

## USING THE WETLAND DEM PONDING MODEL AS A DIAGNOSTIC TOOL FOR PRAIRIE FLOOD HAZARD ASSESSMENT

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### 19.1 ABSTRACT

On the Canadian Prairies the vulnerability of rural municipalities, their infrastructure, and economies to flooding has become a concern in recent years. The usual modelling approaches to assessing flood hazards are unsuitable for Prairie landscapes because of invalid assumptions and their focus on river reaches and the adjacent flood plain rather than the entire landscape. Prairie landscapes, being recently deglaciated, are comprised of complexes of wetlands which can contribute to flooding and are also ungauged. The Wetland DEM (Digital Elevation Model) Ponding Model (WPDM) is a tool that has been introduced to the Land and Infrastructure Resiliency Assessment (LIRA) project to provide improved flood hazard information for Prairie landscapes. The application of the WPDM to LiDAR (Light Detection and Ranging) DEMs has been particularly useful for Prairie landscapes where filling of wetlands is a dominant factor contributing to flooding. The accuracy of spatially distributed runoff information has been verified against ground and aerial photographs, remote sensing imagery, and most importantly community stakeholder experience. The results for two recent LIRA case studies are presented which show the value of this simple, spatially focused approach to assessing flood hazards across wetland dominated landscapes. Stakeholders have used this spatially distributed runoff information for assessing community planning and development, and for considering potential response strategies where flooding has occurred.

## 19.2 RÉSUMÉ

Dans les Prairies canadiennes, la vulnérabilité aux inondations des municipalités rurales, de leur infrastructure et de leurs économies est devenue un sujet de préoccupation ces dernières années. Les approches de modélisation habituelles de l'évaluation des risques d'inondation ne sont pas appropriées pour les paysages des Prairies en raison des hypothèses non valides qu'elles formulent et de l'accent qu'elles mettent sur les tronçons de rivière et sur les plaines d'inondation adjacentes plutôt que sur le paysage dans son ensemble. Les paysages des Prairies, ayant récemment connu une déglaciation, sont composés de complexes de milieux humides pouvant contribuer à des inondations et ils sont également non jaugés. Le modèle altimétrique numérique (MAN) relatif aux zones humides « Wetland Digital Elevation Model (DEM) Ponding Model (WDPM) » a été intégré au Projet d'évaluation de la résilience des terres et des infrastructures (LIRA) pour offrir de meilleures données sur les risques d'inondation pour les paysages terrestres des Prairies. L'application du modèle WDPM aux MAN du LIDAR (détection et localisation par la lumière) a été particulièrement utile pour les paysages des Prairies où le remplissage des milieux humides constitue un facteur dominant qui contribue aux inondations. L'exactitude des données d'écoulement spatialement distribuées a été vérifiée à la lumière des photographies terrestres et aériennes, de l'imagerie de télédétection et, qui plus est, de l'expérience des intervenants communautaires. Les résultats de deux récentes études de cas LIRA sont présentés. Ils témoignent de la valeur de cette approche spatiale simple de l'évaluation des risques d'inondation dans les paysages dominés par les terres humides. Les intervenants ont utilisé ces données d'écoulement spatialement distribuées pour l'évaluation de l'urbanisme et du développement des collectivités et pour la prise en considération des éventuelles stratégies d'intervention là où des inondations se sont produites.

## 19.3 INTRODUCTION

The Land and Infrastructure Resiliency Assessment (LIRA) is a systematic methodology consisting of a land use inventory and benefit-cost analysis designed to assist local and regional municipalities, watershed groups, and other decision makers identify effective adaptation strategies to address the risks due to extreme runoff events (Agriculture and Agri-Food Canada, 2013).

A key input for the economic modelling is a geospatial flood hazard assessment that can help identify urban and rural regions vulnerable to flooding and their intersection with economic infrastructure and/or areas of social or environmental importance. In Prairie landscapes these regions often include hydrological interactions within ungauged basins.

Canadian Prairie hydrology is complicated by the nature of Prairie landscapes (Winter, 1989; Shook and Pomeroy, 2011b; Shaw *et al.*, 2011). The Prairie Pothole Region (PPR), which includes the Canadian Prairies, is marked by numerous wetland depressions capable of receiving and storing runoff and groundwater discharge, recharging groundwater, or functioning as flow-through systems (Euliss *et al.*, 1999). Wetlands can interact hydrologically by connecting and disconnecting, which are complex processes that are influenced by the internal state of the system (the storage water levels and the antecedent soil moisture conditions) and by the local meteorological forcings (Shook and Pomeroy, 2011b; Shaw *et al.*, 2011).

