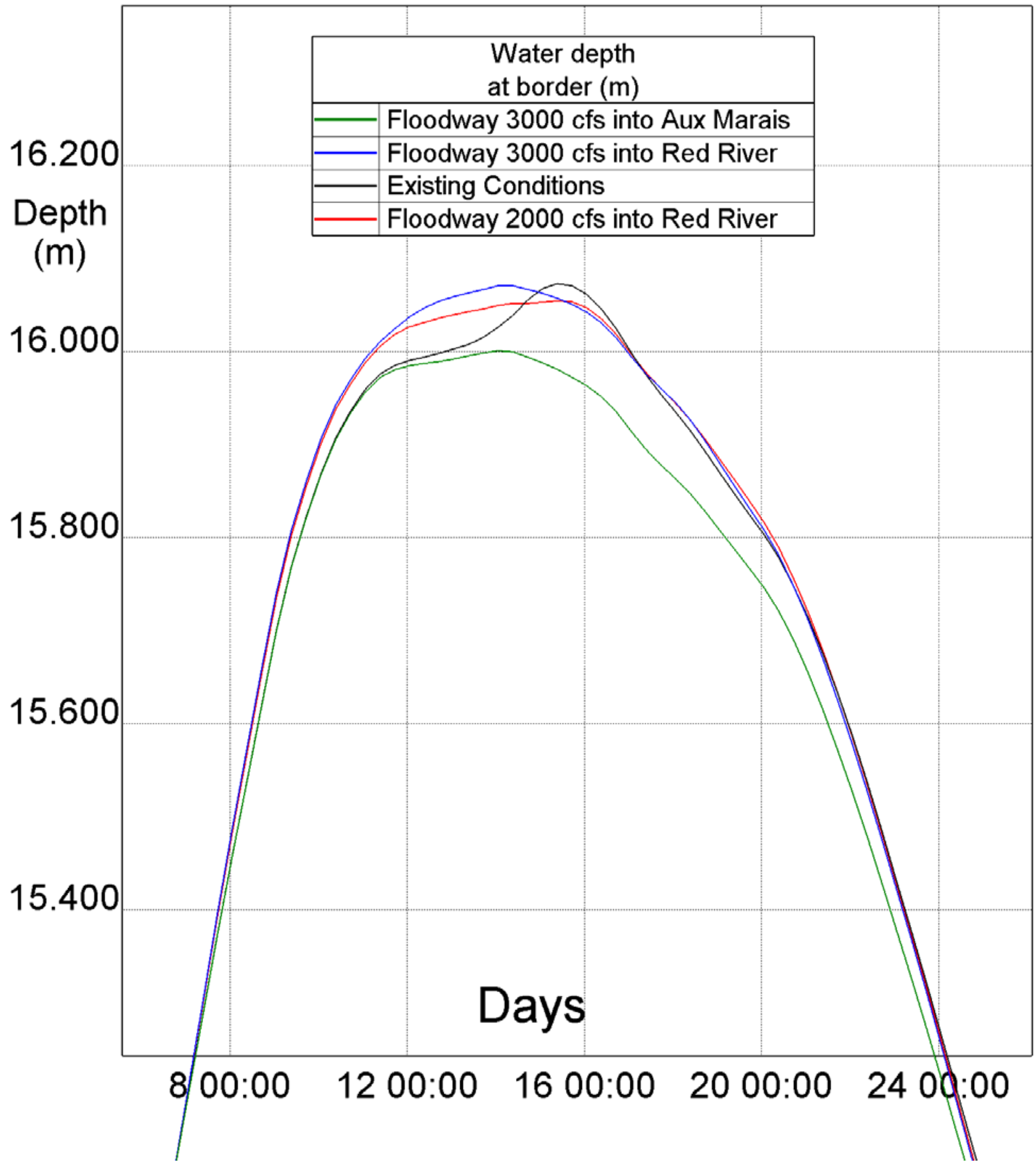


Figure 33 – Scenario 2A, 2B: Depth variation on Red River at the border with Floodway discharging into Red River or Aux Marais

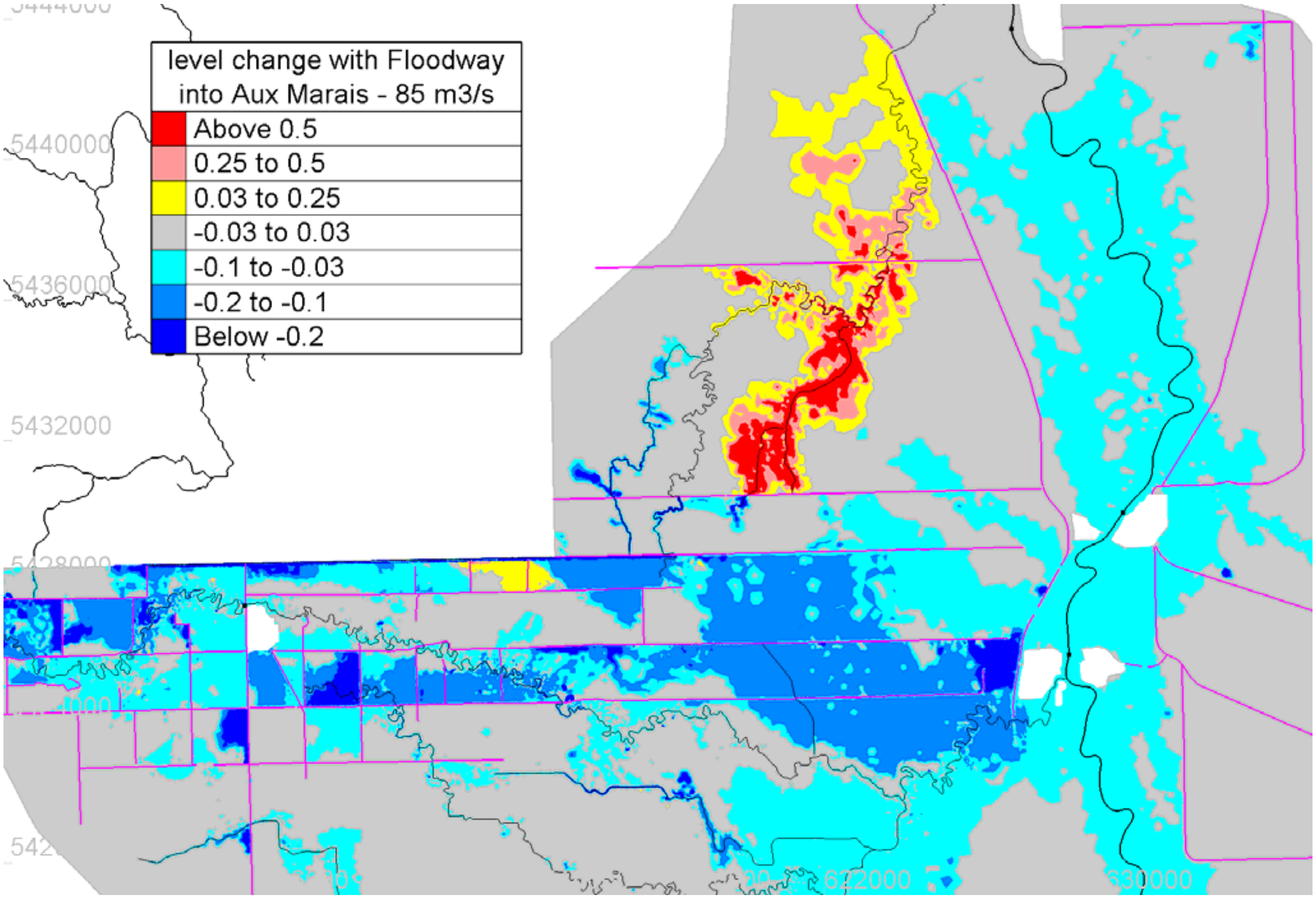


Figure 34 – Scenario 2B: Level change (meters) with a 3000 cfs floodway into Aux Marais

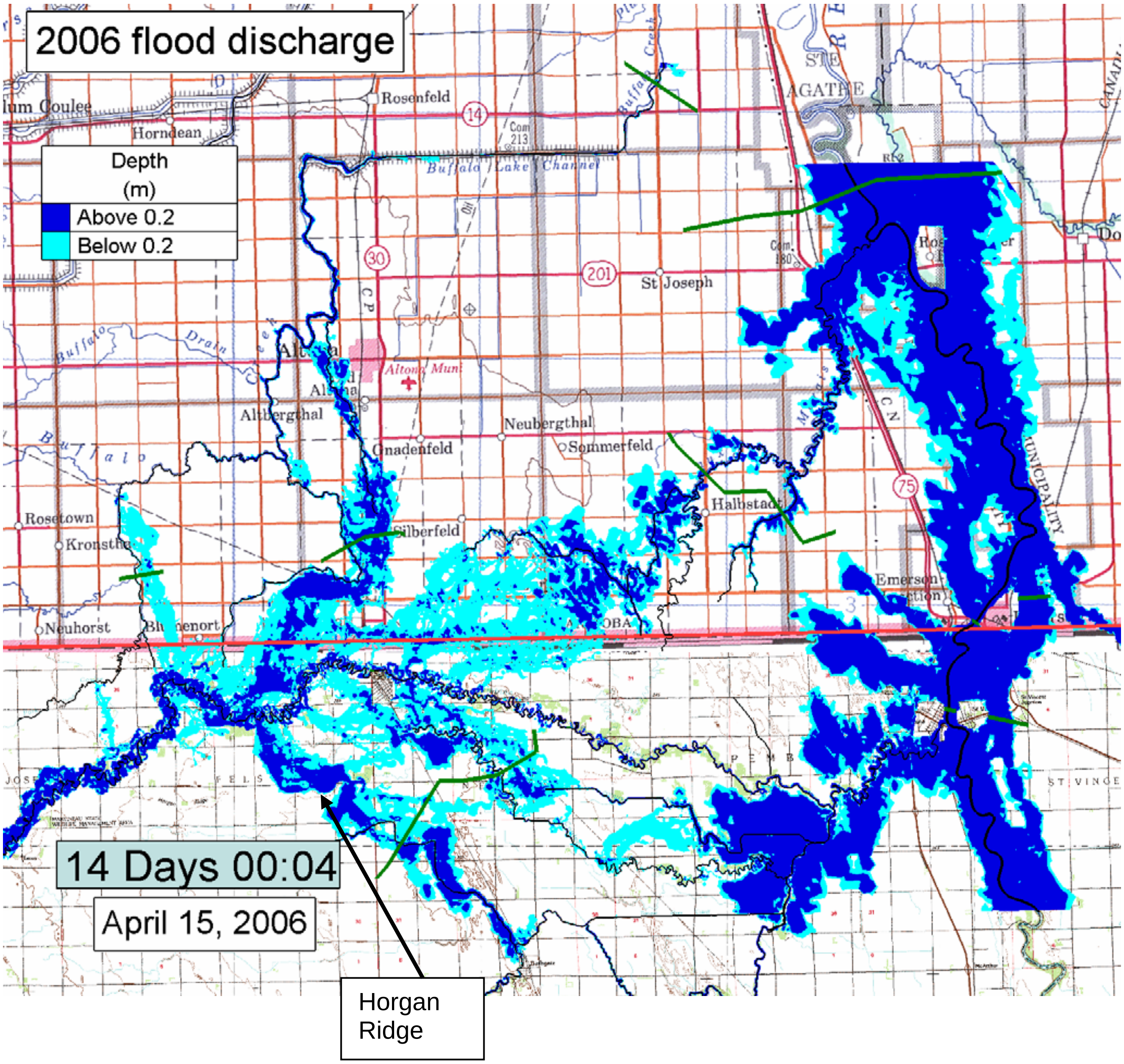


Figure 35 – Scenario 3: Flood extent in natural conditions, 14 days after start of flood hydrograph

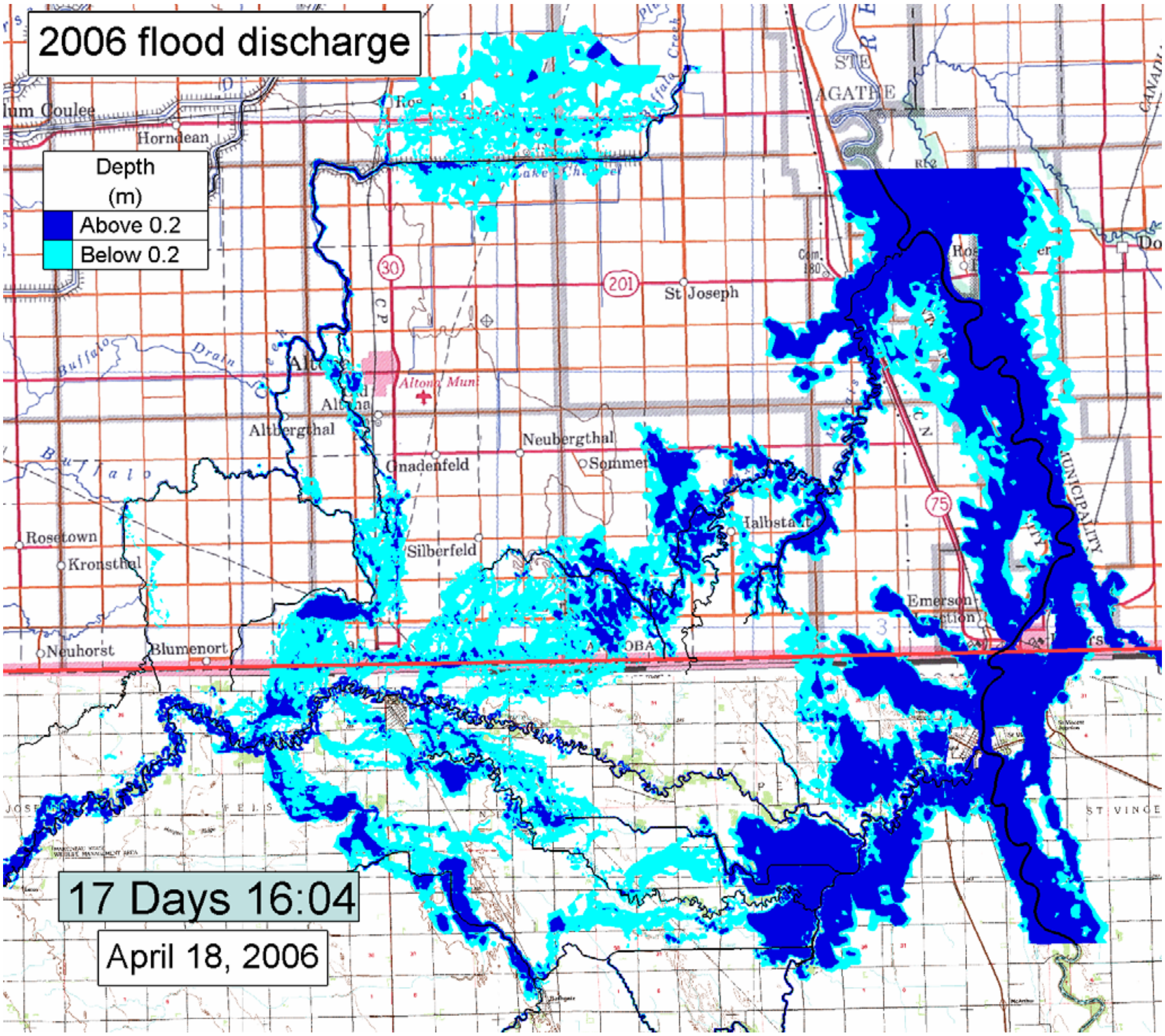


Figure 36 – Scenario 3: Flood extent in natural conditions, 17 days after start of flood hydrograph

