# Integrating scales from 10s of kms to one metre for spatial flood modelling

Stefan W. Kienzle[1,2]

[1]Department of Geography and Environment, University of Lethbridge, stefan.kienzle@uleth.ca
[2]Department of Environmental Sciences, ABEERU, University of South Africa

## ABSTRACT:

Climate change results in more frequent and more extreme flooding and subsequently 100-year floods need to be re-calculated. To provide critical input for regulatory land use planning, flood mitigation purposes, and to make local land use decisions, detailed mapping of flood zones under future (2041-2070) extreme events are required. A study to map the 100-year flood under future climate conditions was recently completed for a 100km$^2$ area near Slave Lake in Alberta. A core task of the study was to integrate spatial data from multiple scales. Daily climate data in Canada are available at a 10km grid scale. Future climate data sets in the form of regional climate models have grid scales of between 22 and 44 km. These climate data needed to be downscaled to the size of hydrological response units (1km$^2$–30km$^2$) used for hydrological simulations of the watershed feeding into the study area. The simulation results are fed into a hydraulic model covering the entire flood study area, which is run on a 1m$^2$ grid cell size (Lidar derived DEM and DSM)) at a time interval of 1 sec for the entire 10-day flood wave, resulting in highly detailed 100-year flood maps. The maximum flood values for each m$^2$ were extracted and overlain with individual houses and roads to create a spatial flood database for the study area.

## 1. Introduction

As flooding becomes more frequent and more extreme due to climate change, the detailed mapping of flood zones under extreme events is essential, as these maps are needed for regulatory land use planning, flood mitigation purposes, and to make local land use decisions. In Alberta, the design flood for planning purposes is the 100-year flood. British Columbia uses the 200-year flood, while Saskatchewan uses the 500-year flood. The determination of a future 100-year flood can be no longer reliably extrapolated from observed annual maximum series, because due to climate change and associated increases in frequency and magnitude of extreme events the historical record is no longer representative of future events. Only physically-based and spatially distributed hydrological models have the means to assess the hydrological response due to climate change, as these models can represent the spatial variability of hydrological processes throughout complex watersheds (Bathurst et al., 2004). Significant downscaling from regional climate models (RCMs) to hydrological response units (HRUs) is required (Table 1). The requisition of 1m$^2$ Lidar-derived digital elevation models (DEMs) and digital surface models (DSM) are essential for the flood mapping. They form the basis of the hydraulic model's spatial resolution, which is required to be in the metre scale to be reliable under unsteady flow conditions in complex terrain.

 Volume DOI: 10.17605/OSF.IO/N6DU5

DSMs are also used for very detailed land cover delineation, a key requirement of hydraulic models.

The objectives of the study were to map the extent of the future (2041-2070) 100-year flood for the Swan River First Nation Reserve (Figure 1) and overlay the flooded areas with local infrastructure. This required the simulation of the 100-year future flood of the Swan River Watershed (Figure 1) using a physically-based hydrological model as well as the hydraulic simulation of the 100-year flood wave through the study area, thus determining flooded areas.

## 2. Methods & Data

The 1200km² Swan River Watershed in central Alberta is the hydrological modelling study area, which is gauged by a WSC (Water Survey Canada) gauging station (Figure 2). The physically-based agro-hydrological modelling system ACRU (Agricultural Catchment Runoff Unit), developed at the School of Bioresources Engineering and Environmental Hydrology (formerly the Department of Agricultural Engineering) at the University of Kwa-Zulu-Natal, South Africa, since the late 1970s (Schulze, 1995) and adapted for cold-climate conditions (Kienzle and Schmidt, 2008; Kienzle et al., 2012) was set up to simulate the future 100-year flood. ACRU is a multi-purpose, multi-level, distributed physical-conceptual model that is designed to simulate total evaporation, soil water and reservoir storages, land cover and abstraction impacts, snow water dynamics and streamflow at a daily time step. The simulated future 100-year flood wave was then used as input into a HEC-RAS (Hydrologic Engineering Center River Analysis System), a hydraulic model developed by the Hydrologic Engineering Center, Corps of Engineers, U.S. Army, Davis, California, and the de facto standard for flood simulations in North America and recommended under the Alberta Flood Assessment Guidelines. Maximum water levels during the 10-day period of a 100-year flood wave were simulated for the approx. 100 km² study area. The maximum water levels were used to overlay with infrastructure (houses, roads) using a spatial resolution of 1 m².