Complexes of wetland depressions may contribute runoff to larger systems when a series of interconnected depressions drains into a waterway. As a result, Prairie floods are due both to rising streams and to the fill-and-spill of interconnected depressions. Therefore the ‘basins’ that require modelling include those of the interconnected wetland depressions, whose size and connectivity change dynamically with the changes to the water stored within them.

Although some Prairie streams are gauged, the complexes of wetlands and the ephemeral streams which connect them are not, so the hydrological responses of complexes of Prairie wetlands depend upon the prediction of ungauged basins. The ability to model the interactions among wetlands is critical for determining runoff contributing areas, estimating discharge rates and runoff volumes, and identifying potential flood hazard zones. Unfortunately, standard hydrologic and hydraulic practices lack consideration of the wetland-dominated Prairie hydrology. Conventional hydrological models cannot reproduce the dynamic contributing fractions of Prairie basins, and hydraulic models are generally only applicable for connected channelized water flows.

Therefore current methods cannot generate geospatial flood hazard assessments that consider potential flood zones, for both rural and urban landscapes, within ungauged Prairie basins. Nevertheless, this type of

assessment is a key input to LIRA case studies in the Prairie region of Canada (Agriculture and Agri-Food Canada, 2013). LIRA required a diagnostic tool to provide estimates of the spatial distributions of runoff and the possible extents of flood hazards over entire landscapes.

## 19.4 METHODS

### The Wetland DEM Ponding Model (WDPM)

The Wetland DEM Ponding Model (WDPM) was developed at the Centre for Hydrology of the University of Saskatchewan (Shook and Pomeroy, 2011b; Shook *et al.*, 2013). The original purpose of the program was to model changes in the contributing area of wetland-dominated Prairie basins, due to the changes in the states of wetland storage; however, as the WDPM computes the spatial distribution of ponded runoff on a Prairie landscape, it has also been applied as a diagnostic tool to identify areas within the landscape vulnerable to runoff / flooding hazards.

The WDPM models the destination of surface runoff by applying the algorithm of Shapiro and Westervelt (1992) to a depth of water which is added to the entire DEM. The depth of water may be chosen arbitrarily; however, reference water depths have been applied to examine the potential spatial limits of runoff and flooding boundaries within the entire landscape. The reference depths applied are generally equivalent to annual extreme 24 hour return-period rainfall totals (e.g., 1:100 yr, 1:200 yr) and to other extreme rainfall cases that can contribute to flooding on the Prairies. The Vanguard, SK flood in July 2000, in which 300 mm of rainfall fell in 8 hours (Hunter *et al.*, 2003), is of great interest in the Prairies, and was used as reference depth of water in the runoff simulations. Because the model assumes that all of the applied water runs off, the simulations exaggerate the extent of actual flooding that would be due to rainfall events; however, the simulations are still considered to be useful as a qualitative description of the location of the destination of runoff, as they represent worst-case scenarios.

The WDPM is well suited to routing runoff throughout Prairie landscapes and basins. Conventional overland flow models are limited to identifying runoff directions from a DEM cell to the single direction having the steepest slope; the Shapiro and Westervelt (1992) algorithm allows water to drain in all downhill directions, simulating the convergence and divergence of fractional flow, which generates realistic runoff patterns. The algorithm is also useful in

that the water is moved physically between cells across the entire DEM. The iterative nature of the algorithm allows the runoff paths to change dynamically as wetlands fill and connect, but it can be very slow to converge, typically requiring hundreds of thousands of iterations. Although the WDPM is written in Fortran 95 for speed, very large DEMs have resulted in model runs lasting many hours or days. Improved coding and parallel processing have subsequently reduced computation times by more than order of magnitude.

## 19.5 DIGITAL ELEVATION MODELS

The WDPM requires a digital elevation model (DEM) formatted as a gridded 2D ESRI ASCII file as input. In Canada, freely available elevation data products with moderate spatial resolutions of 30 m or 90 m include Canadian Digital Elevation Data (CDED), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Shuttle Radar Topography Mission (SRTM) data surveyed in February 2000.