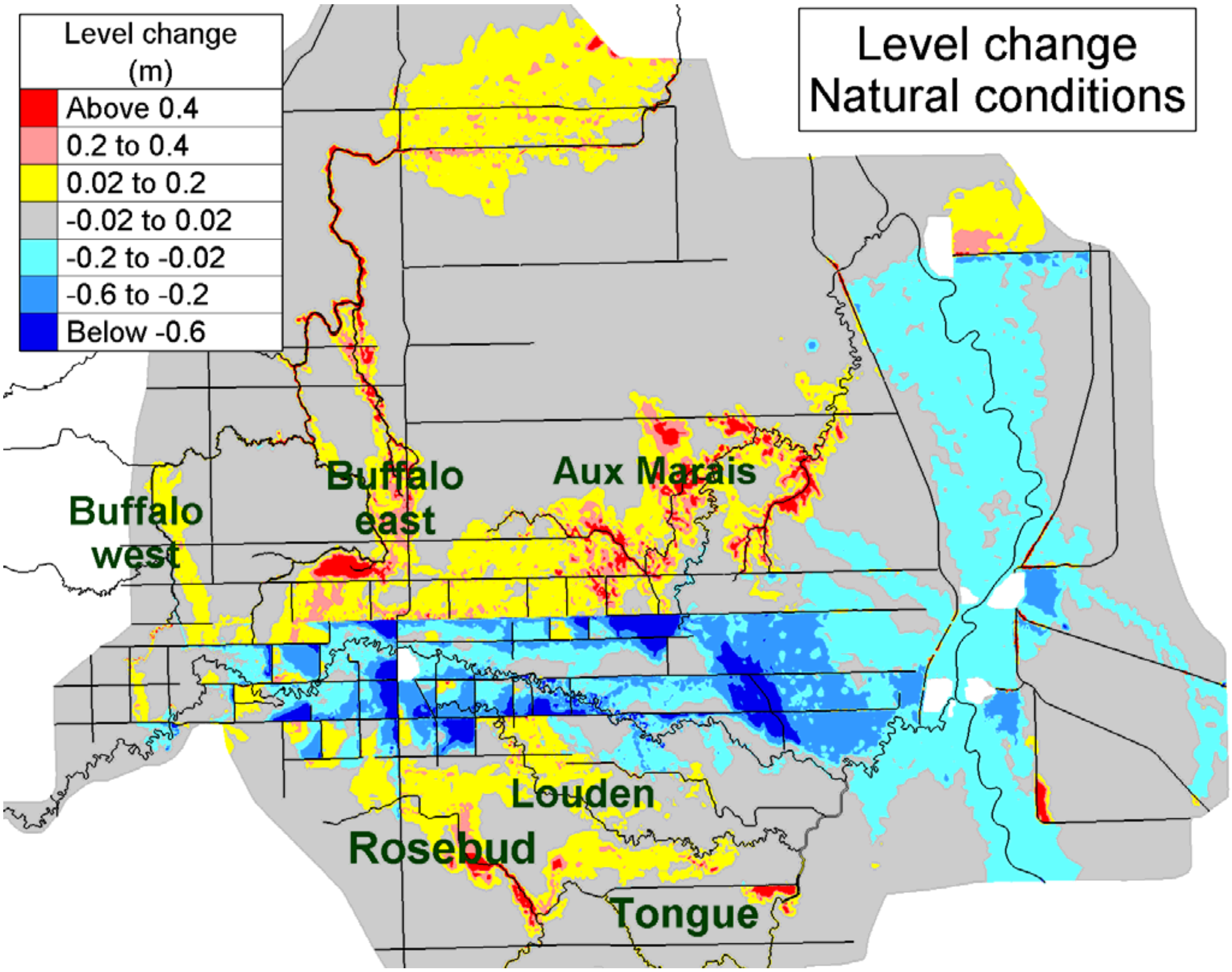
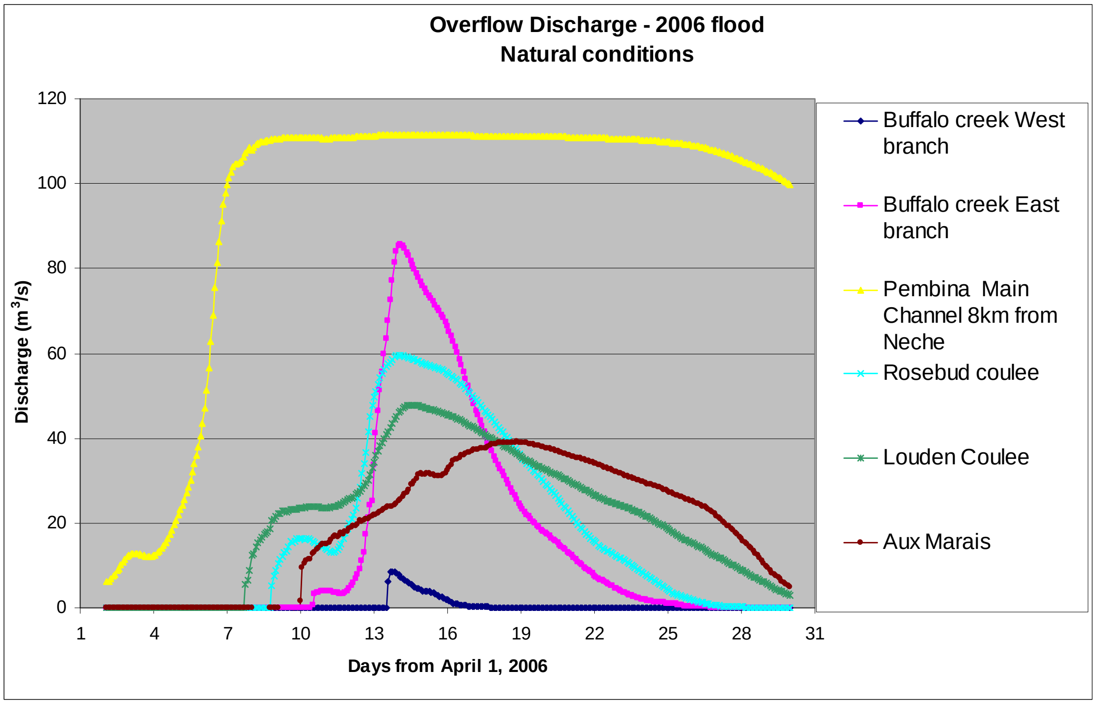


Figure 37 - Scenario 3: Change in maximum water levels in natural conditions compared to existing conditions



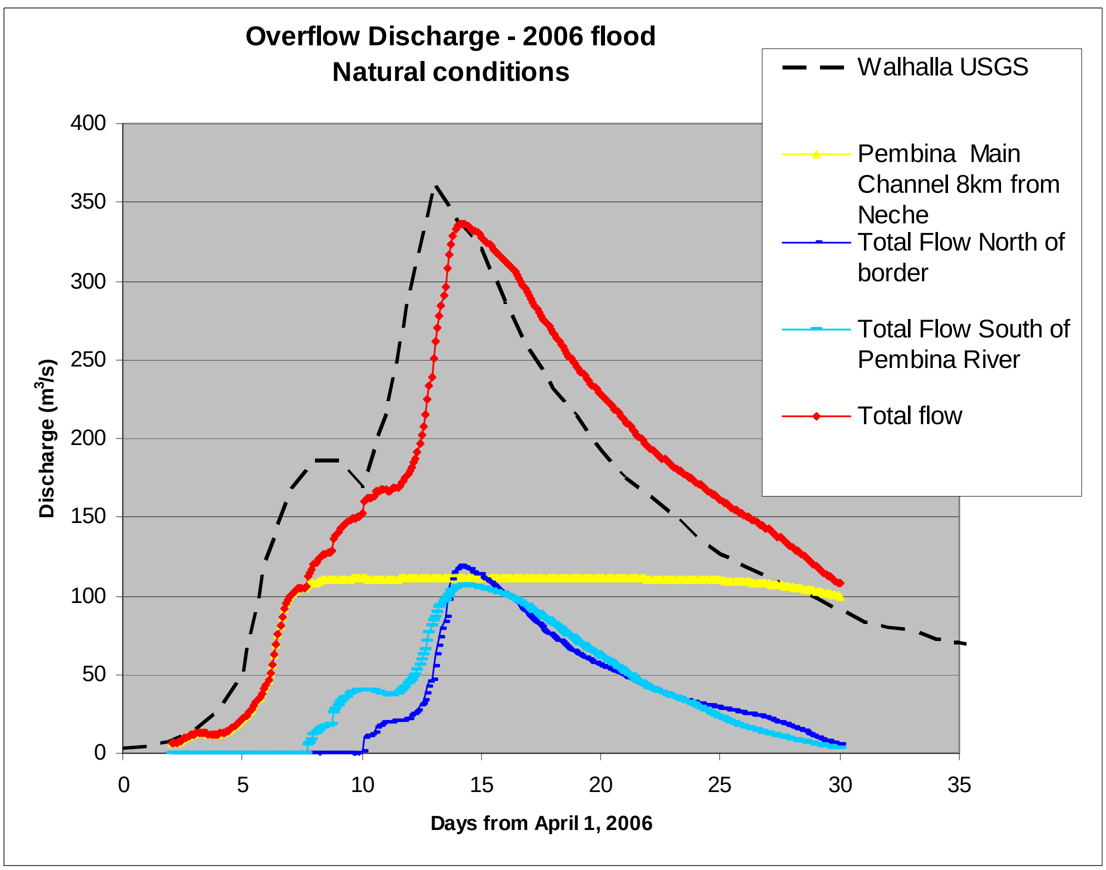


Figure 38 –Scenario 3: Discharge through various channels, during Natural Conditions

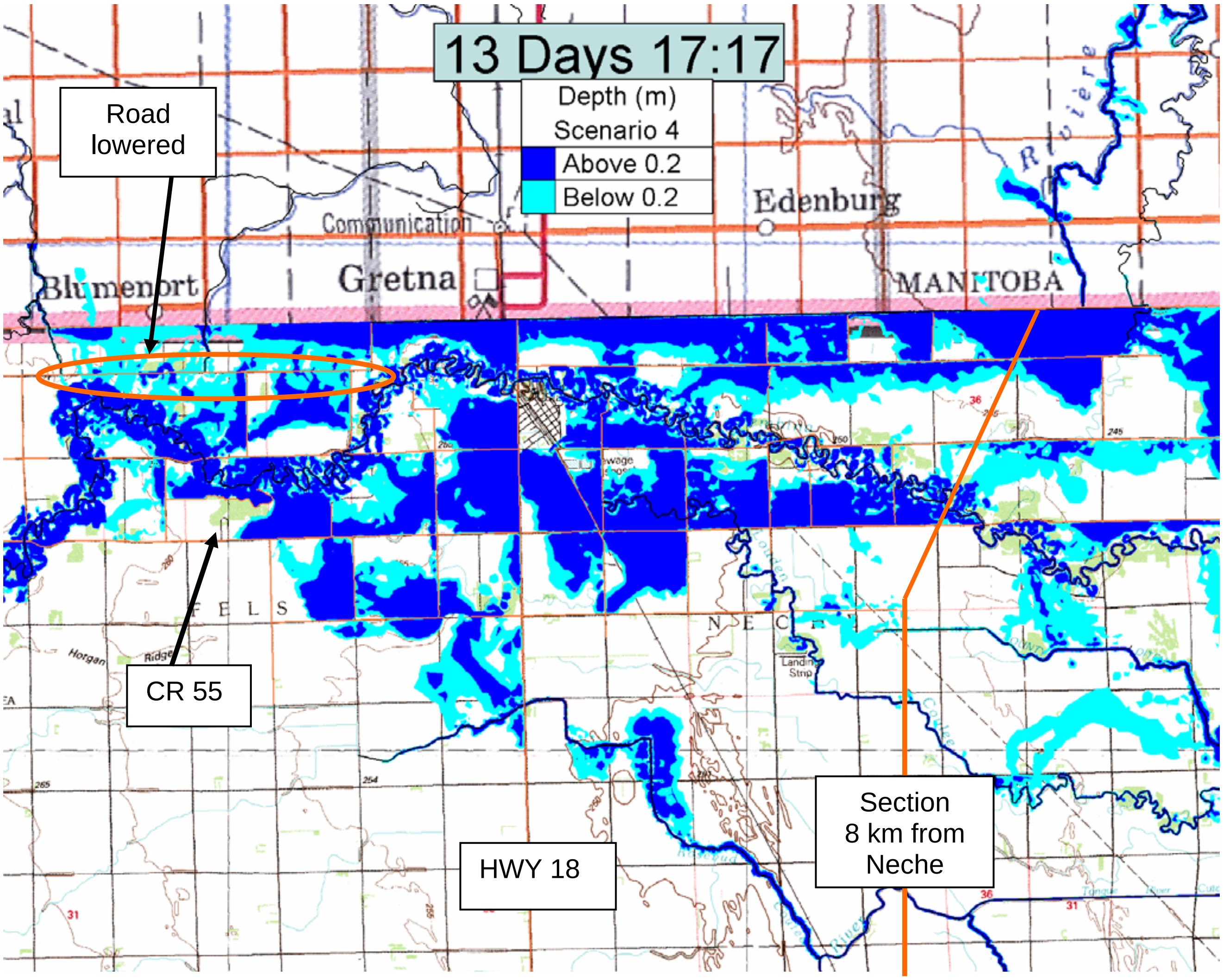


Figure 39 - Scenario 4: Flood extent after removal of road 1/2 mile south of border