### *2.1 Hydrological Simulations*

ACRU was applied to simulate historical (1951-2017) and future (2041-2070) daily streamflows at the WSC gauging station. Model validation is the most important part of the hydrological modelling framework. The following five steps were executed to verify that the simulated streams mimic the observed ones:

1) ACRU was set up based on best available data (Kienzle, 1993, 1996), which includes elevation and terrain derivatives such as the sloped area under-estimation factor and daily solar radiation, climate variables such as minimum and maximum temperatures, precipitation, solar radiation, and estimates of relative humidity and wind speed, a range of land cover variables, a wide range of soil variables, and a spatial delineation of hundreds of hydrological response units.
2) A 10-year period which includes wet, dry, and normal years was chosen for the verification analyses. During the verification process, variables impossible to measure such as the proportion of outflow from an HRU on any given day, or the baseflow recession index, were adjusted within physically meaningful ranges to match available observations. A wide range of objective functions were used to statistically describe the success of the simulations quantitatively.
3) Once verification analyses were completed (Kienzle et al., 2012), ACRU was run for the entire simulation period (here: 1951 to 2017). Validation statistics were again computed for a wide range of objective functions to evaluate the quality of the simulations.

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4) Changing only model parameters that govern daily runoff, ACRU was re-calibrated to best fit the annual maximum series to represent flood peaks.
5) Finally, ACRU was applied with the same bio-physical parameter sets for each HRU to simulate future streamflows, where the only assumed change is a different set of daily climate time series (Warburton et al. 2010).

Three RCMs representing future climate projections (Barrow and Sauchyn, 2017) for the period 2041 to 2070 for relatively wetter/cooler to relatively warmer/drier conditions were bias-corrected and downscaled to match the existing 10 km Canadian climate grid.

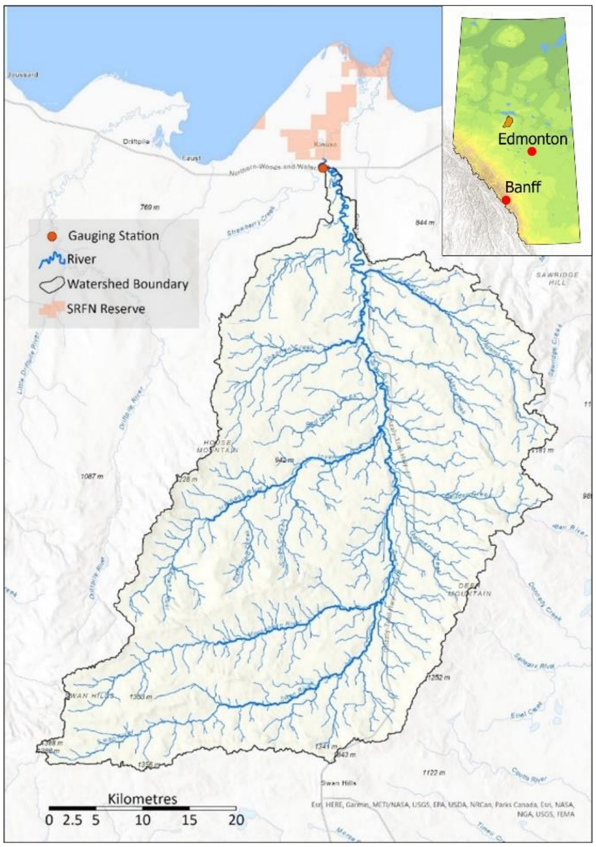


Figure 1: Study area (orange in the inset map) of the Swan River Watershed for the simulation of future 100-year floods