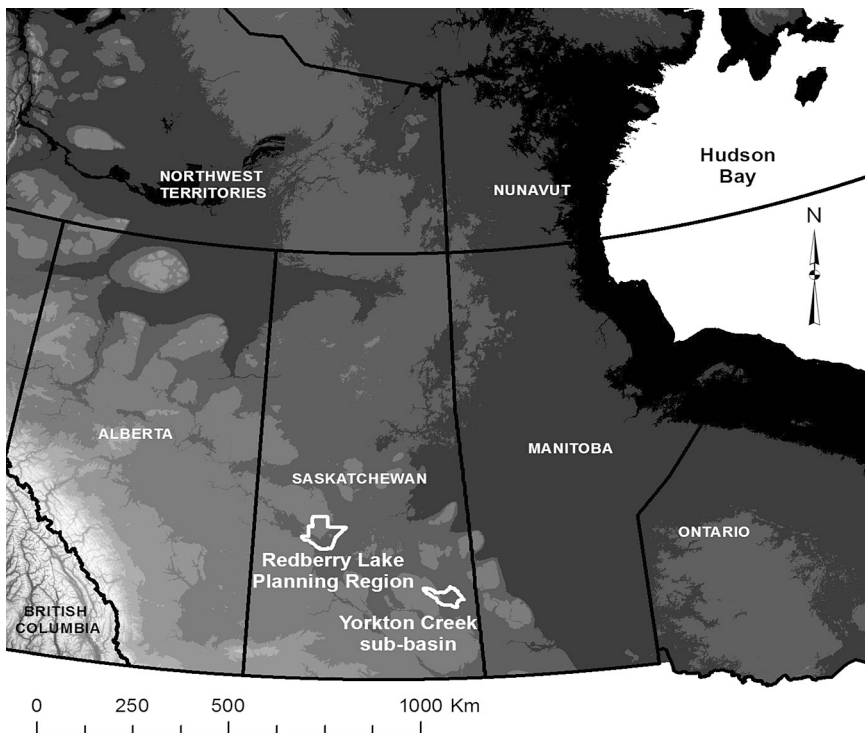
All surface elevation datasets contain errors and / or artefacts which limit their potential suitability for derivative analysis. Deep holes and trenches in the 30 m ASTER data (attributed to the limited contrast in relief), contour artefacts embedded in the 30 m CDED data, and the coarser spatial resolution of SRTM V4 (90 m) rendered these data unsuitable for WDPM simulation purposes. A second source of SRTM data considered was SRTM V3 which is a global void-filled downscaled (re-interpolated) version of the SRTM 90 m elevation data having a horizontal resolution of 30 m. The suitability of SRTM V3 data for any given application will generally depend on the backscatter noise in the DEM due to topographic and vegetation characteristics (Bhang and Schwartz, 2008; Hancock *et al.*, 2006).

Remotely sensed LiDAR survey data, although costly, provide the greatest level of surface elevation detail and accuracy possible for producing a DEM. This method generates massive point clouds from measured laser pulses reflected (returned) from any contacted surface objects. A general limitation of LiDAR is that due to the size and detail, the data can be difficult to work with, and may require conditioning to enhance the hydrological connectivity of infrastructure such as culverts.

Two sources of elevation data were considered for the LIRA case studies in Prairie locations. Not surprisingly, the WDPM simulations based on LiDAR provided the most accurate and useful information. Simulations based on

SRTM V3 data were useful in some areas but were not nearly as accurate or as detailed as the LiDAR simulations. Visual inspections of runoff simulations based on SRTM V3 suggest that the lower resolution data are generally more useful in areas characterized by undulating topography where drainage into wetlands, lakes, and along channels is relatively well defined, and tall vegetation is sparse.

Less information is generally obtained from areas of relatively low relief, where drainage is poorly defined and vegetation is dense, obscuring the underlying topographic variability (Bhang and Schwartz, 2008). Due to the timing of the SRTM data capture (during the winter in Canada) and to processing (downscaling), and where the topographic relief is low or vegetation is dense, the SRTM V3 dataset may not be suitable for WDPM in some Prairie locations.



**Figure 19.1** Locations of Redberry Lake Planning Region and Yorkton Creek sub-basin in Saskatchewan, Canada. Shaded relief is based on Canada 3D DEM obtained from Natural Resources Canada.

For the purpose of this paper, LiDAR survey data with a vertical accuracy of  $\pm 15$  cm were available for a portion of the Redberry Lake planning region located in Saskatchewan. The accumulated water depths generated from LiDAR based analysis are more likely to be correctly resolved than outputs generated from SRTM V3 which has a vertical accuracy of 16 m.