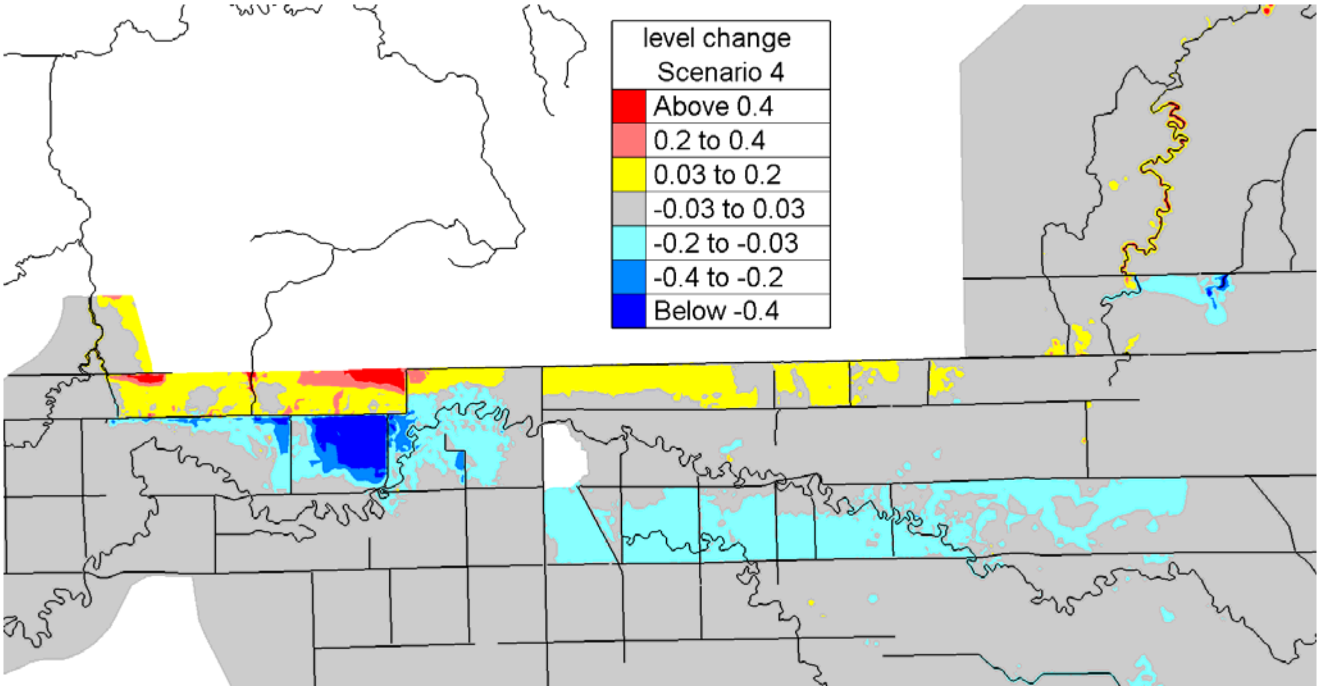


Figure 40 - Scenario 4: Change in maximum levels compared to existing conditions

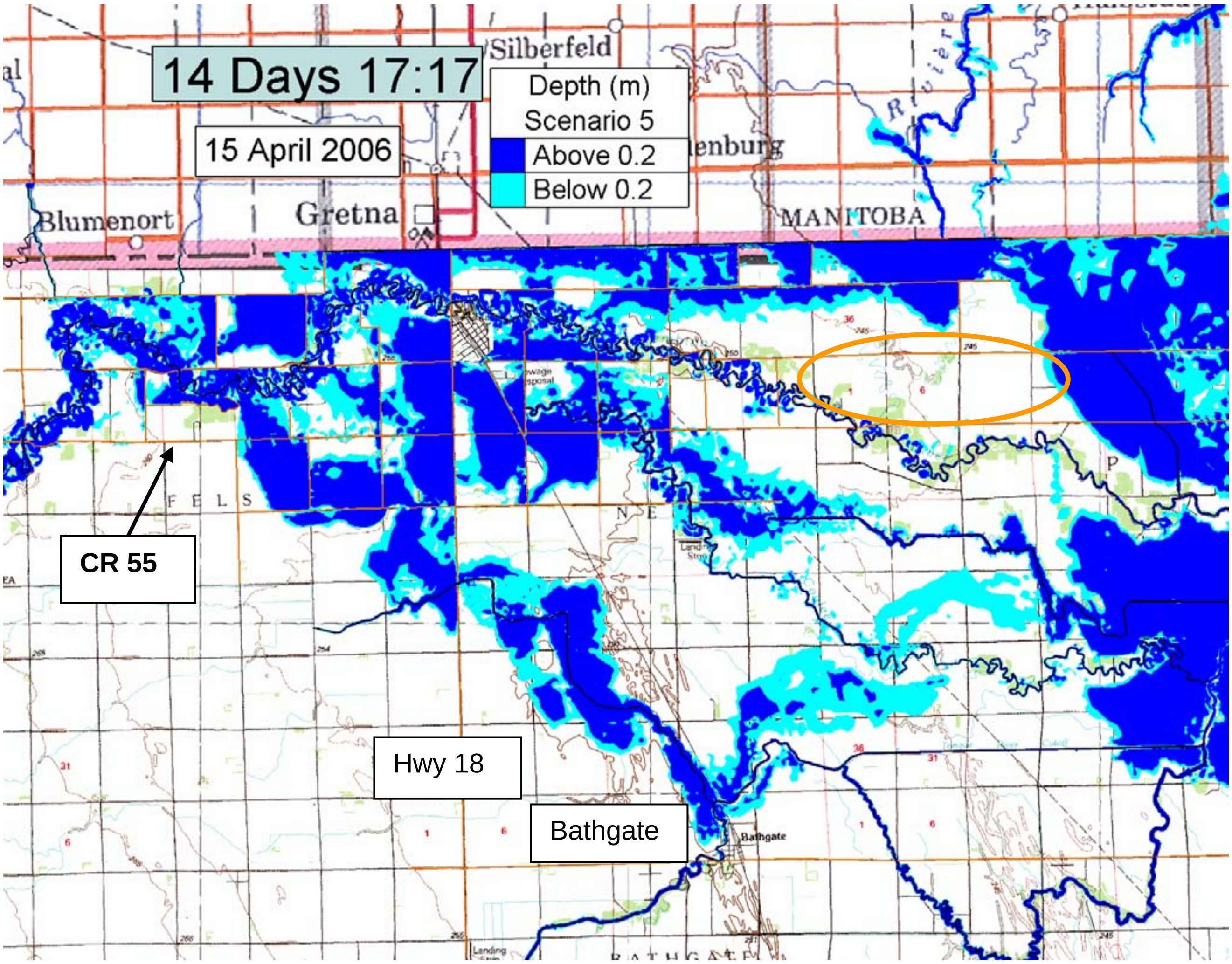


Figure 41 – Scenario 5: Flood extent on April 15, after lowering County Road 55

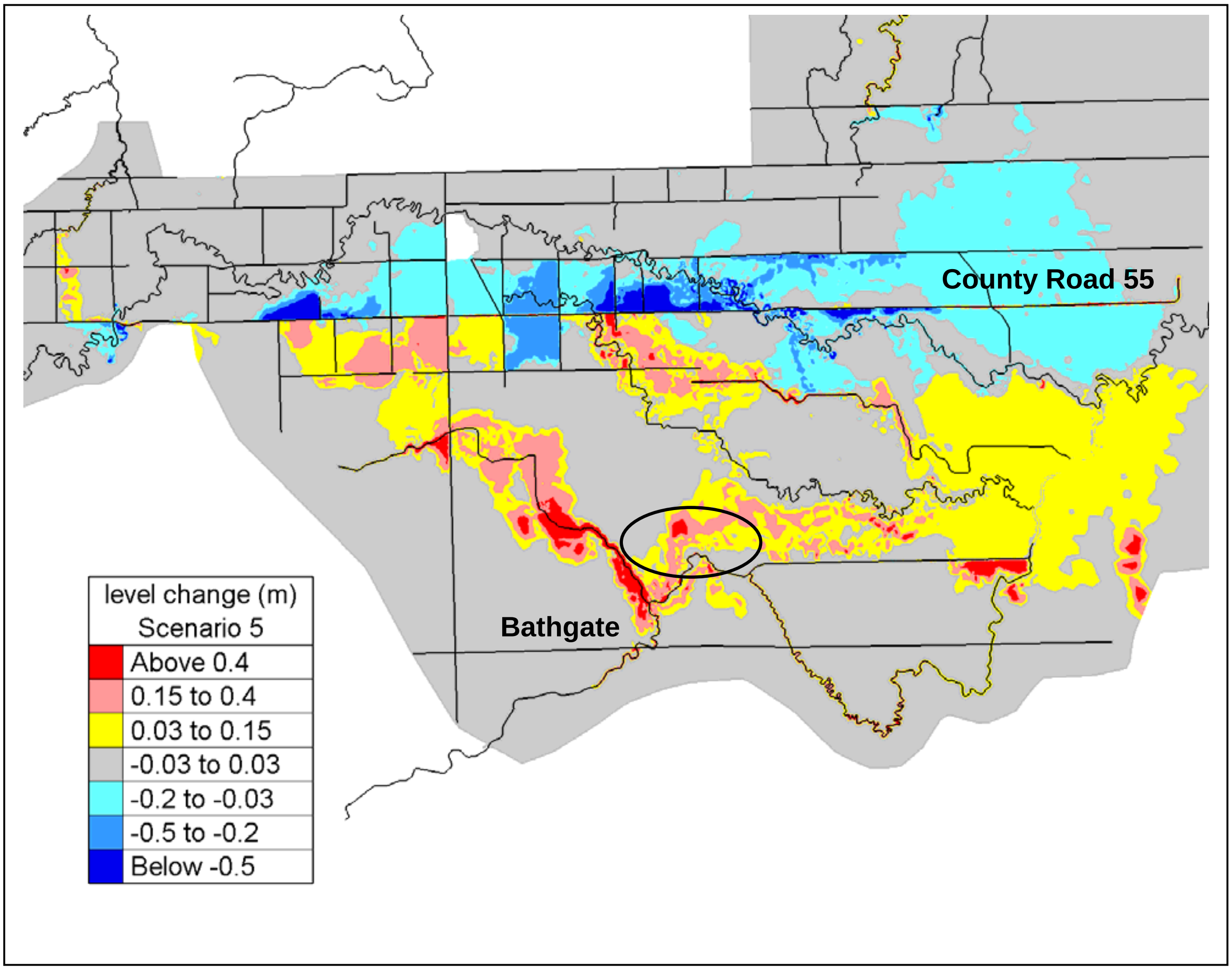


Figure 42 - Scenario 5: Change in maximum water levels after lowering of County Road 55, compared to existing conditions

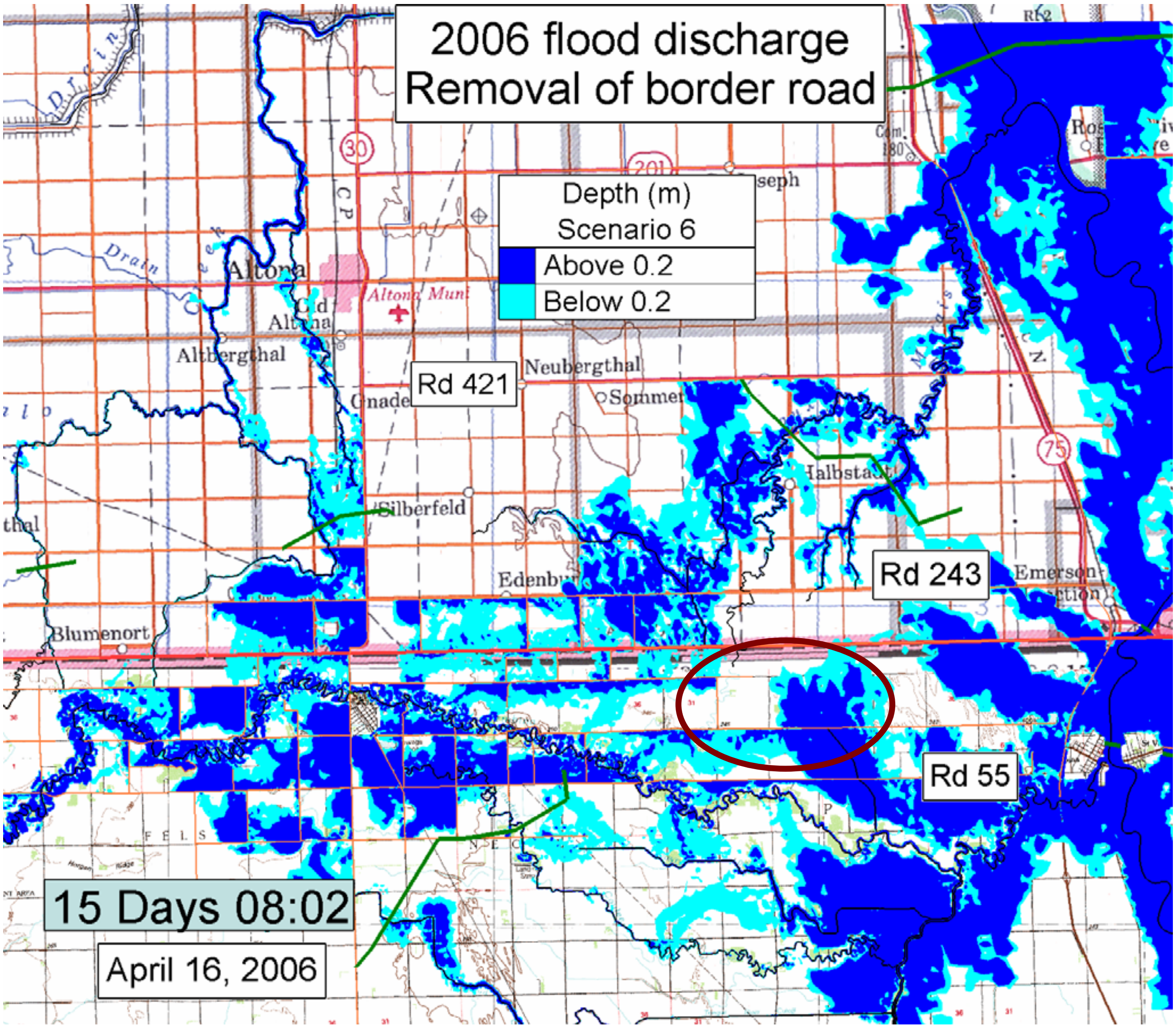


Figure 43 - Scenario 6: Flood extent without the border road

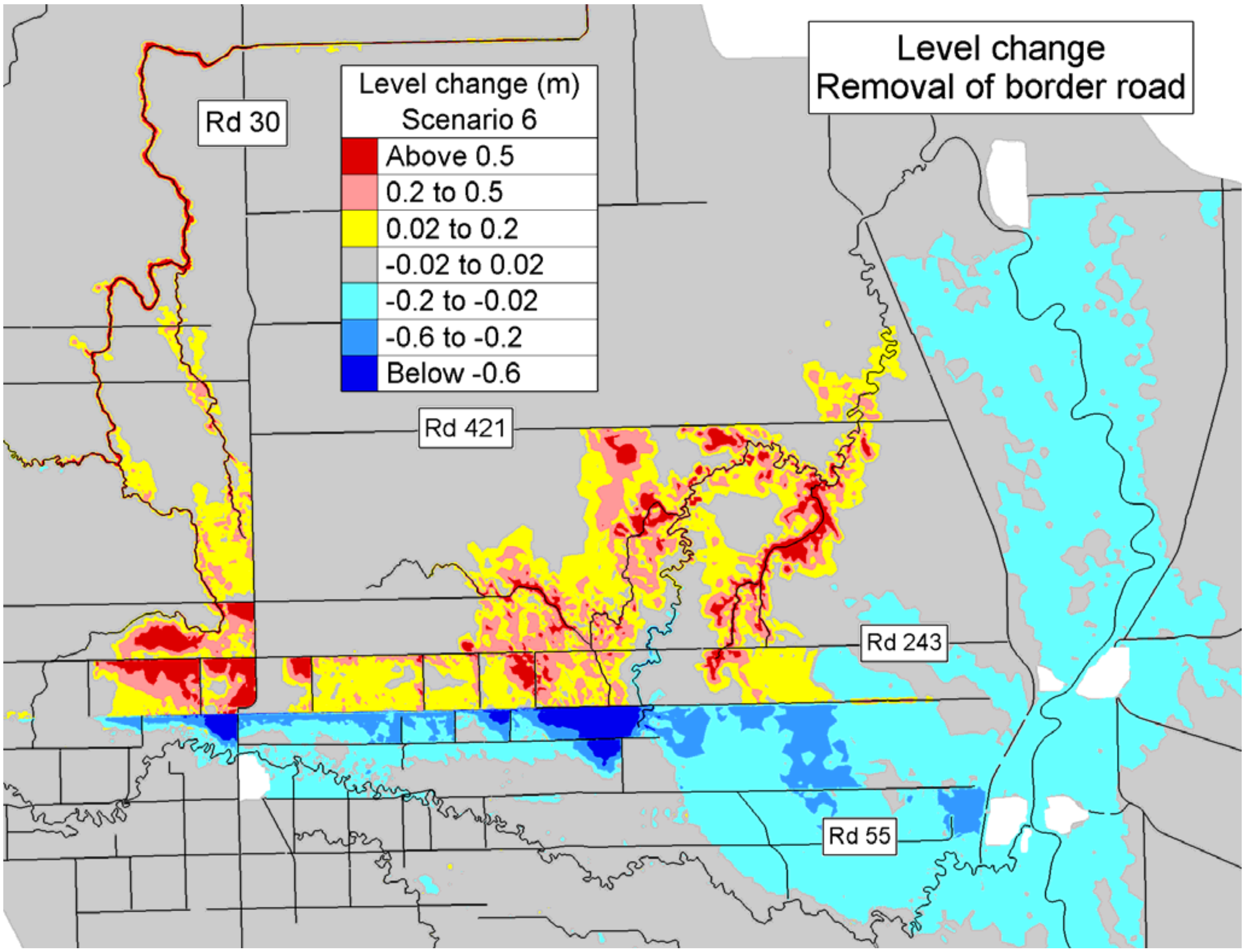
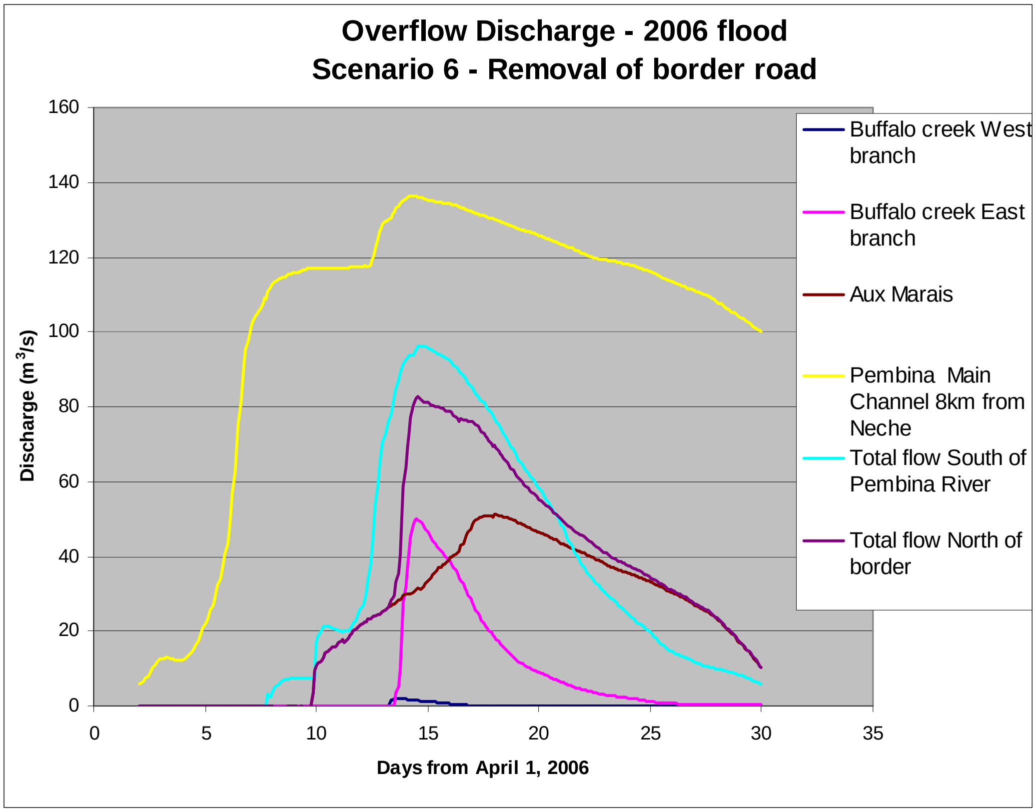


Figure 44 - Scenario 6: Change in maximum water levels after removal of the border road, compared to existing conditions