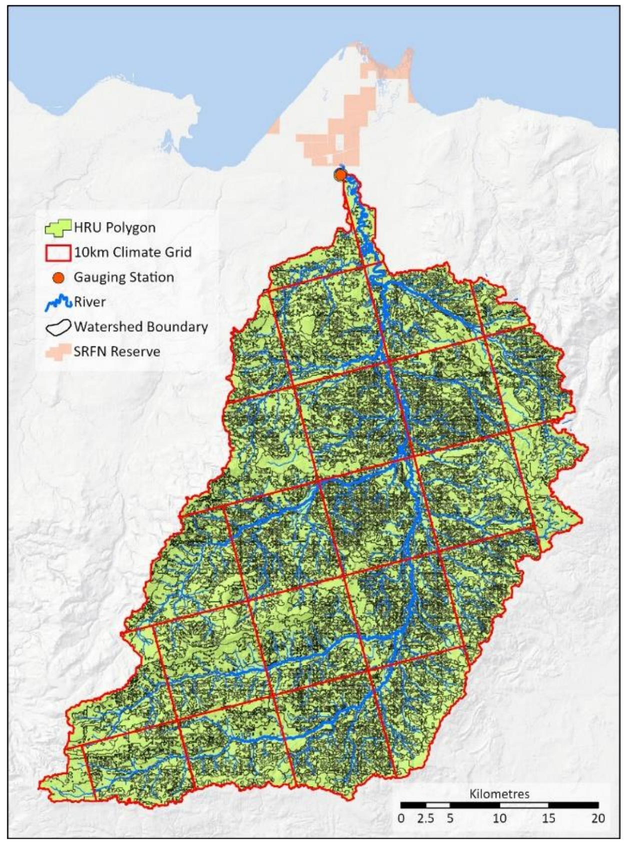


Figure 2: HRUs and 10km by 10km climate grid that "feeds" the HRUs with individual daily time series of precipitation, minimum and maximum temperatures, relative humidity, solar radiation, sunshine hours, and windspeed.

## *2.2 Downscaling*

Since the regional climate model data and hydro-climatological data are available in spatially separated time series, it was important to spatially downscale the RCM data using an area-weighting ratio based on the spatial overlay of the 10km climate grids and the RCM climate grids (Figure 3a). The downscaling and bias correction procedures were based on Thiessen Polygons for each RCM grid point (Figure 3a), followed by area-weighting and calculation of monthly correction ratios, multiplicative with precipitation, and additive with temperature. Once all 30-year future time series (2041-2070) were available in the 10km climate grid, corrections of daily temperature and precipitation to HRU level (Figure 3d) were carried out using local monthly lapse rates and correcting air temperatures for incoming solar radiation and land cover.