## 19.6 EXAMPLES OF FLOOD HAZARD ASSESSMENT

LIRA has been involved in three case studies within the Prairie region of Saskatchewan; at Corman Park, SK from 2006-2009 (Agriculture and Agri-Food Canada, 2013), and in the case studies presented here. The flood hazard assessment methodology which was initially developed for the Corman Park study was improved by the introduction of the WDPM. As described above, for simplicity the soil surface was assumed to be impervious to infiltration for the runoff simulations, which maximizes the assessment of the flood hazard. The cases presented are for a coarse DEM simulation in the Yorkton Creek sub-basin, which is located within the Assiniboine watershed in eastern Saskatchewan, and a fine DEM simulation for the Redberry Lake Planning Region, which is located in central Saskatchewan. The locations of these regions are shown in Figure 19.1.

### Assiniboine case study: Yorkton Creek sub-basin

In the Yorkton Creek region, the simulation was performed using SRTM V3 data, as no LiDAR data were available. An example of the runoff simulation output for Yorkton Creek is shown in Figure 19.2. This simulation used a reference water depth of 110 mm applied to the DEM. The reference depth was derived using Environment Canada's (2012) Gumbel distribution of annual maximum rainfalls (1:200 year, 24 hour rainfall depth). The spatial pattern of accumulated runoff is generally realistic, as it coincides with the large streams and accumulation zones within lakes and larger wetland areas depicted in the overlaid hydrography in Figure 19.2. Although the information is derived from coarse DEM data, the runoff simulation can provide some useful flood hazard information.

Figure 19.2 indicates that the simulated runoff accumulates in two large depressional features in the city of Yorkton, which are where storm water retention ponds were built in 2011 in response to the storm water flooding that occurred in July 2010. The general agreement between simulated runoff and real flood hazard zones within Yorkton and the surrounding area is



encouraging. A key limitation of this relatively coarse dataset, is that the simulation may cause water to accumulate at locations that may not be real features. Also roads cannot be resolved at the scale of this DEM, so the influences of roads on drainage patterns cannot be considered directly. Therefore the simulation outputs must be used with caution, and the



**Figure 19.2** Yorkton Creek region. Gray shaded areas indicate accumulated runoff from the runoff simulation model (WDPM) output based on 110 mm of water added to the SRTM 30 m DEM. Black outlines are the surface hydrography blue lines and water bodies from the National Hydrography Network.

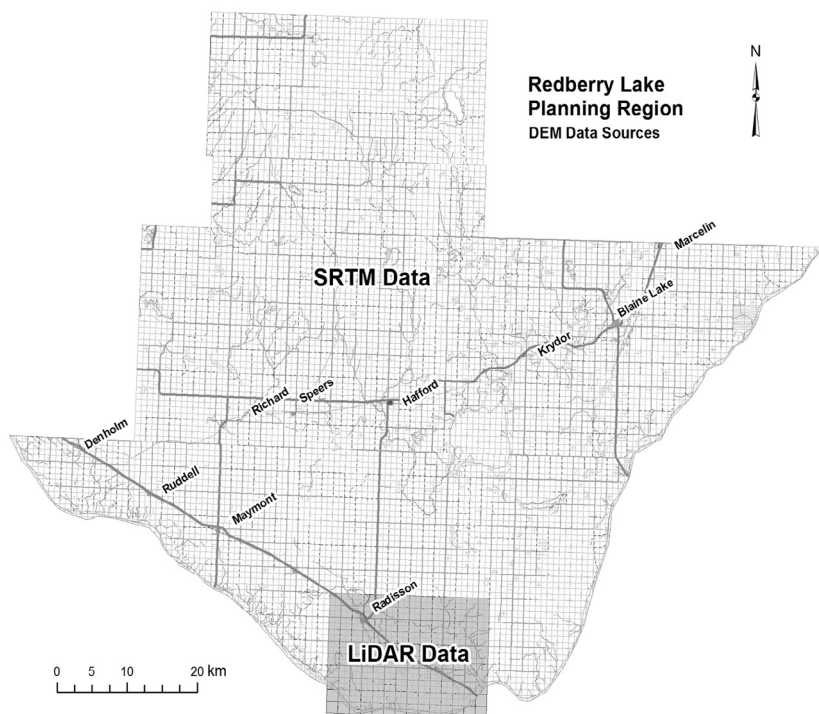


personal experiences of stakeholders are crucial to verifying the general accuracy and usefulness of the information.