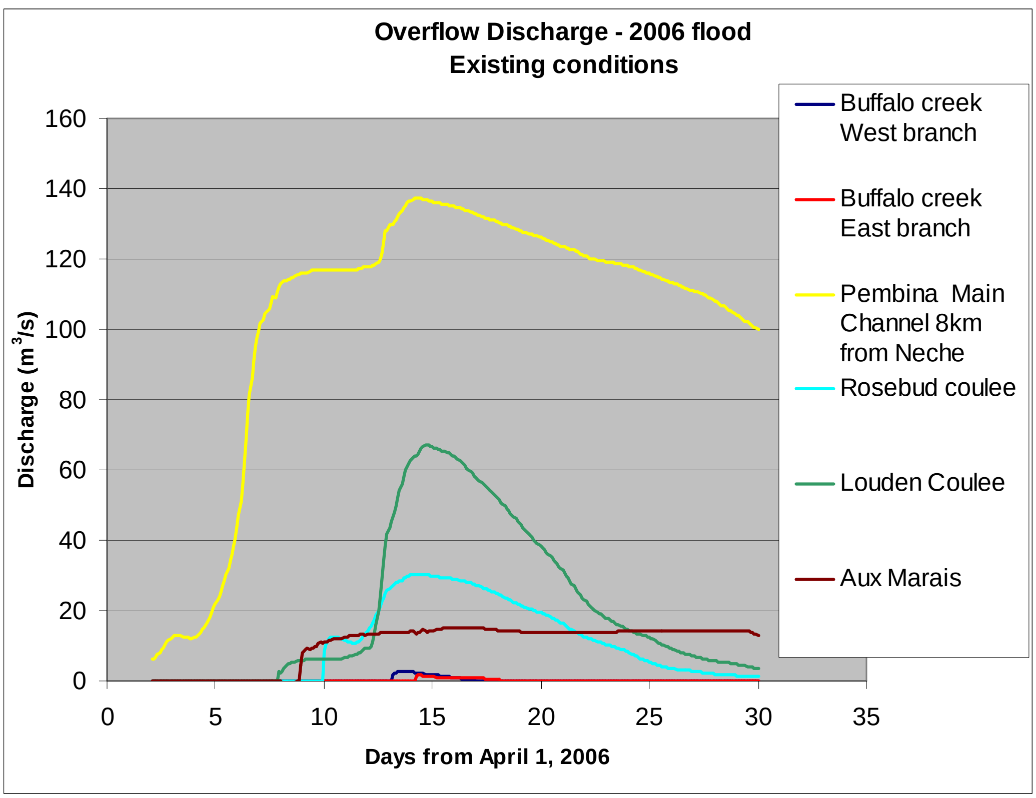


Figure 45 - Scenario 6: Discharge through various channels, with the removal of the border road, in comparison with the existing conditions

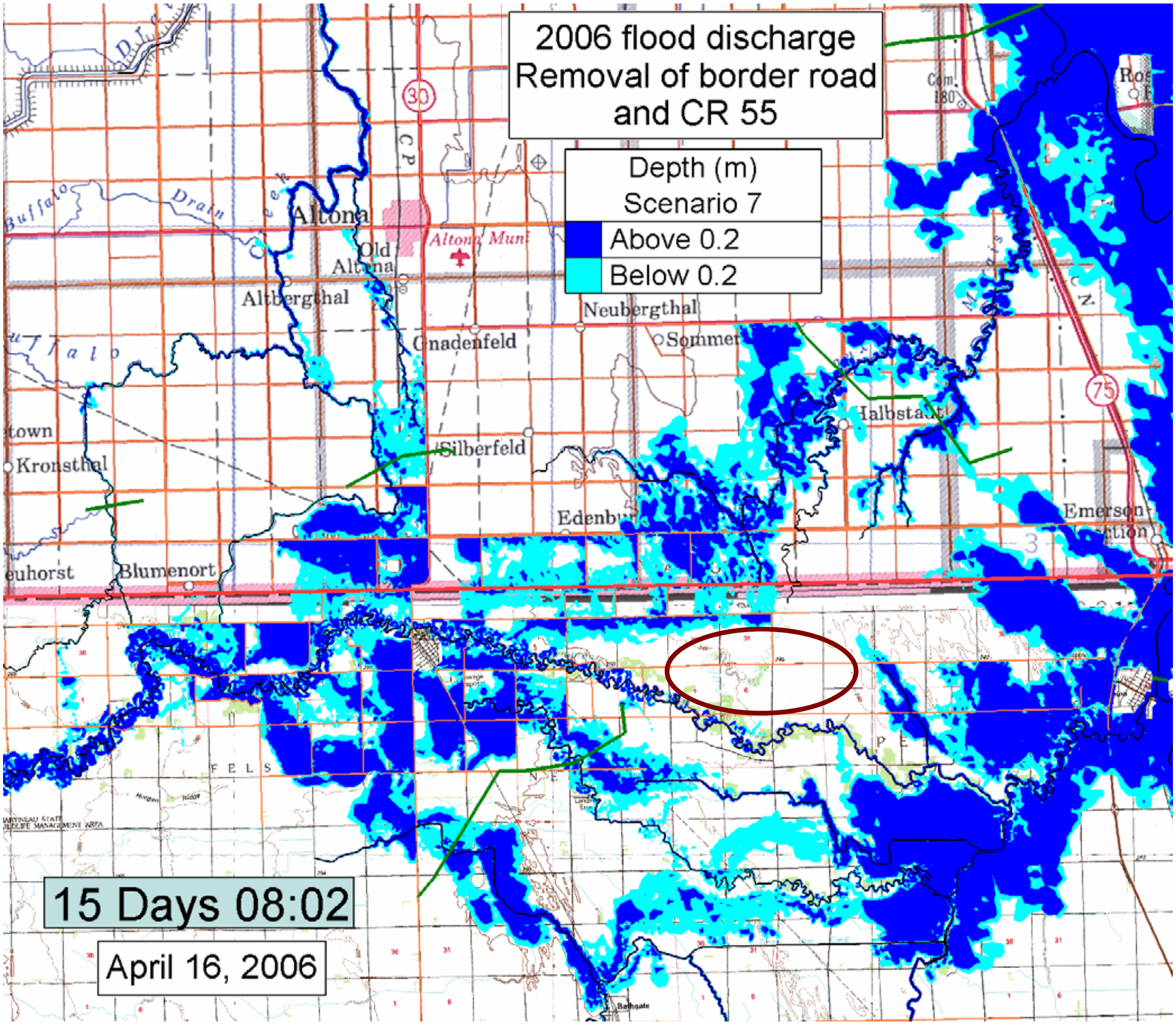


Figure 46 - Scenario 7: Flood extent without the border road and County Road 55

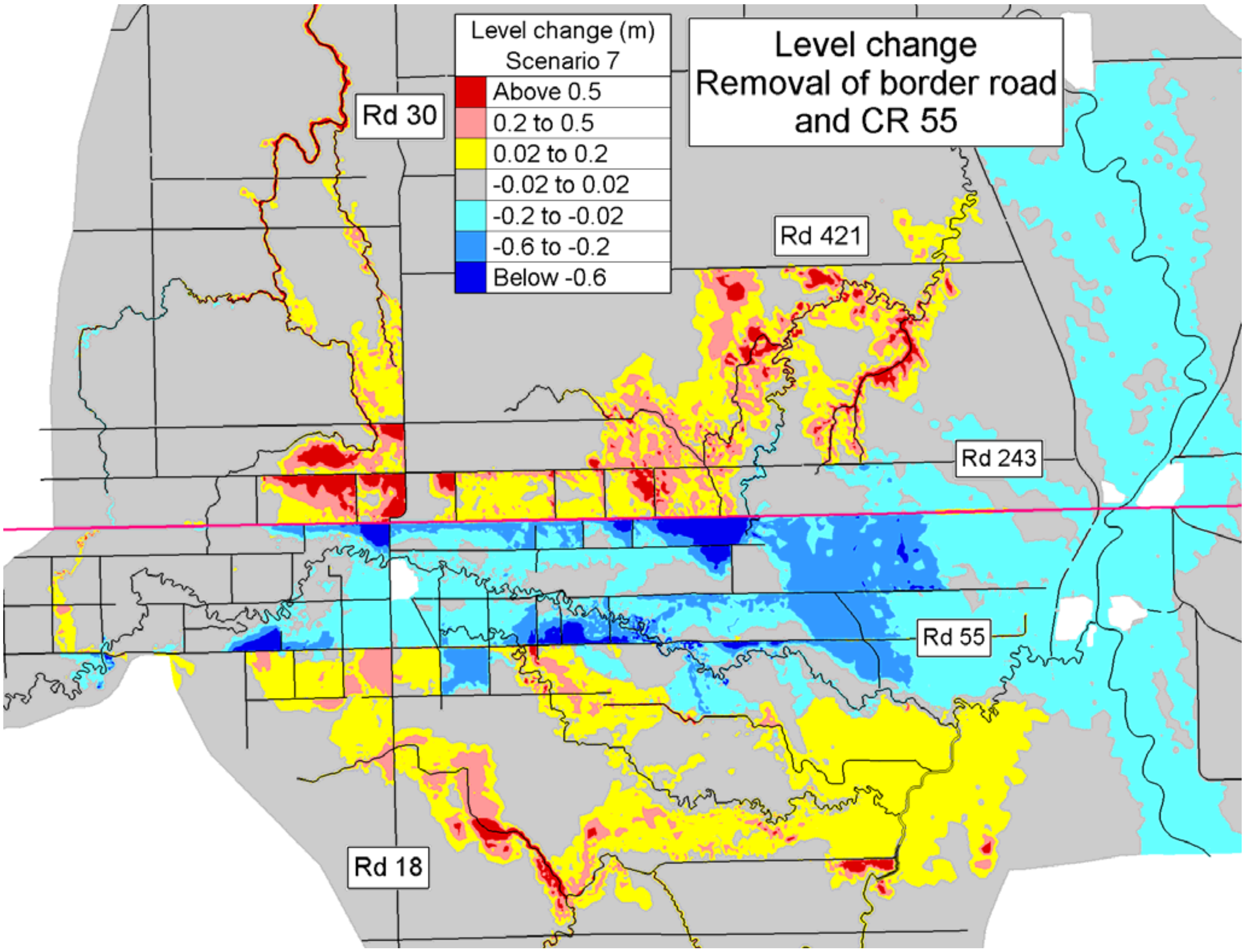


Figure 47 - Scenario 7: Change in maximum water levels after removal of the border road and County Road 55, compared to existing conditions

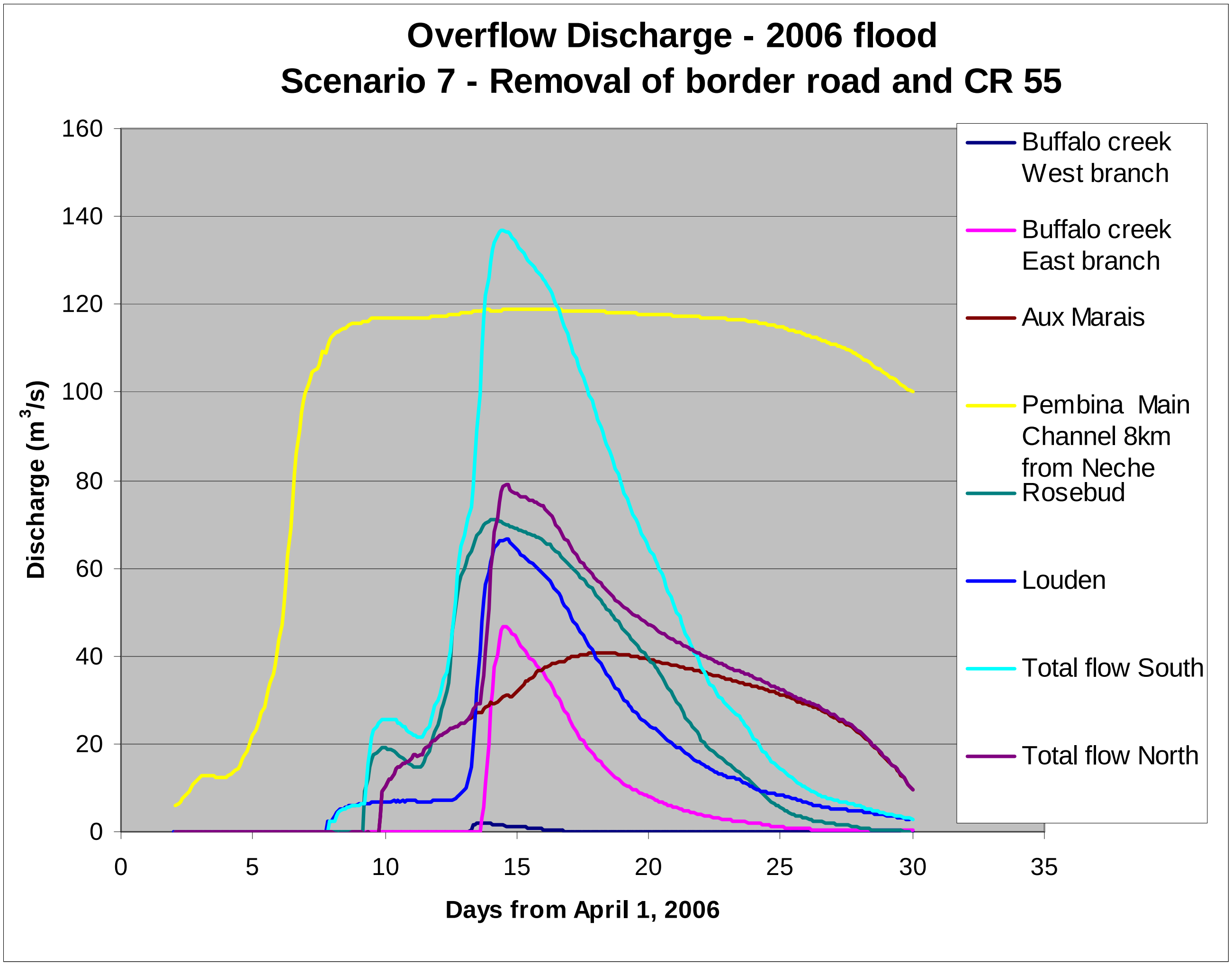


Figure 48 - Scenario 7: Discharge through various channels, with the removal of the border road, and County Road 55