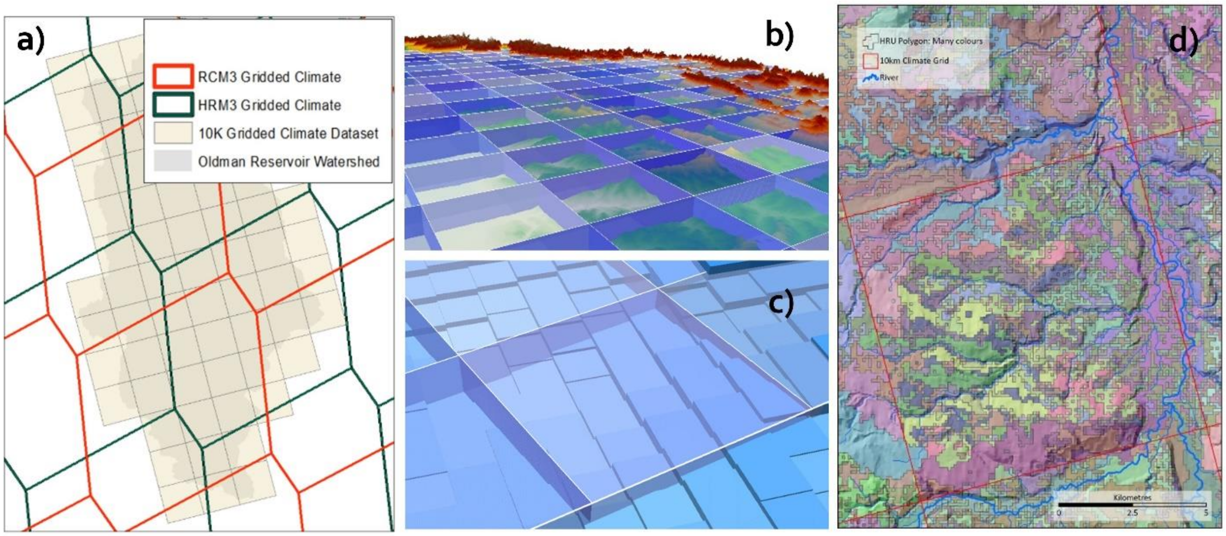


Figure 3: Downscaling from a) RCMs to 10km Climate Grids, b) 10km Climate Grids to 10m DEM, c) 10km Climate Grids to 2000m PRISM (Parameter-elevation regression on Independent Slopes Model) climate normal grid, and d) 10km Climate Grids to HRUs.

## *2.3 Hydrological Response Units*

HRUs are spatial units with relatively homogeneous hydrological behaviours that can be delineated based on a selection of similar physical characteristics (Kienzle et al., 2012). A digital elevation model (DEM) was used with a spatial resolution of 10m grid cells (equivalent to 1:20,000 scale maps in accuracy). For the creation of HRUs, terrain derivatives such as sloped area under-estimation factor and solar radiation were calculated and then resampled to a 100m grid cell size. The 100m DEM was classified into 100m interval elevation bands. The 10km climate grids were included for the HRU delineation, so that the HRUs could be fed by an individual climate time series, enabling more realistic hydrological simulations. The landcover shapefile was reclassified into eight land cover classes. The mean annual solar radiation was calculated using the Solar Radiation tool in ArcGIS 10.5, aggregated from quarter-hour intervals for the entire year for each 100m grid cell. The annual output was then reclassified into four quartiles.

The resulting HRUs were then analyzed for their area and HRUs with an area smaller than $1km^2$ were iteratively aggregated into neighboring HRUs until the smallest HRU was at least $1km^2$ in size (about 1/10th percent of the watershed area). The final number of HRUs was 506 (Figures 2, 3d). Each HRU was then parameterized to have a unique combination of hydrological variables, most of which were derived by GIS overlay analysis.

## *2.4 Verification Analysis*

The objective functions tested against performance criteria suggested by Moriasi et al. (2007) and Smithers and Schulze (1995) included:

- Percentage difference between the sum of simulated daily flows and observed daily flows, which is equivalent to the Percent Bias (PBIAS).

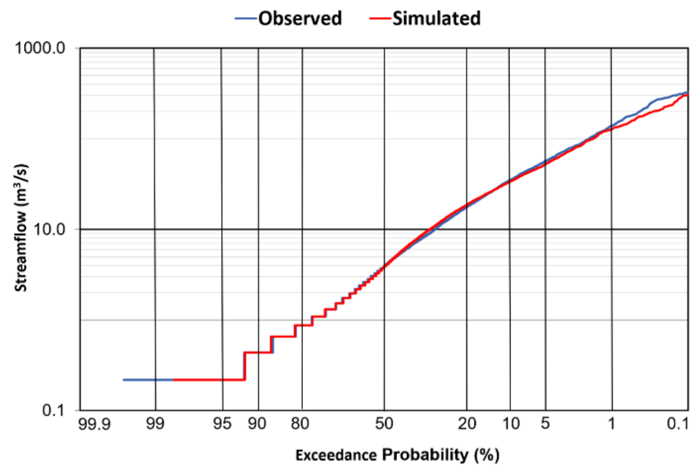


Figure 4: Comparison of exceedance probabilities of simulated and observed daily streamflows for the period 1971-2000, Gauging Station 07JB001 (Swan River at Kinuso).

- Percentage difference between standard deviations of simulated daily flows and observed daily flows.
- Coefficient of determination ($r^2$) for both daily and monthly flows.
- Regression coefficient (slope as a ratio),
- Ratio of the root mean square error to the standard deviation of measured data (RSR), and
- Nash-Sutcliffe efficiency coefficient (NSE).

In addition, a visual comparison of observed and simulated daily hydrographs and exceedance probability plots (Figure 4) were used for the evaluation.