### Redberry Lake planning region case study

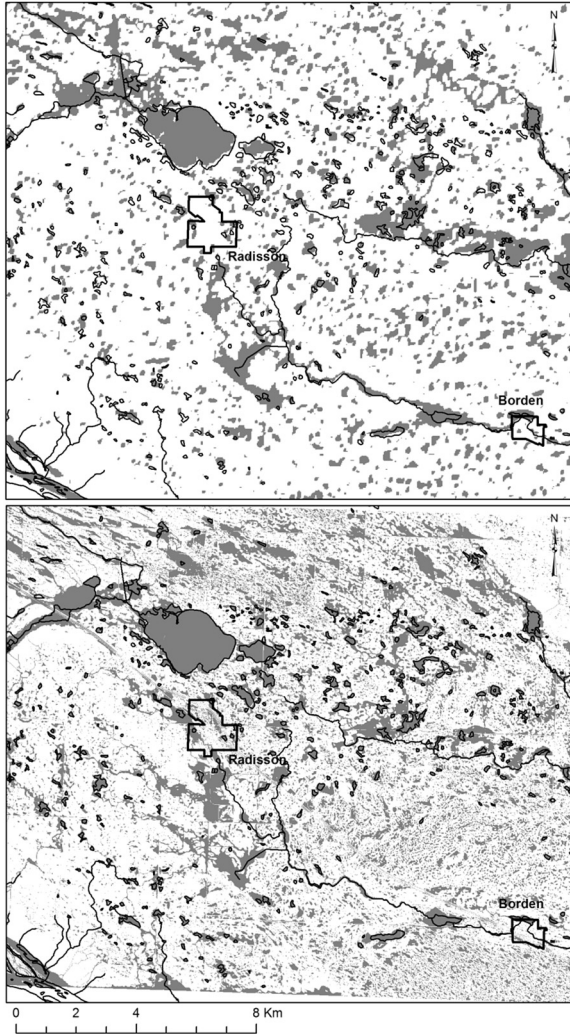
Rural municipalities within the Redberry Lake planning region are currently engaged in studies for future planning and development. Through consultations with project proponents and community stakeholders, a region that included the town of Radisson and village of Borden was identified as being vulnerable to runoff flooding. This region was considered to be a logical site for testing the utility of WPDM on a fine scaled LiDAR DEM that could be verified by the personal experiences of stakeholders. The location of the study and of the LiDAR survey data are indicated in Figure 19.3.

For comparative purposes, runoff simulation results are presented in Figure 19.4 for both the SRTM V3 and the LiDAR survey DEM data. The maps demonstrate the differences in the outputs when 100 mm of water was



**Figure 19.3** Redberry Lake planning region. Extent of SRTM 30 m and 5 m LiDAR data surveyed in October, 2011.

added to each DEM; approximately the 1:100 year, 24 hour rainfall amount for this region. The improvement in the diagnostic level for a flood hazard assessment is demonstrated by the detailed results for the simulations using the 5 m LiDAR DEM and the SRTM V3 30 m DEM in the Redberry Lake planning region plotted in Figure 19.4.



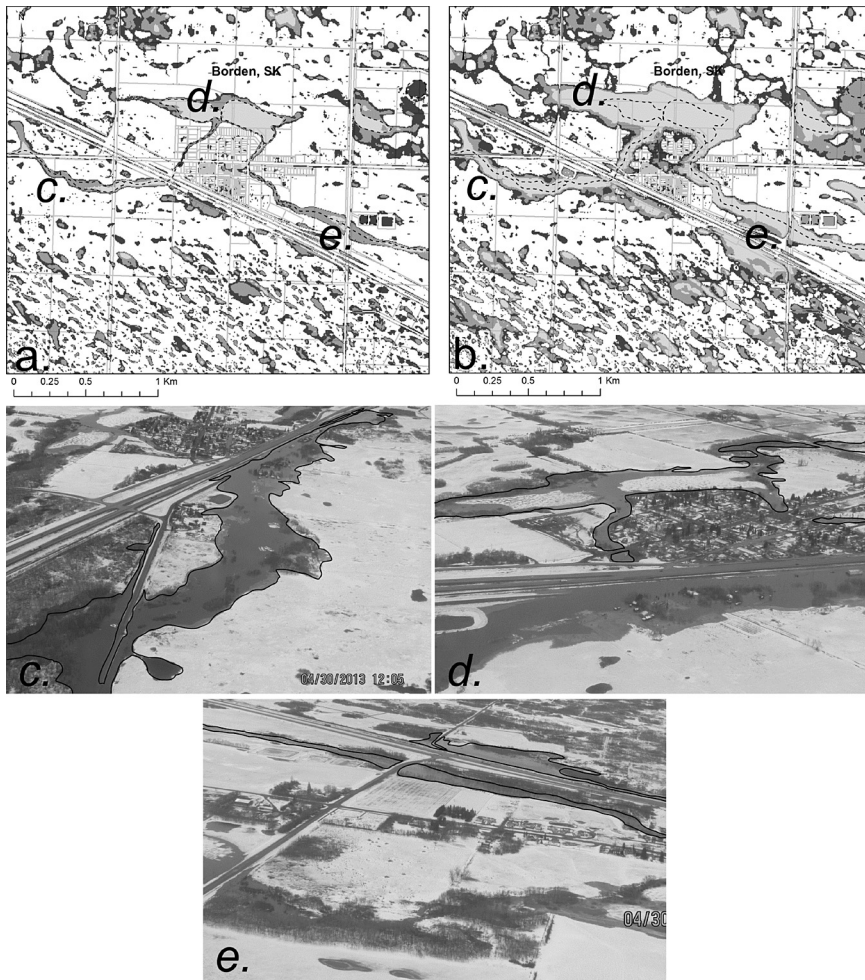
**Figure 19.4** Radisson and Borden area. Runoff simulation model (WDPM) output based on 100 mm of water added to the SRTM 30 m (top) and LiDAR 5 m (bottom) DEM data. Gray shaded areas indicate accumulated runoff. Black outlines are the surface hydrography blue lines and water bodies from the National Hydrography Network.