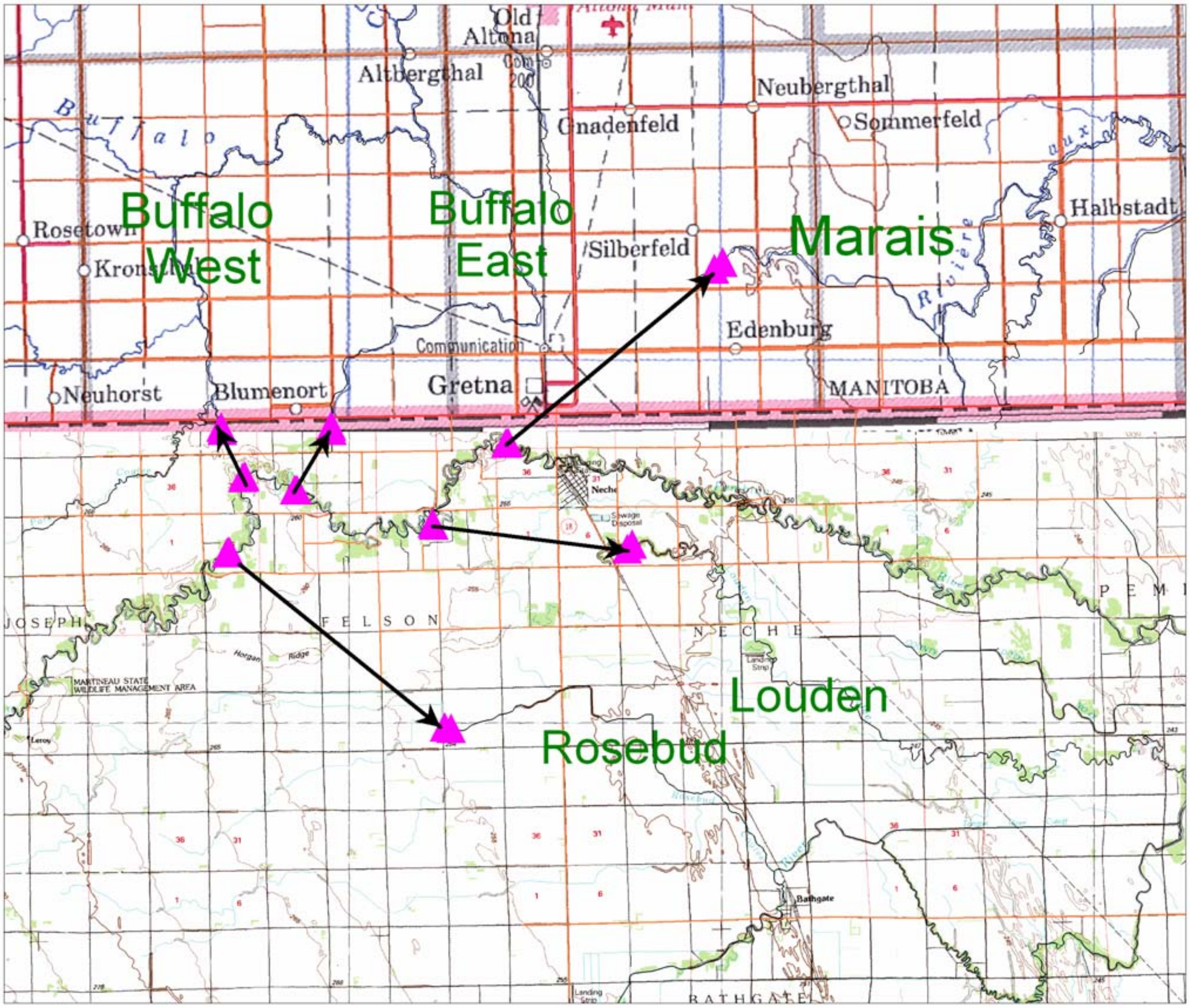


Figure 49 - Scenario 8: Location of the five diversions

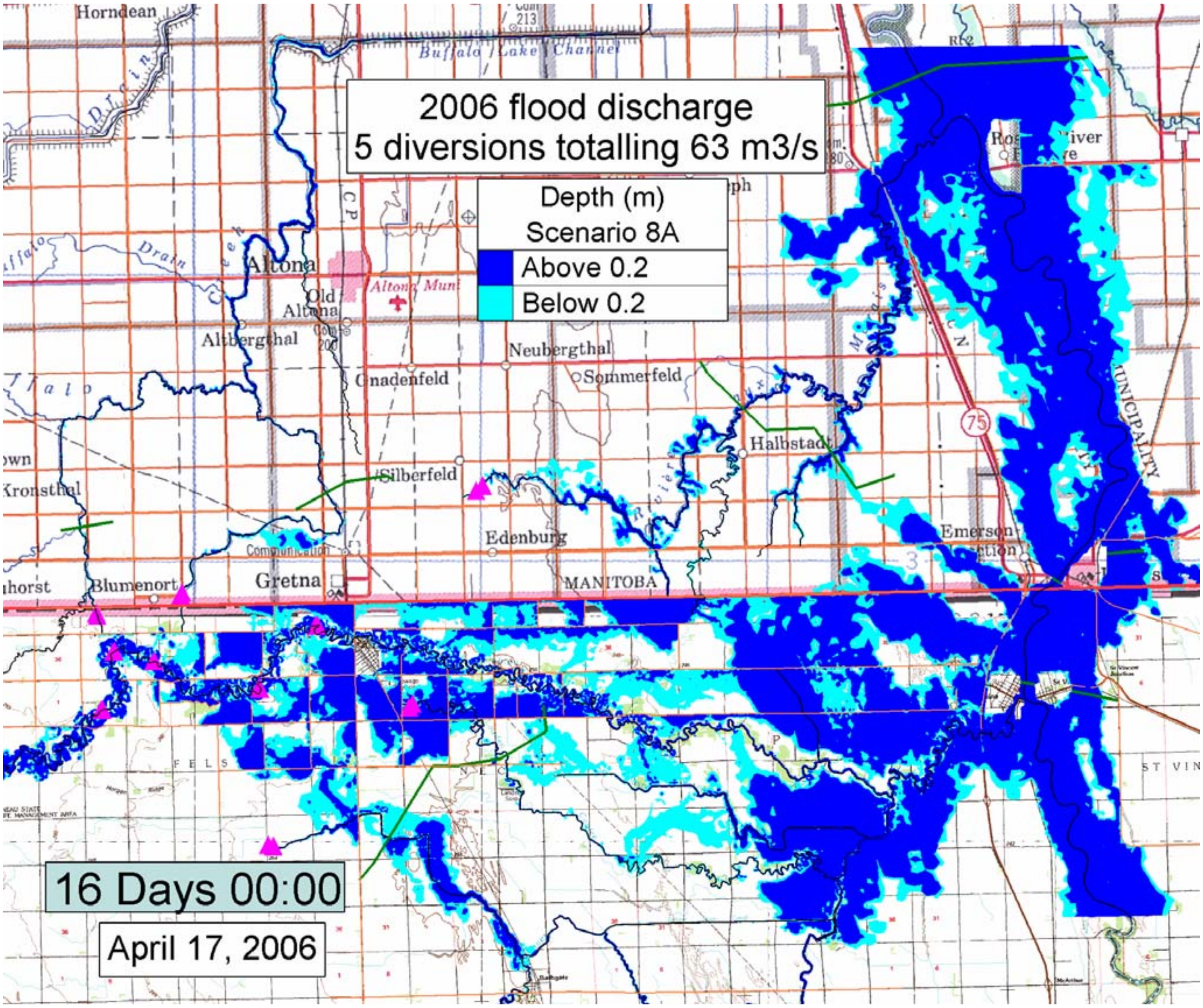


Figure 50 - Scenario 8A: Flood extent with 5 diversions (63 m^3/s total flow) without widening the existing culverts and coulees

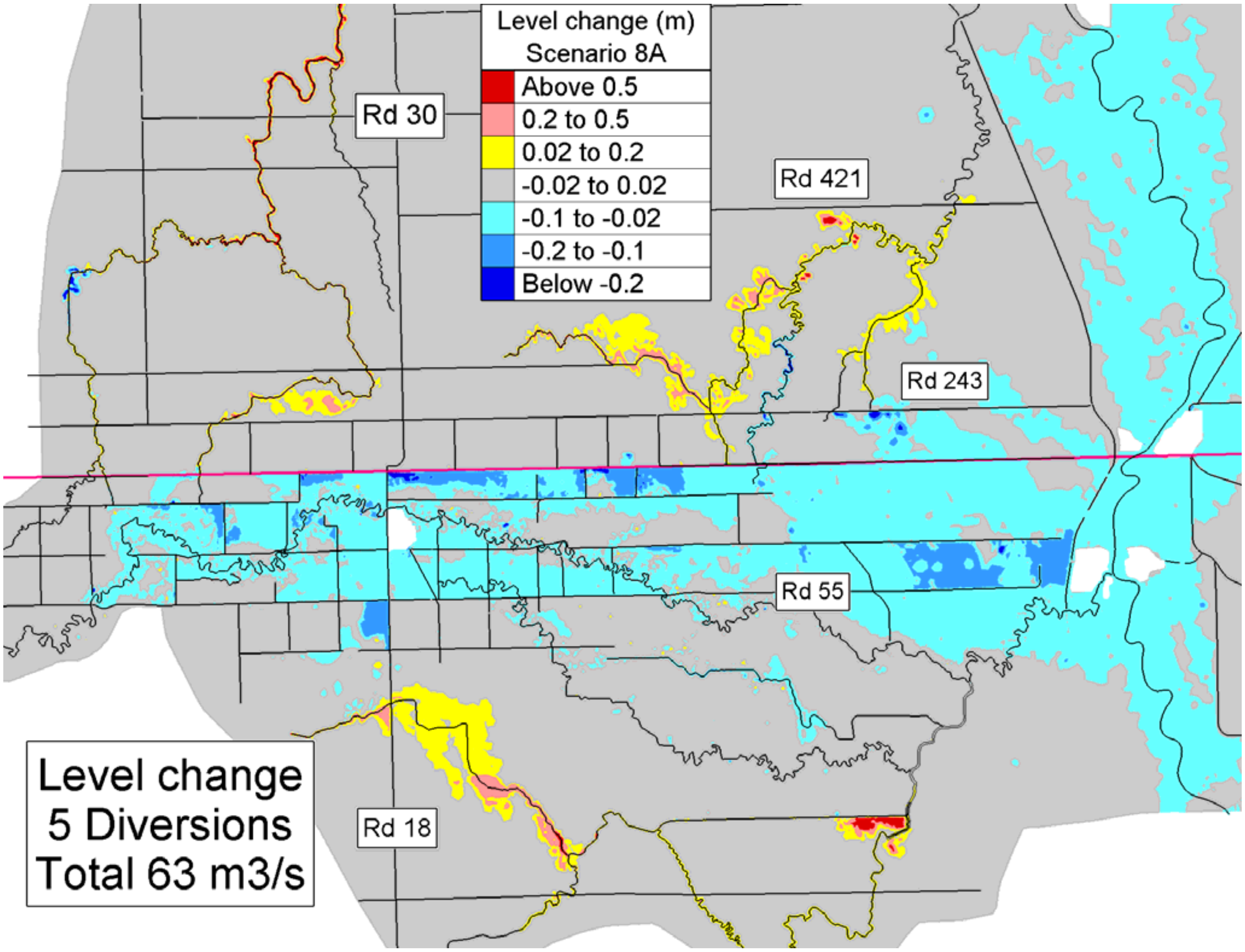


Figure 51 - Scenario 8A: Level change with 5 diversions (total flow 63 m^3/s), compared to existing conditions. No widening of existing culverts and coulees

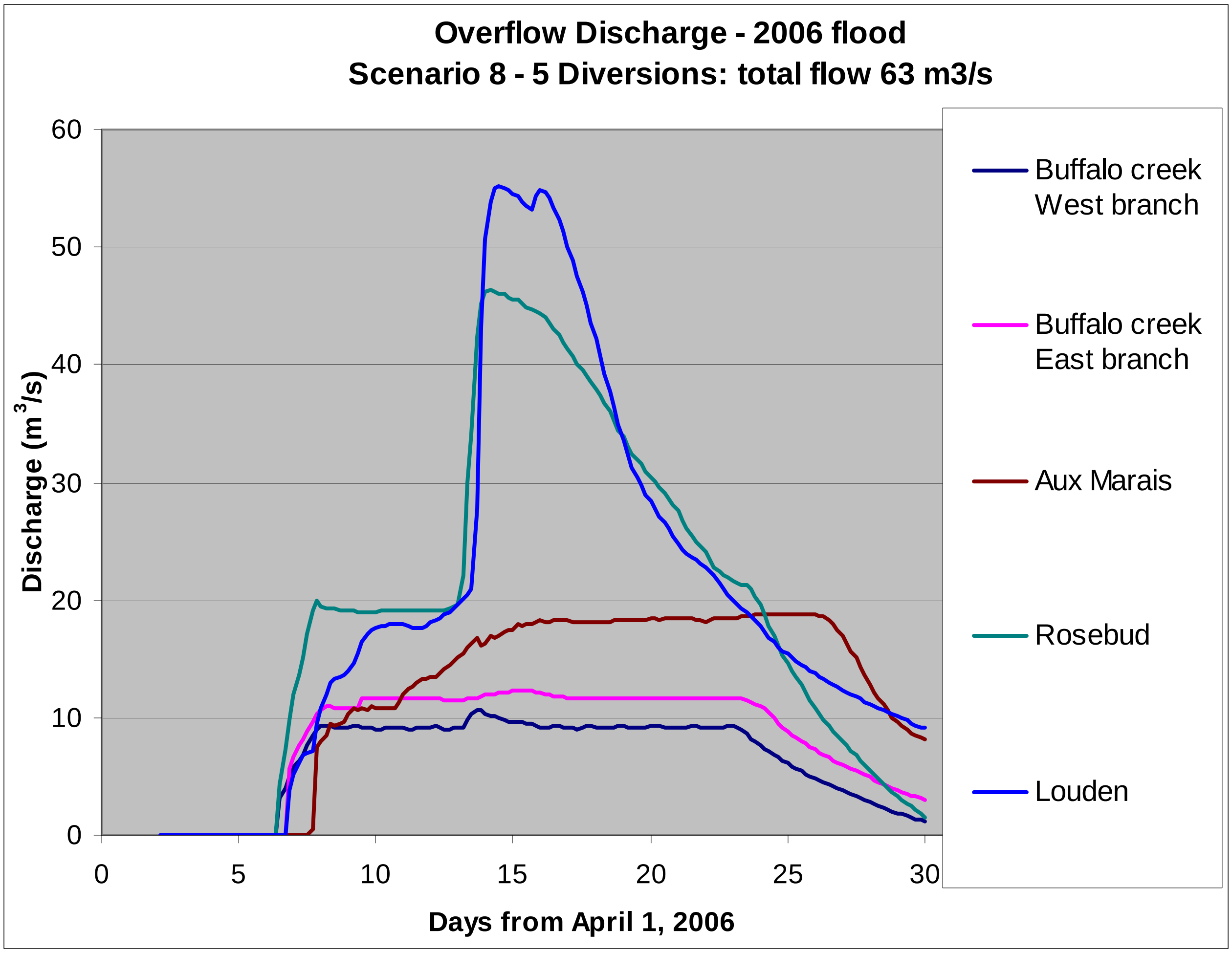


Figure 52 - Scenario 8A: Discharge through various channels, with 5 diversions totalling 63 m^3/s

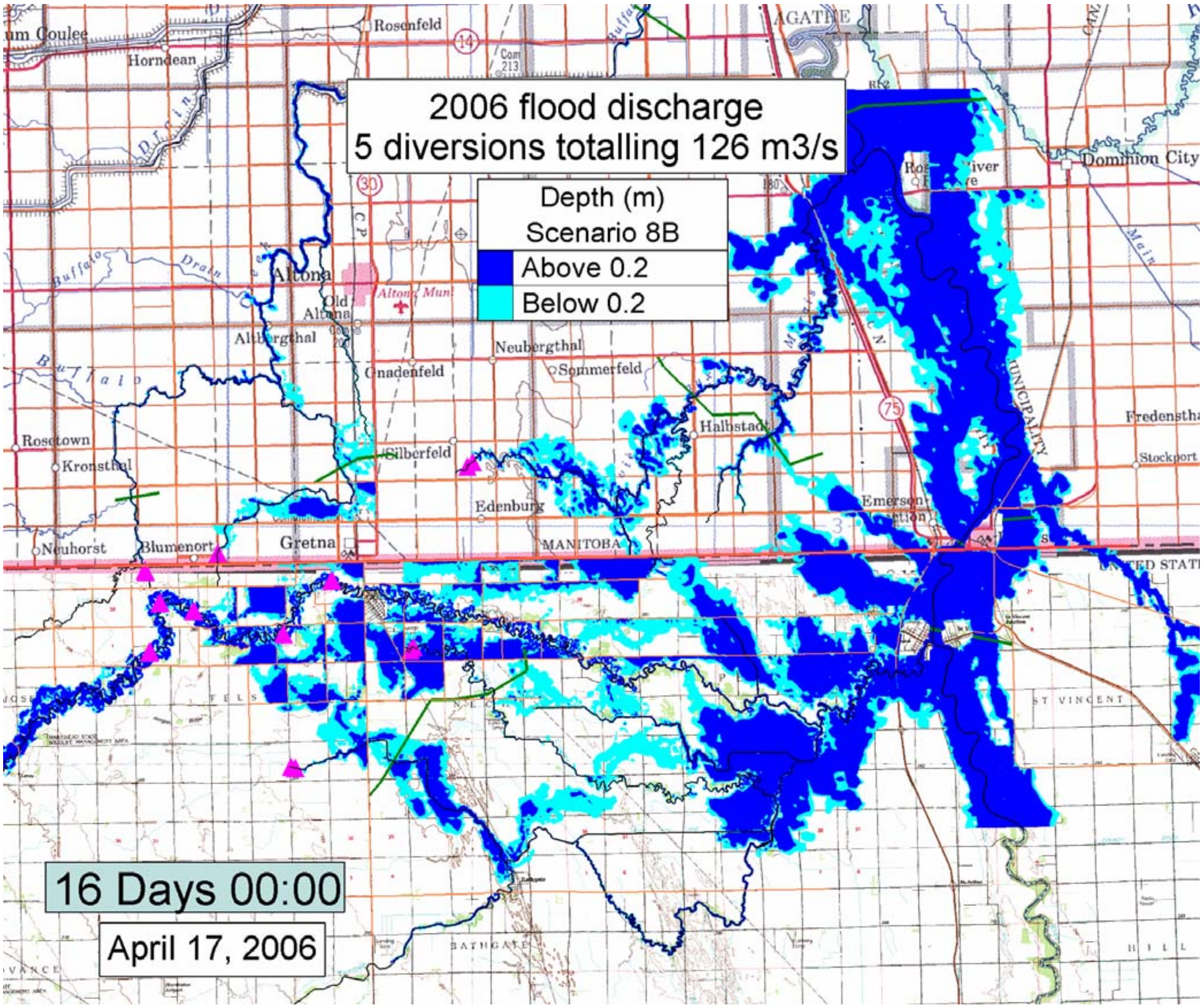


Figure 53 - Scenario 8B: Flood extent with 5 diversions (126 m^3/s total flow) without widening the existing culverts and coulees