In general, the spatial water extent and connectivity of surface water, produced by the simulations using the detailed LiDAR data, cannot be matched by those using the SRTM V3 data. The higher-resolution LiDAR simulation indicates greater potential for water ponding within the landscape, and for backflooding influenced by roads. Based on a visual inspection of the outputs, it is asserted that the spatial extent of runoff for the SRTM V3 data is overestimated in some areas compared to the LiDAR derived spatial extents, and underestimated in other areas. These simulation maps are valuable for identifying locations where more detailed hydrologic or hydraulic analysis may be required to assess areas affected by changes to a drainage design, or areas of inundation associated with rising water levels.

### **Verification of WDPM Runoff Simulation Output**

In late April 2013, the town of Radisson and the village of Borden declared a state of emergency due to large depths of spring melt runoff which resulted in rising flood waters. Aerial photos taken during the flooding are related to WDPM outputs for verification purposes for both the Borden (Figure 19.5) and the Radisson (Figure 19.6) regions. For each region, results for the application of 100 mm (Figure 19.5a and Figure 19.6a) and 300 mm (Figure 19.5b and Figure 19.6b) of water to the DEMs are presented. Both sets of simulations are included to demonstrate the differences in the estimated spatial extents of the outputs, the magnitudes of the hazards depicted, and whether either scenario is realistic. Overlaying the township fabric onto the respective flood hazard assessment maps allows users to trace the location of water movement through the towns and along the roads and evaluate possible intersections with economically or socially important receptors.

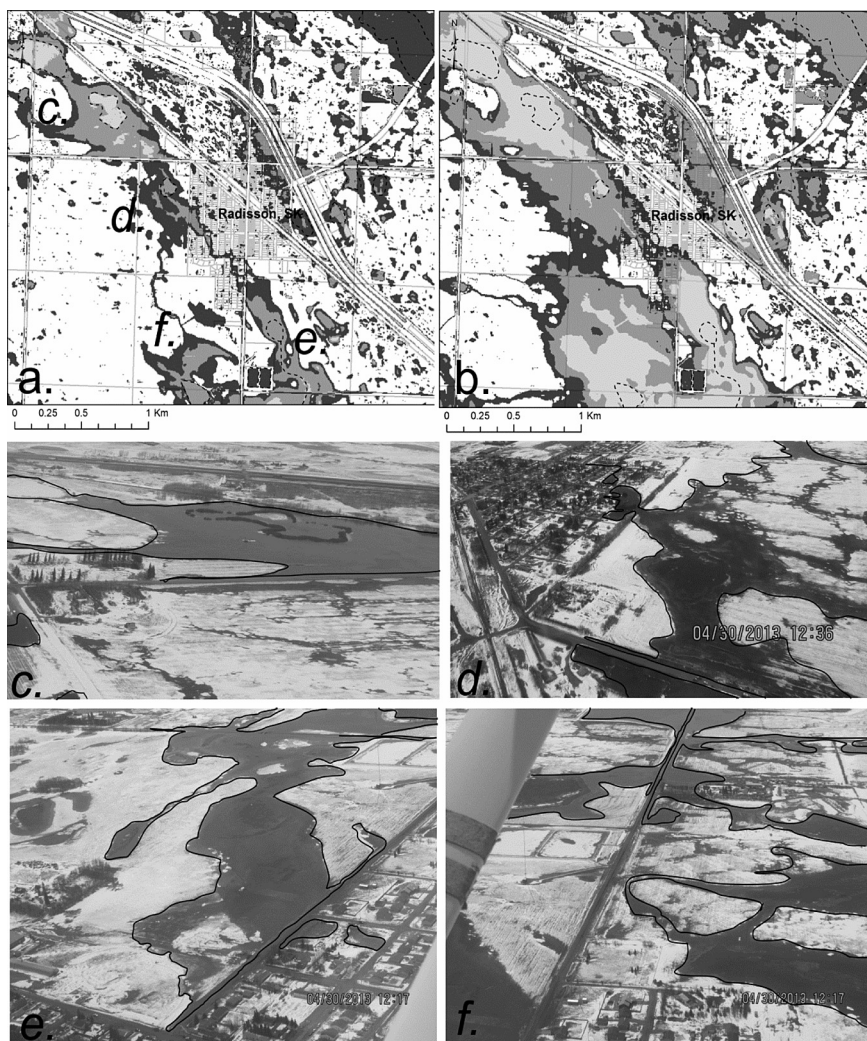
For the village of Borden (shown in Figure 19.5) various portions of the 100 and 300 mm water depth simulation results appear to agree with flooding observed in photos 5c - 5e (outlined in black); for example, the extent of flooding outlined in photo 5c flowing into Borden from the west, appears to be better represented by the results for the 300 mm simulation (Figure 19.5b). By comparison, the majority of flooding outlined in photo 5d (through and around the village) appears to be better reflected by the 100 mm simulation results (Figure 19.5a); and a smaller portion in the upper right of the photo, by the 300 mm simulation. Similarly, the area of high water outlined in photo 5e (east of the village) appears to be better reflected by the spatial extent of runoff in the 100 mm simulation results.



**Figure 19.5** Example of WDPM output for the Borden area from applying, (a) 100 mm water depth and (b) 300 mm water depth. Photos (c - e) link the WDPM output to verified areas of flooding outlined in black. Aerial photos were provided courtesy of Frank Fox, Saskatchewan Water Security Agency.

For the town of Radisson the general shapes of the flooded areas surrounded by higher land features can be visually compared with the WDPM output in Figure 19.6a. The flooding observed in photos 6c - 6f appears to better capture the results for the 100 mm simulation (Figure 19.6a). The respective high water outlines (in black) in the photos have been linked to the outputs; land marks in the photos and runoff output serve as useful references for navigation purposes. It should be noted that flood waters shown in photo 6c