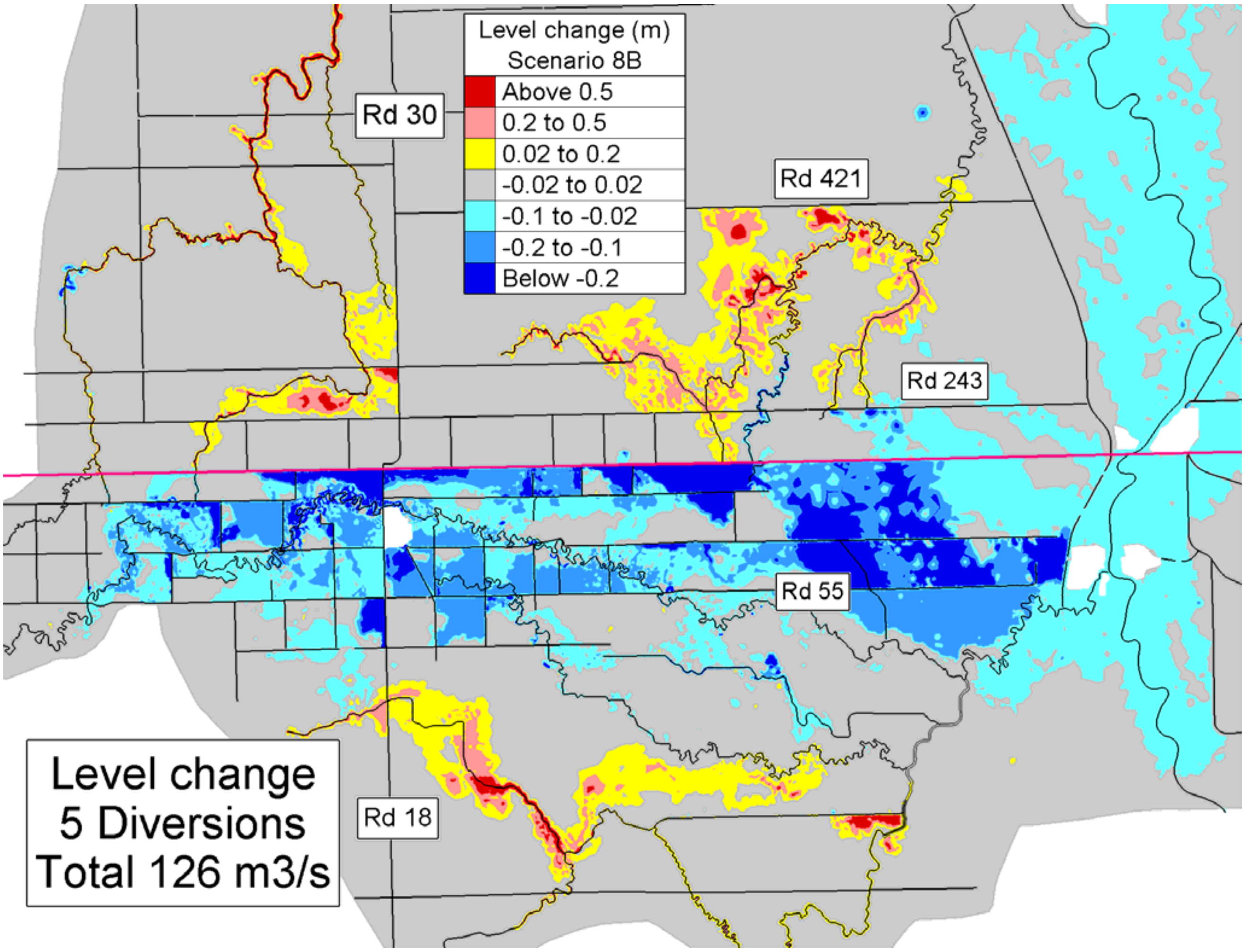


Figure 54 - Scenario 8B: Level change with 5 diversions (total flow 126 m^3/s), compared to existing conditions. No widening of existing culverts and coulees

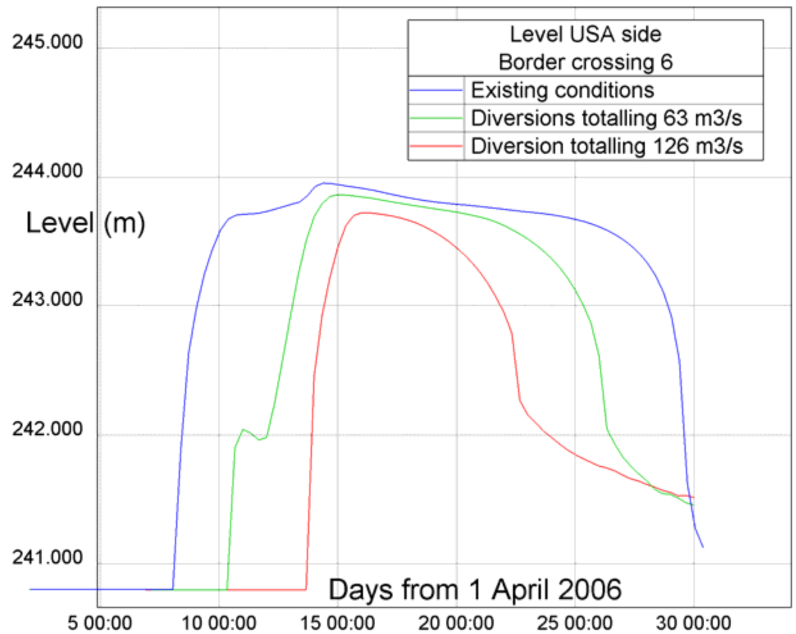


Figure 55 - Scenario 8: Level at border crossing 6

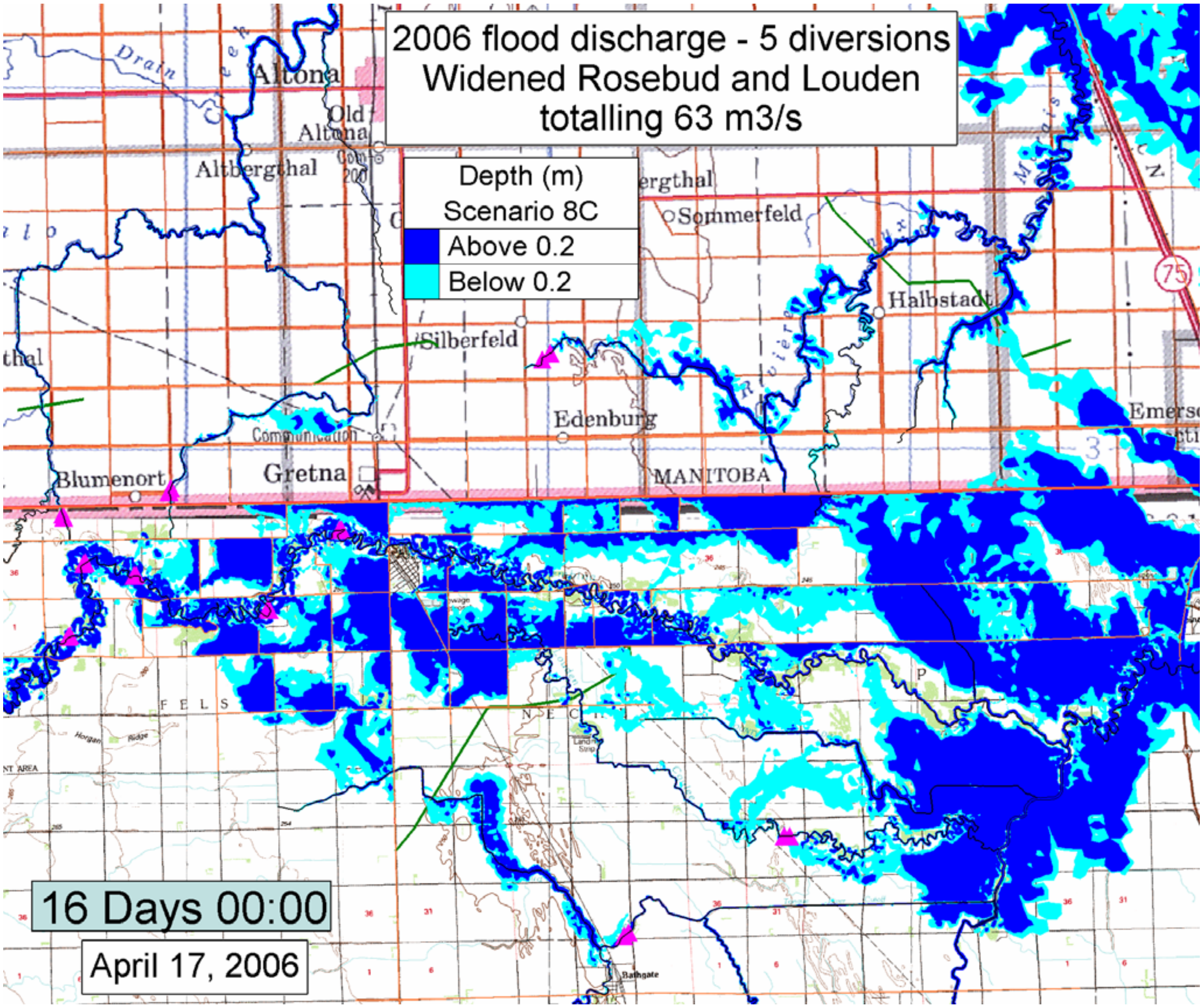


Figure 56 - Scenario 8C: Flood extent with 5 diversions (63 m^3/s total flow) with widening of Rosebud and Louden Coulees

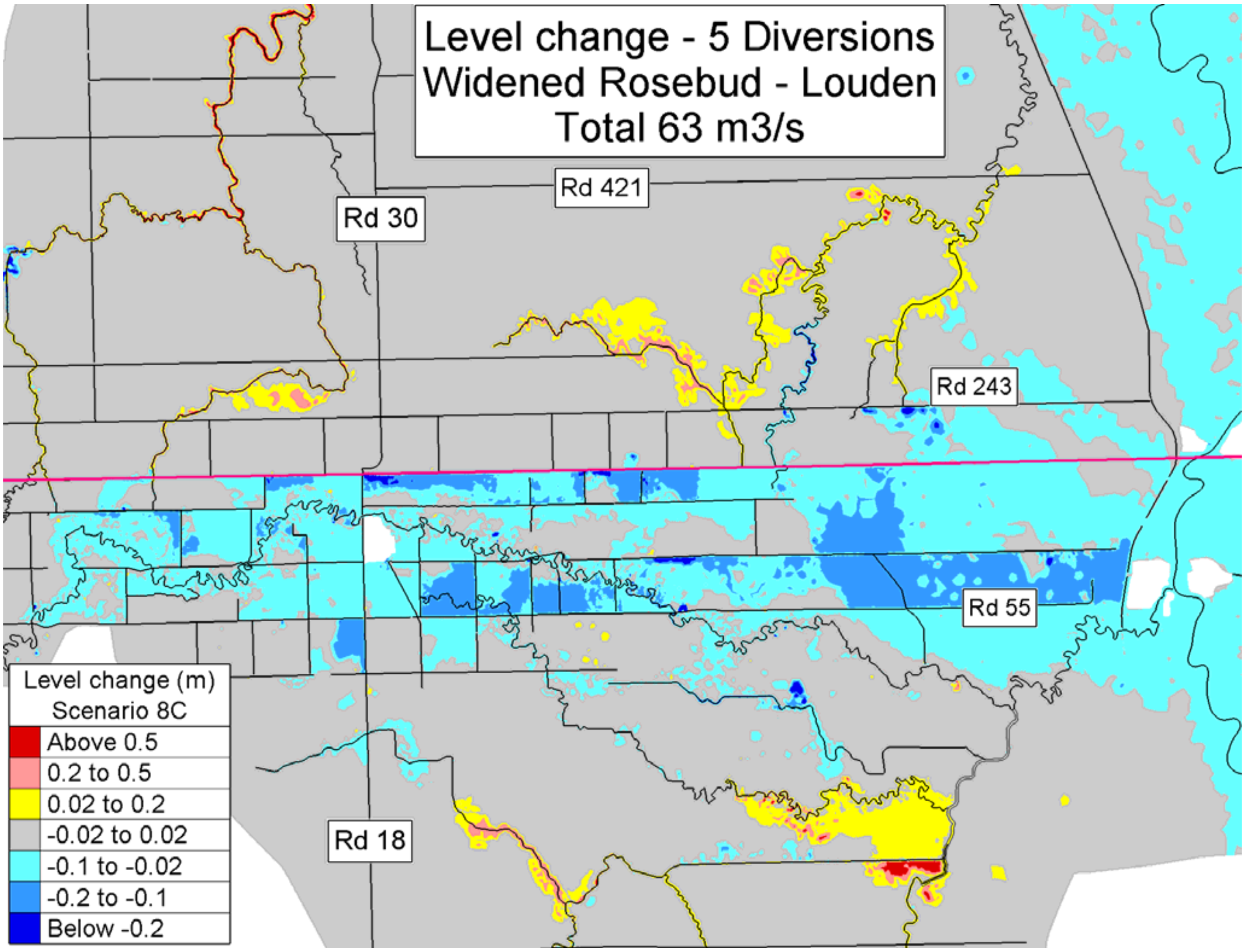


Figure 57 - Scenario 8C: Level change with 5 diversions (total flow 63 m^3/s), compared to existing conditions, after widening of Rosebud and Louden Coulees

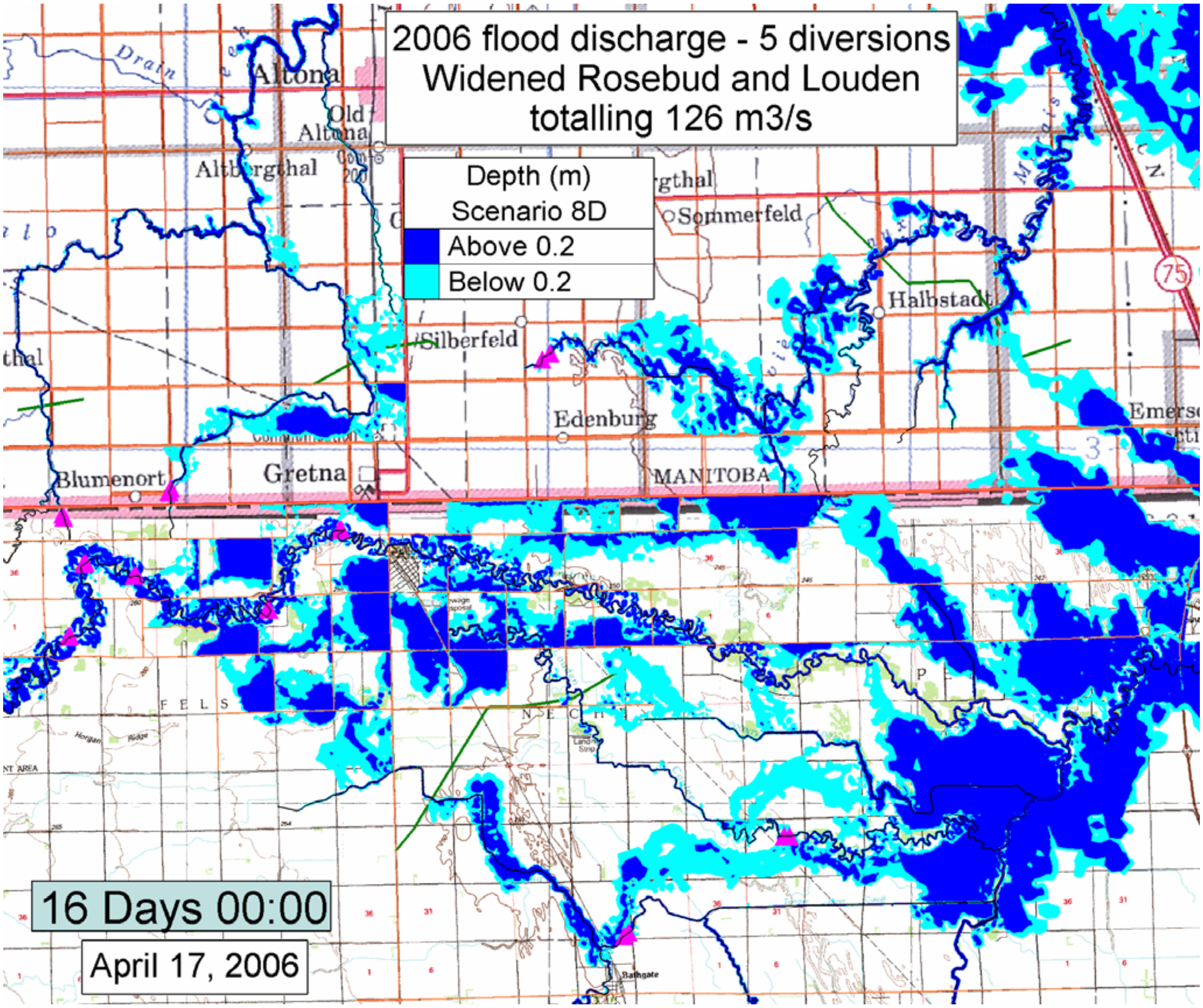


Figure 58 - Scenario 8D: Flood extent with 5 diversions (126 m^3/s total flow) with widening of Rosebud and Louden Coulees