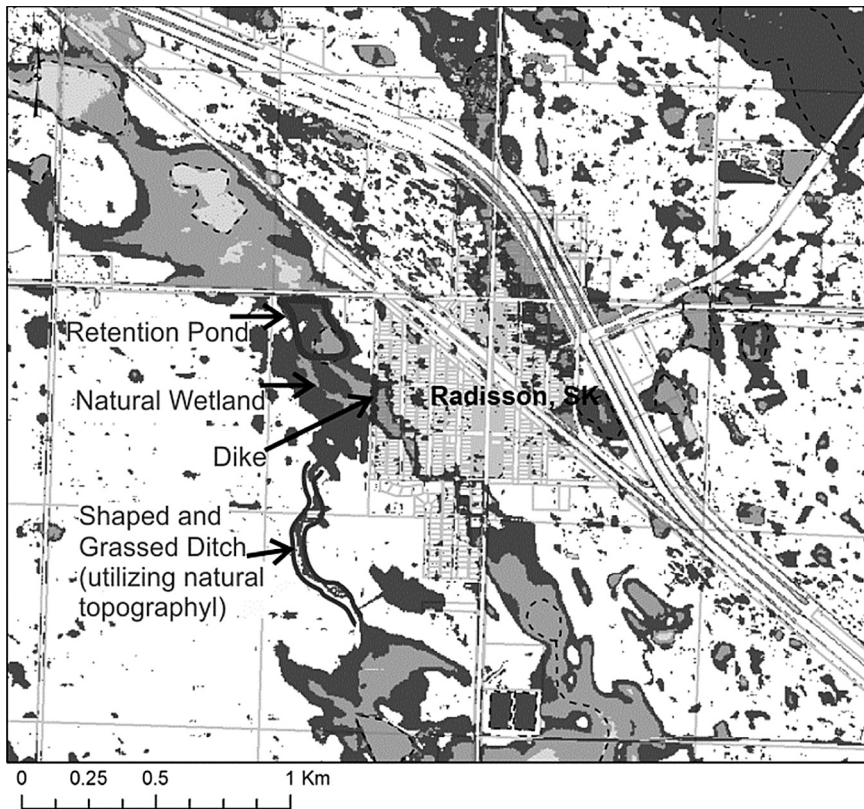




**Figure 19.6** Example of WDPM output for the Radisson area from applying, (a) 100 mm and (b) 300 mm of water. Photos (c - f) link the WDPM output to verified areas of flooding outlined in black. Aerial photos were provided courtesy of Frank Fox, Saskatchewan Water Security Agency.

were being pumped into the natural wetland area shown in photo 6d which artificially increased the area being actively flooded in that region.

Based on the available observations, the flood hazard information provided by the 300 mm simulation generally appears to be unrealistic for the Radisson area, which illustrates a limitation of the modified LIRA methodology for



**Figure 19.7** Example of potential adaptation option based on a flood hazard assessment and elevation profiles generated from LiDAR data (courtesy Frank Fox, Saskatchewan Water Security Agency).

assessing flood hazards in Prairie landscapes. Although the simulations based on reference values have provided useful information to stakeholders, the scientific and technical rigor could be enhanced by linking the spatial simulations to runoff estimates provided by a hydrological model that considers a full range of Prairie processes. The Cold Regions Hydrological Modelling (CRHM) platform, which was also developed at the Centre for Hydrology, has been developed to model the full range of hydrological processes that are responsible for producing runoff on the Canadian Prairies (Pomeroy *et al.*, 2007). Work is ongoing on uniting the physical process simulations of CRHM, with the spatial representation of the WDPM.

## **Input for Potential Adaptation Strategies**

Stakeholder and community feedback has been valuable for verifying the accuracy of runoff outputs; particularly their personal accounts of where past flooding has occurred (or not) and where it might occur in future events. The runoff simulation maps can be useful for stakeholders in rural communities to assess their vulnerability to flood hazards without increasing the danger of their doing nothing, based on a probabilistic assessment of a flood occurrence.

The simulation outputs allow decision makers to trace the pathways of surface water over the landscape, which can aid in the development of adaptation strategies. Figure 19.7 shows an example of one adaptation option generated for the town of Radisson (through LIRA) that might include building a retention pond, dike, and grassed ditch along a natural drainage pathway. Stakeholders have indicated that a well-drained area exists further south where surface water does not generally accumulate, and that this location may be able to absorb the redirected runoff. Of course, the potential hydrological and hydraulic impacts of any adaptation strategy also need to be assessed.

## **19.7 CONCLUSIONS**

The recent large-scale flooding events in the Prairie Provinces have demonstrated the need for better flood protection and mitigation strategies in the region, which includes many ungauged basins. Conventional flood hazard modelling approaches are generally unsuitable for assessments in Prairie landscapes that are dominated by complexes of wetlands. A new diagnostic runoff simulation tool, the WPDM, was used to generate estimates of runoff flood hazard locations in Prairie landscapes.

The accuracy of the spatially distributed runoff map is partly dependent on the quality and scale of the input digital elevation model (DEM) and also on the depth of water applied to the DEM. LiDAR derived runoff maps provide the greatest detail and also include the influence of roads on water accumulation. Verification of runoff map outputs using ground and aerial photographs, and stakeholder experience demonstrated that the runoff maps, despite their inaccuracies, can be useful for assessing flood hazards in ungauged Prairie basins where fill-and-spill flooding is of key concern.



The methods applied here for the purpose of LIRA rely on the application of reference water depths which are generally equivalent to return-period rainfall amounts and the historical Vanguard event. The technical rigor of the method could be improved by using runoff water depths provided by a physically based Prairie hydrological model. Nevertheless, when verified against recent flooding events in the spring of 2013, the ponding model depicted the observed paths of rising waters and flood zones through the communities and the surrounding landscape surprisingly well.

Conventional flood plain hazard assessments generally show the inundation areas only along river reaches. Comprehensive flood hazard maps for the Prairies should include entire landscapes, and could be generated by combining estimated flood plain hazard zones and spatially distributed runoff information provided by the WDPM. Specifically, combining the spatial runoff modelling of the WDPM and a hydrological model capable of simulating the unique aspects of Prairie hydrology may allow the generation of spring melt runoff maps that are based on return-period runoff events.

## **19.8 ACKNOWLEDGEMENTS**

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