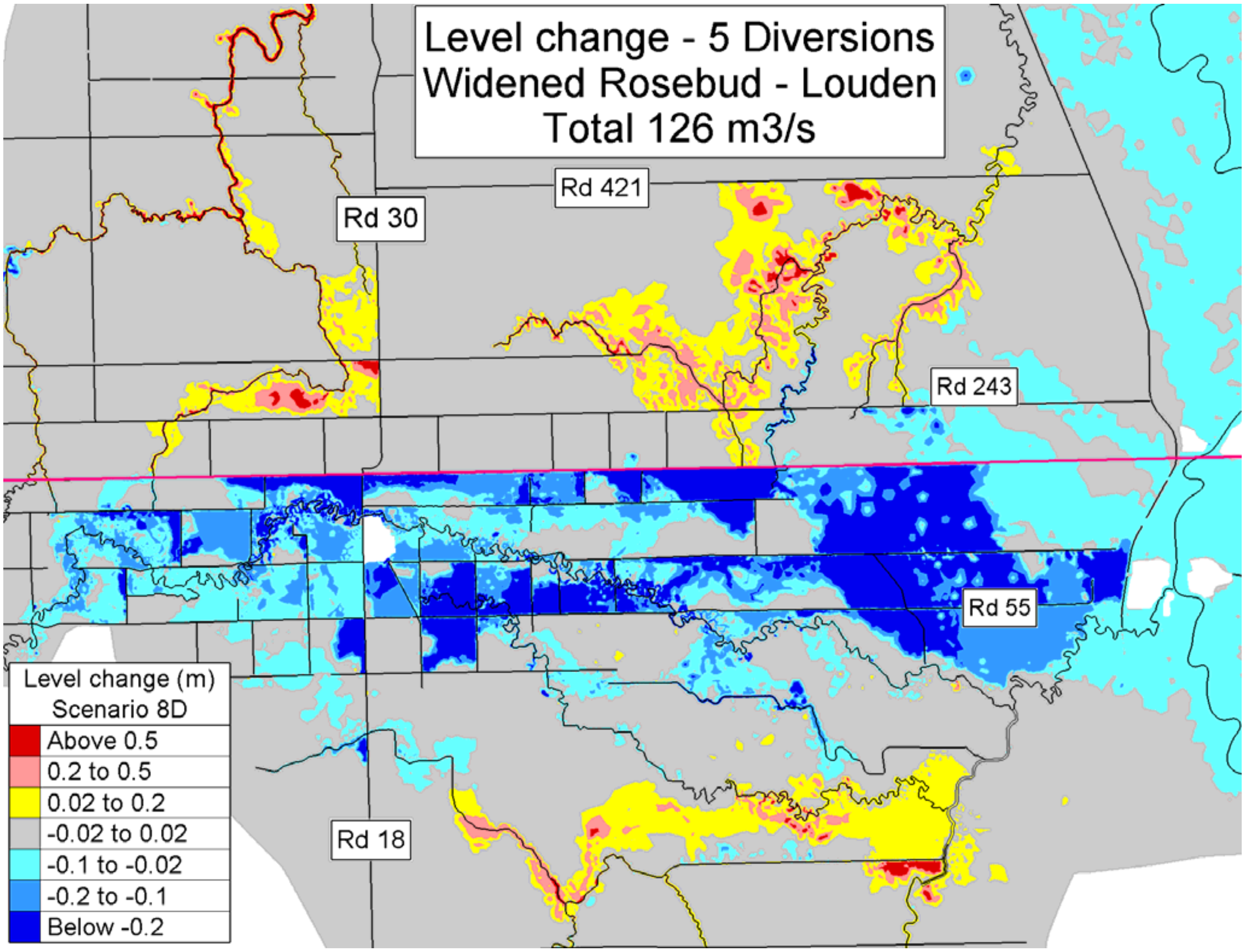


Figure 59 - Scenario 8D: Level change with 5 diversions (total flow 126 m^3/s), compared to existing conditions, after widening of Rosebud and Louden Coulees

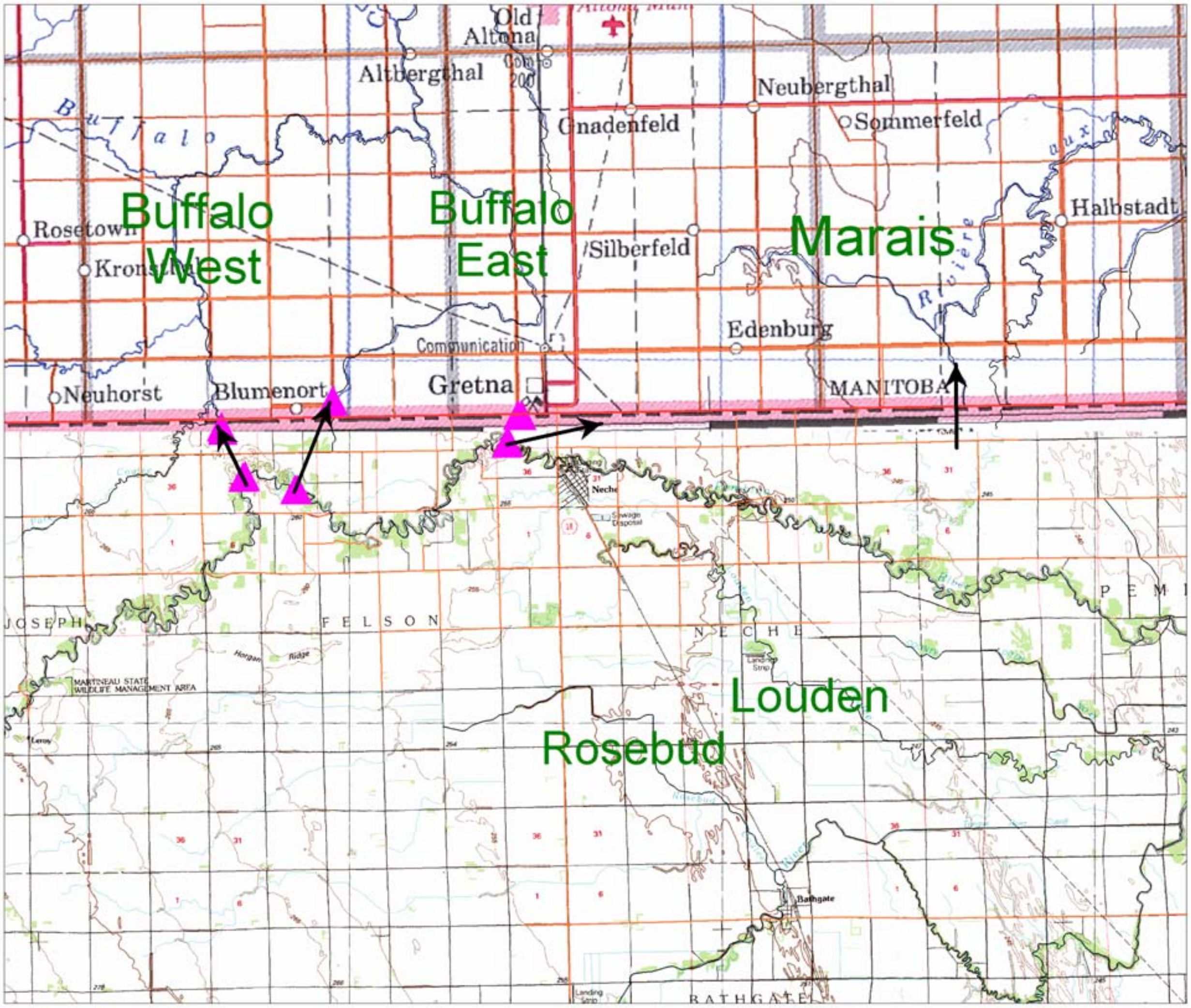


Figure 60 - Scenario 9: Location of the three diversions

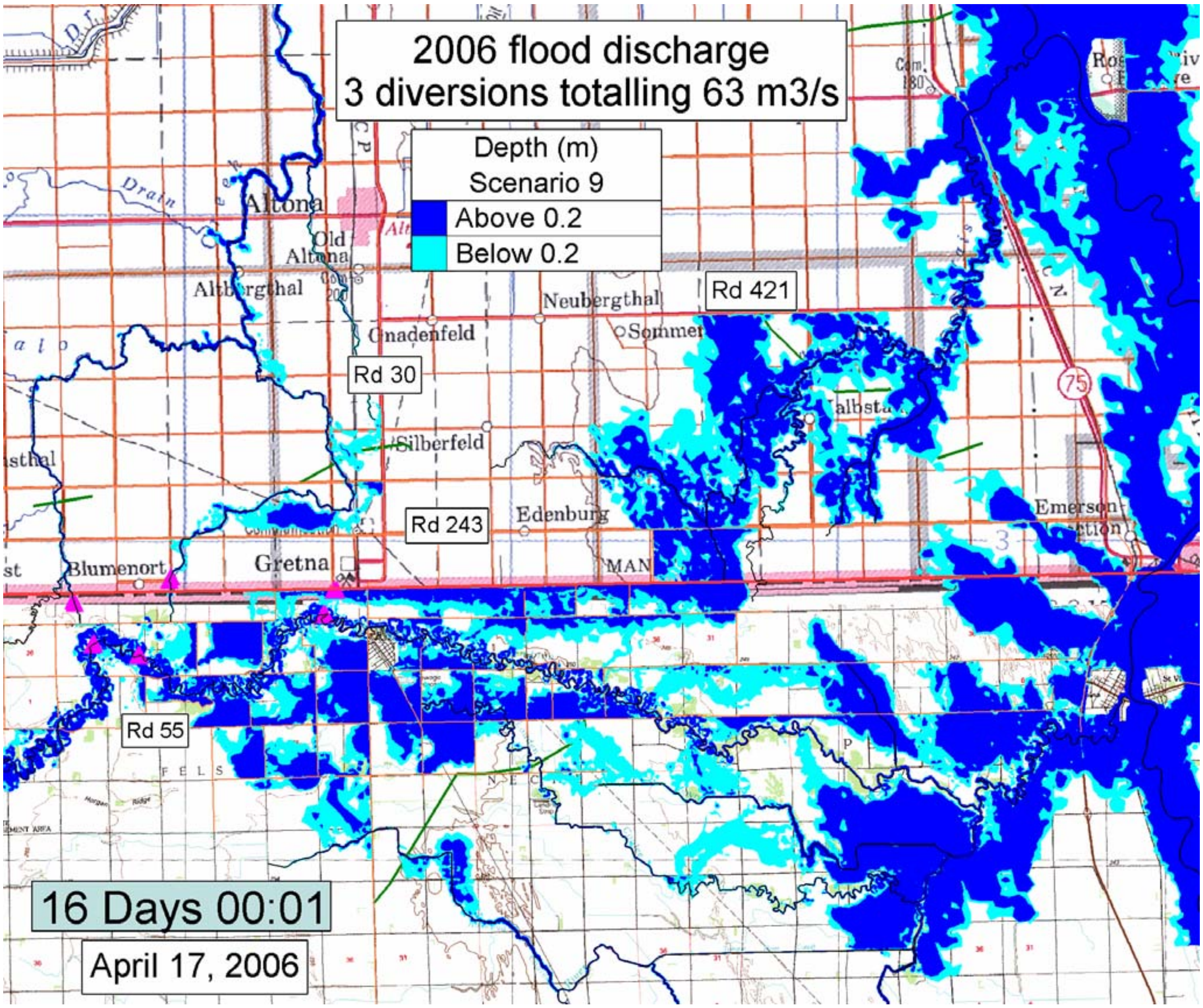


Figure 61 - Scenario 9: Flood extent with 3 diversions (63 m^3/s total flow) discharging into Buffalo Creek and the border drain

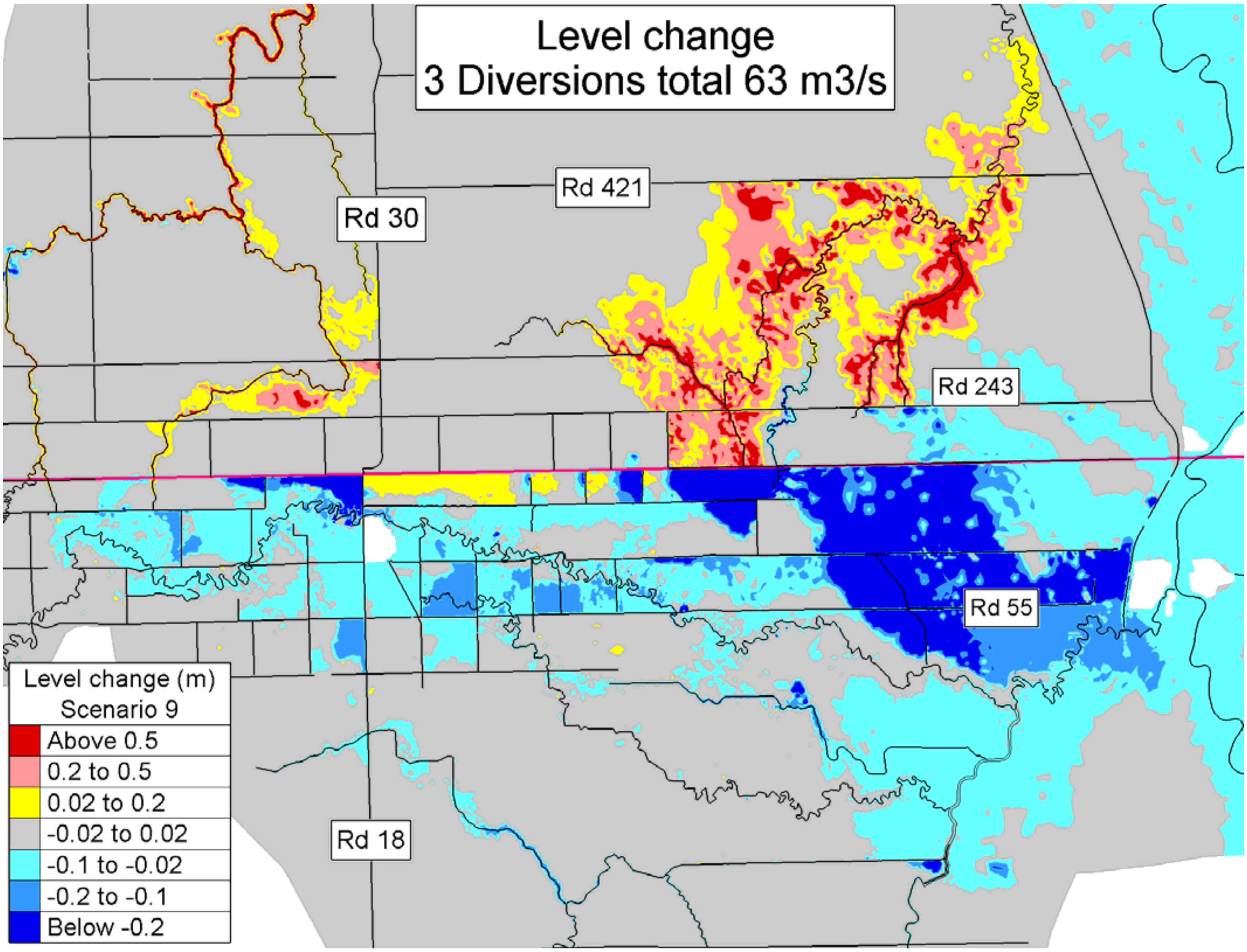


Figure 62 - Scenario 9: Level change with 3 diversions (total flow 63 m^3/s), compared to existing conditions

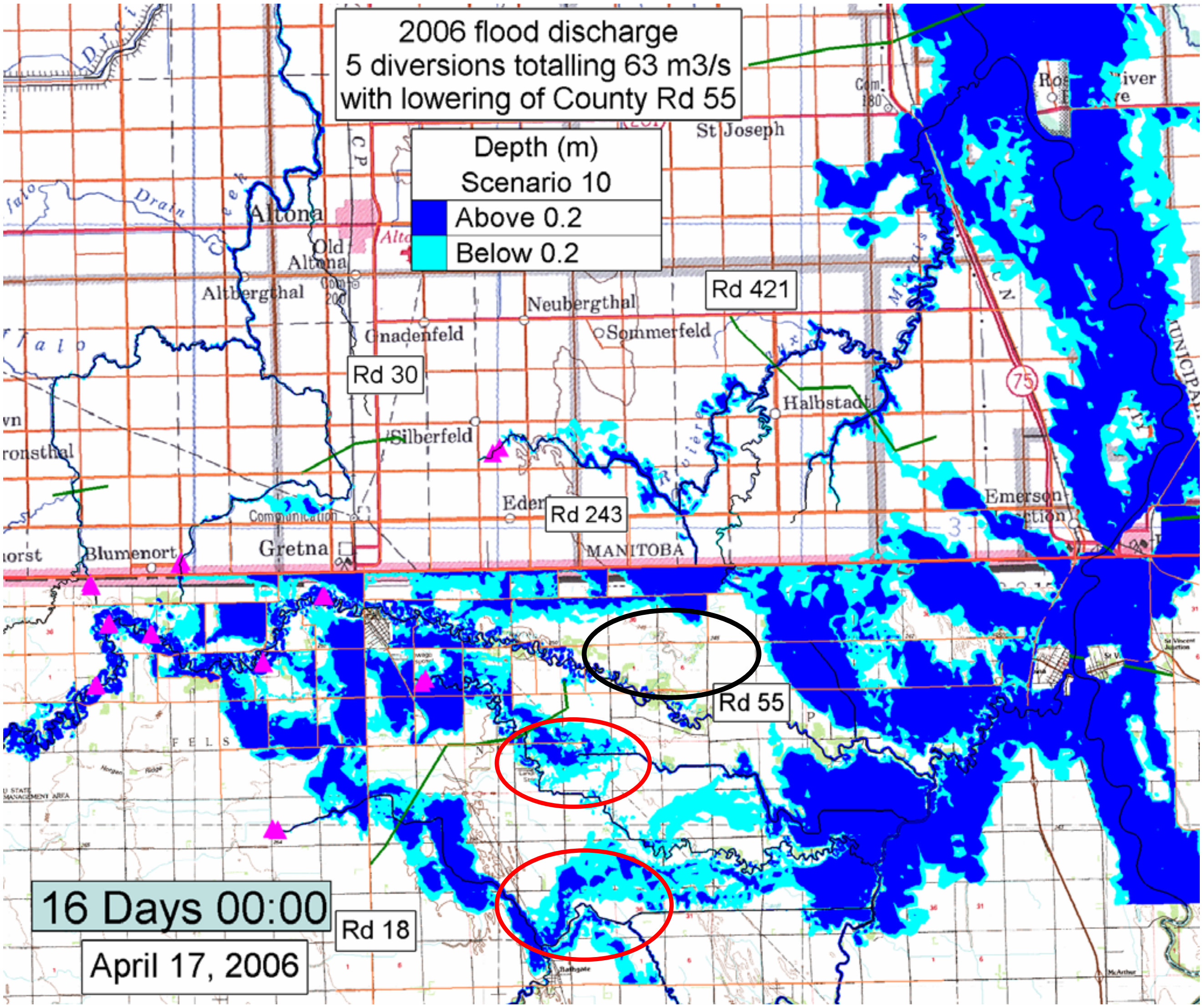


Figure 63 - Scenario 10: Flood extent with 5 diversions and the lowering of County road 55

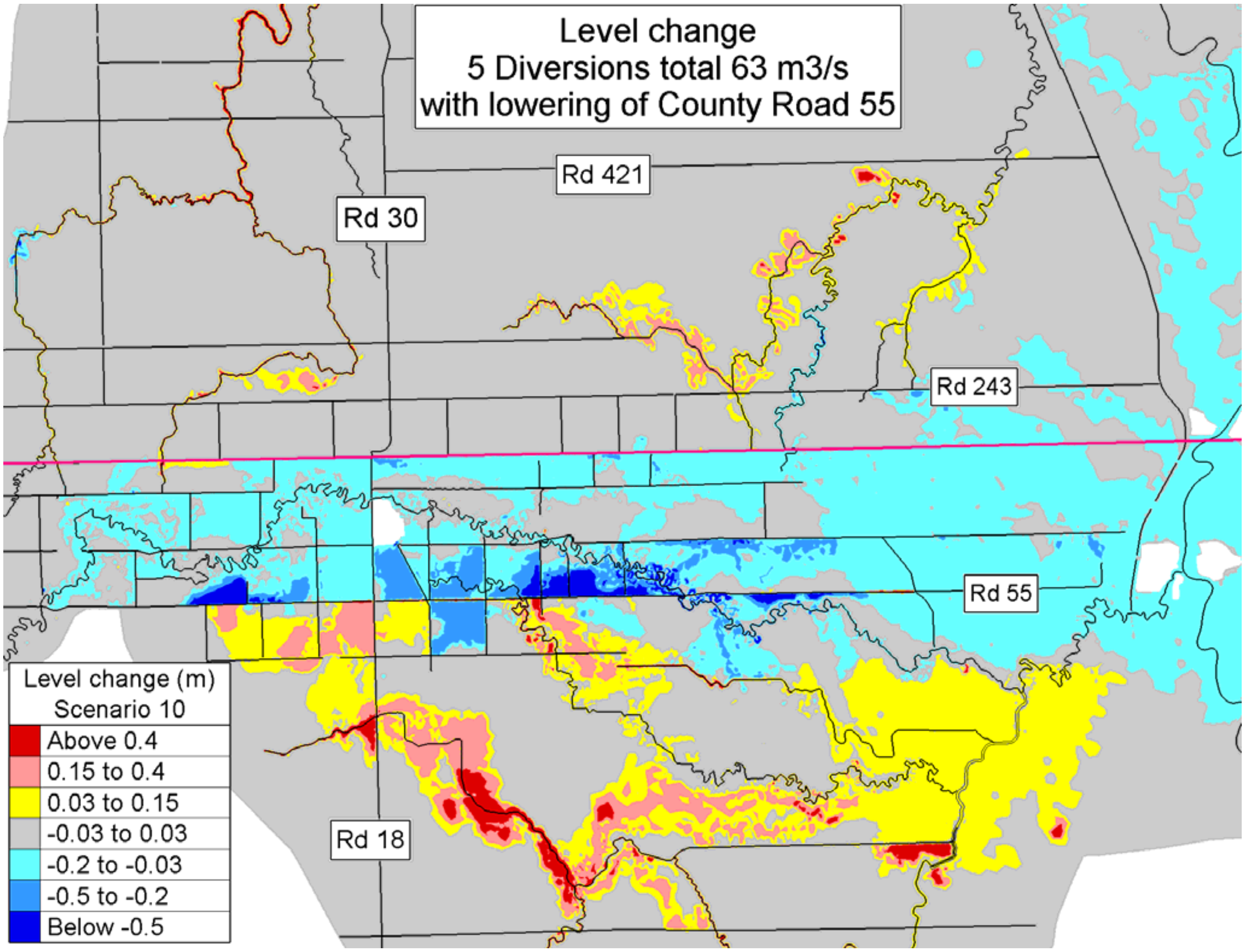


Figure 64 - Scenario 10: Level change with 5 diversions (total flow 63 m^3/s), and the lowering of County Road 55, compared to existing conditions

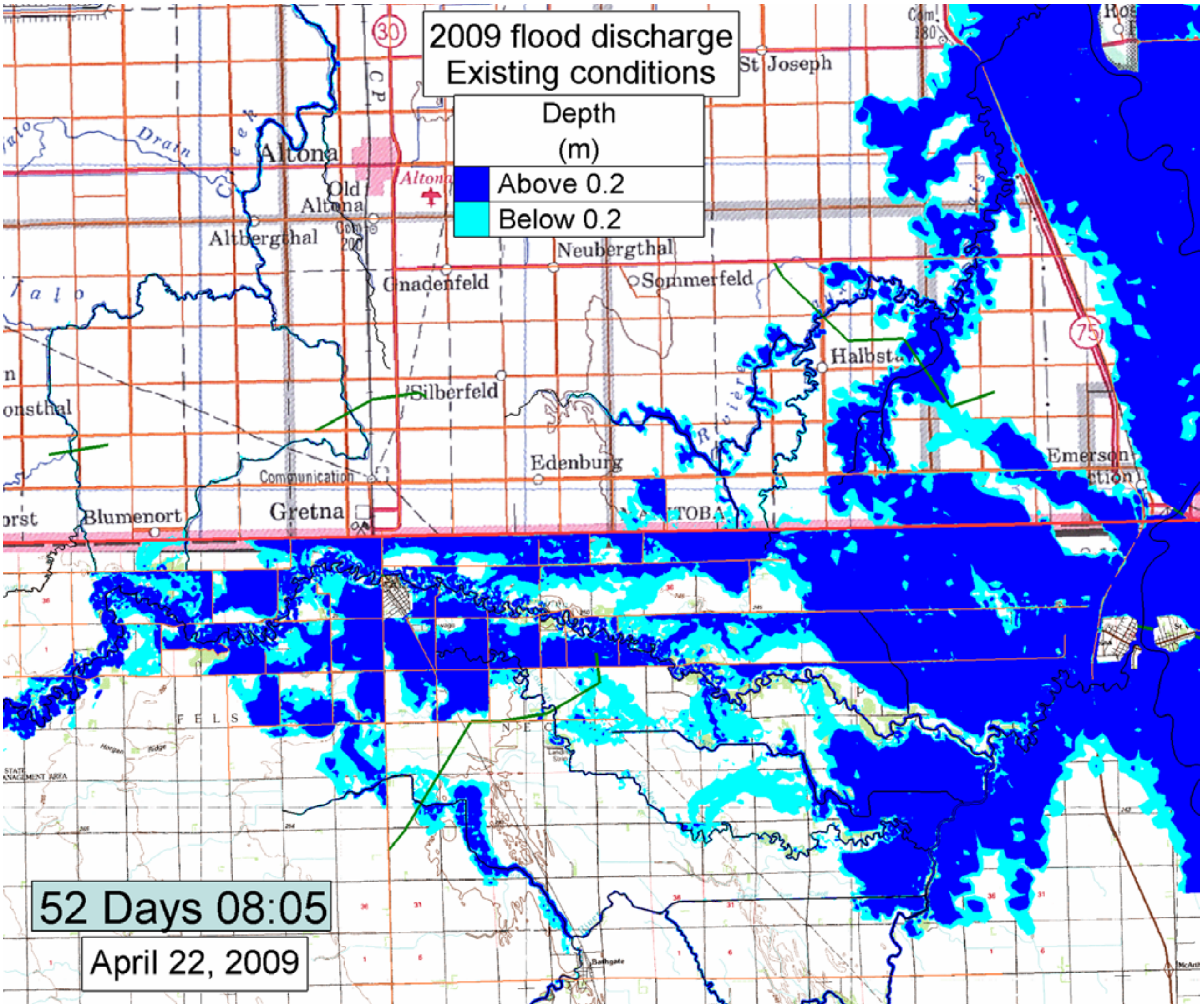


Figure 65 - Flood extent during the 2009 flood (existing conditions)

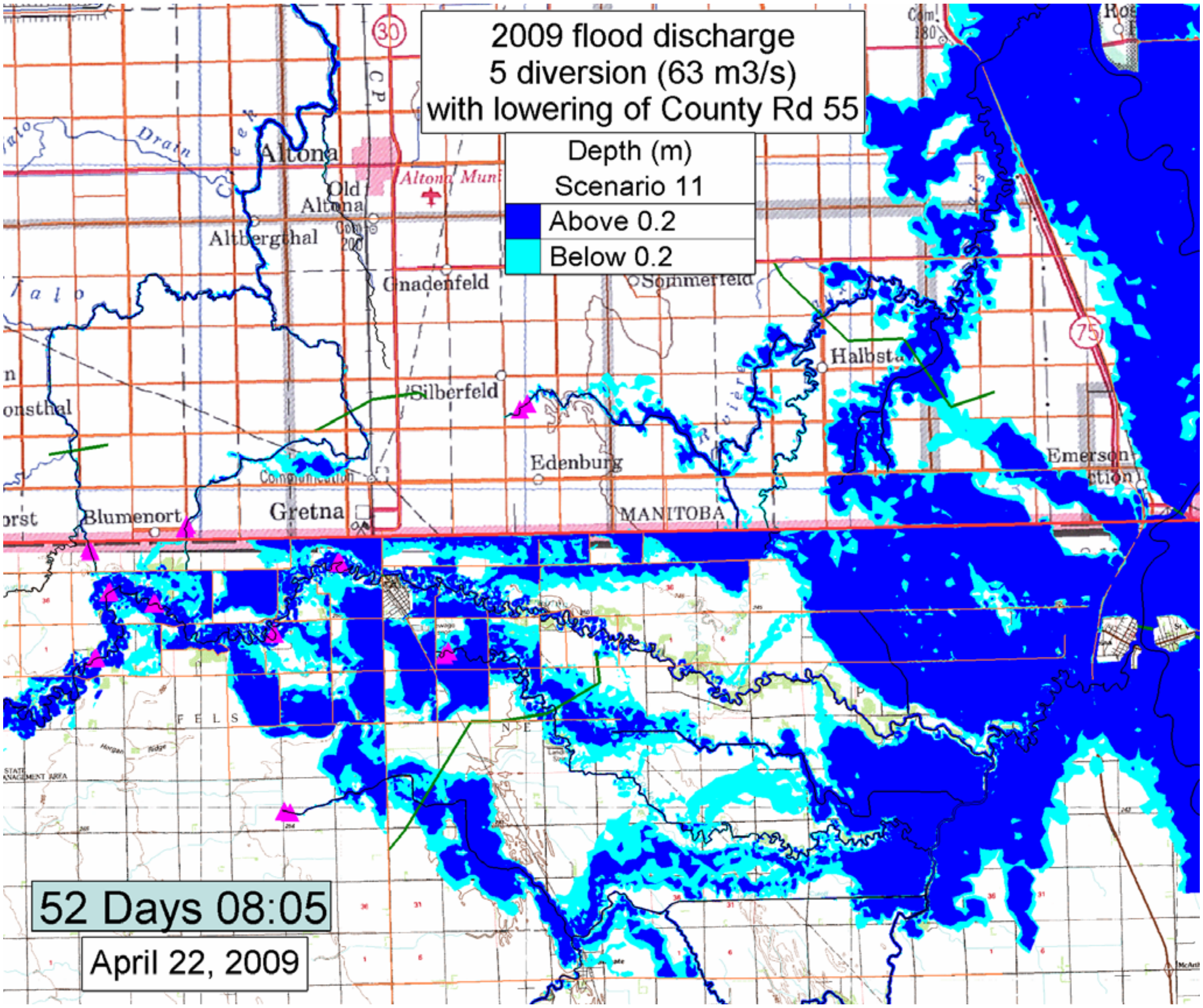


Figure 66 - Scenario 11: Flood extent with 5 diversions and the lowering of County road 55 during a 2009 type flood

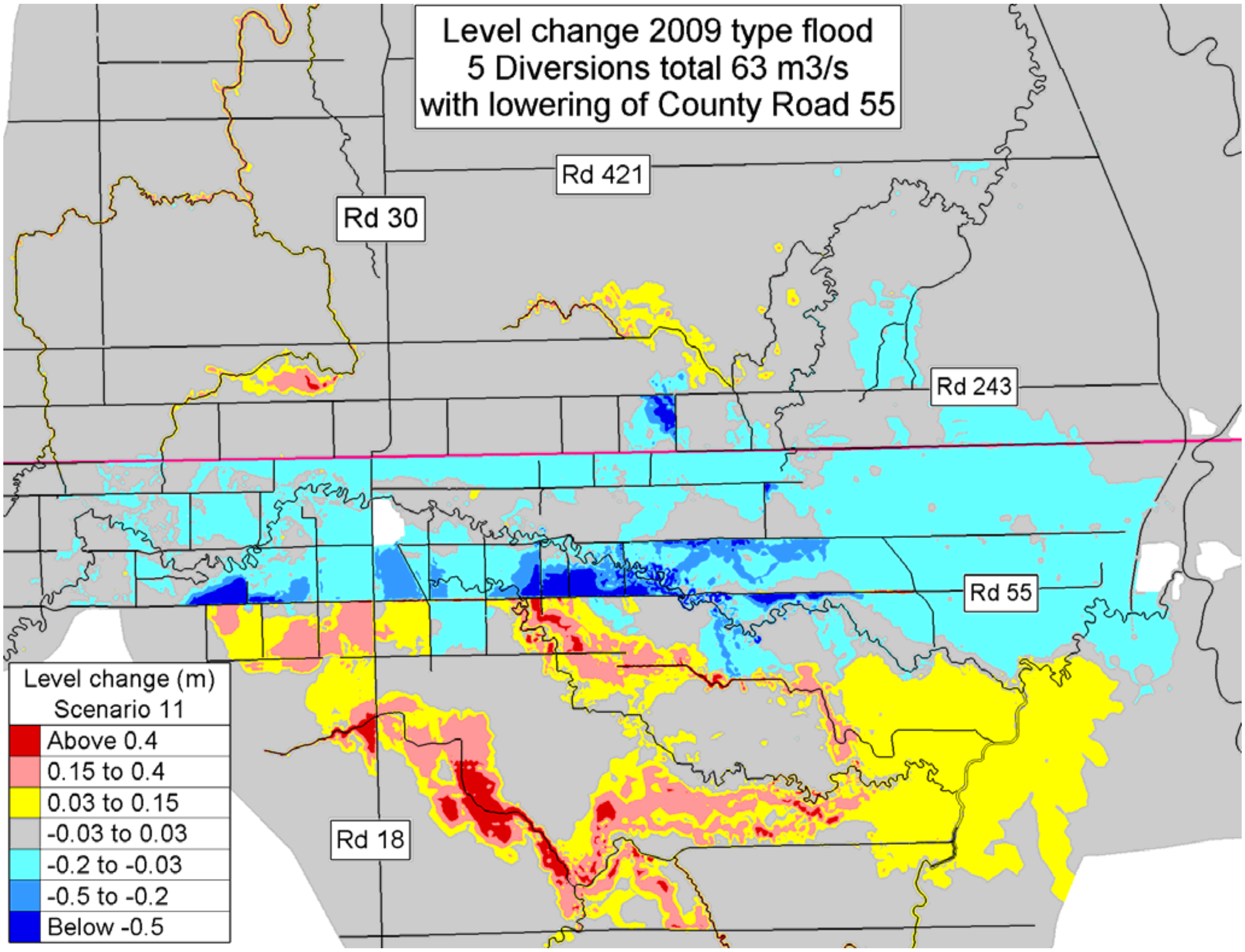


Figure 67 - Scenario 11: Level change with 5 diversions and the lowering of County Road 55, compared to existing conditions, during a 2009 type flood