After successful calibration using the full range of streamflows, ACRU was re-calibrated to match the annual maximum flows to represent flood flows, which are mostly under-simulated due to spatially coarsely sampled climate data. The only ACRU parameters changed were the proportion of daily generated streamflow that flows into the downstream HRU as surface water, interflow, or groundwater. For this task, only the annual maximum series of observed and simulated streamflows were statistically compared. After successful calibration (Figure 5), this ACRU setup was then used to simulate three future climate projections, from which individual annual maximum series were derived. This laid the foundation for flood frequency analysis, from which historical baseline (1971-2000) and future (2041-2070) 100-year flood flows were analyzed.

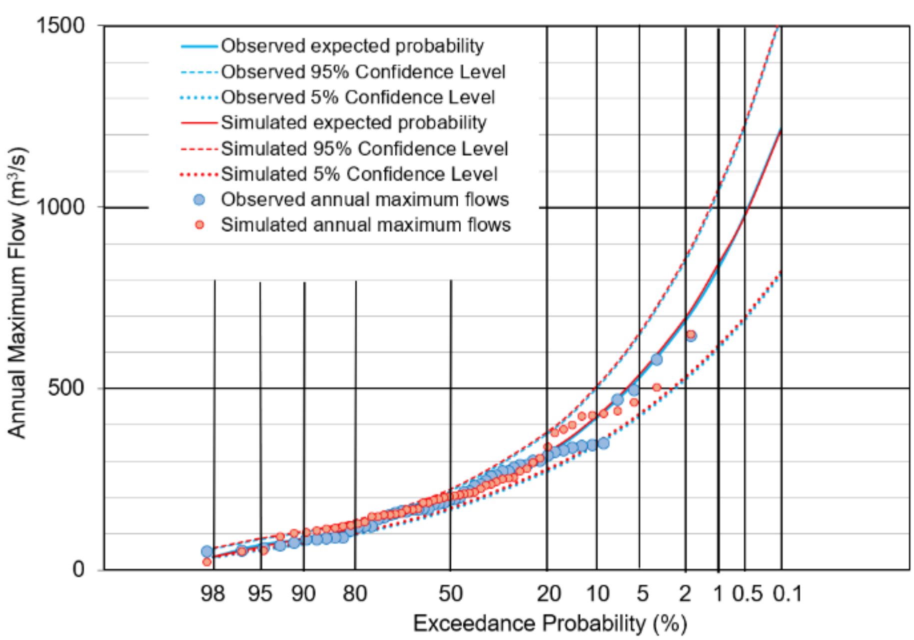


Figure 5: Comparison of simulated and observed annual maximum streamflows and fitted Log-Normal distributions, with 5 and 95% confidence levels.

Several standard distribution models were tested using the observed annual maximum series. Based on this analysis, the Log1-Normal distribution was selected as best representing the distribution of observed data (Figure 5). The correlation coefficient between observed and simulated annual maximum flows is 0.973. Now ACRU was readily setup for the simulation of future flood peaks.

From the RCM analyses, both climate models HRM3 (Hadley Regional Model 3) and RCM3 (Regional Climate Model Version 3) resulted in almost identical 100-year flood estimations for the period 2041-2070 (Table 1). The third estimate based on the Canadian Regional Climate Model (CRCM) is lower than the historically observed, and therefore does not represent a conservative measure. Consequently, a future 100-year flood value of 1200m³/s was used for flood risk mapping.

Table 1: Historical and future100-year flood values(m³/s)

| Observed 1961-2017 | Simulated 1961-2017 | HRM3 2041-2070 | CRCM 2041-2070 | RCM3 2041-2070 |
|---|---|---|---|---|
| 827 | 838 | 1196 | 808 | 1195 |

## *2.5 Hydraulic Analysis*

All flood events were simulated using the HEC-RAS model (Version 5.0.7) simulating unsteady (changing) flow conditions and 2-dimensional full momentum mode (Brunner, 2019). Running HEC-RAS in 2D mode required, in addition to a terrain layer, the careful setup of a computational mesh, and the selection of an appropriate computational time step, which was 1-sec. due to high water velocities. The creation of meaningful results of the model depends on careful data setup in terms of:

- Terrain (1m),
- land cover (lm, derived from DSM),
- computational mesh (3 -12.5 m)
  - main river,
  - watershed bounda-ries,
  - roads,
- roughness coefficients (1m, derived from DEM), and
- computational time interval (1 sec)

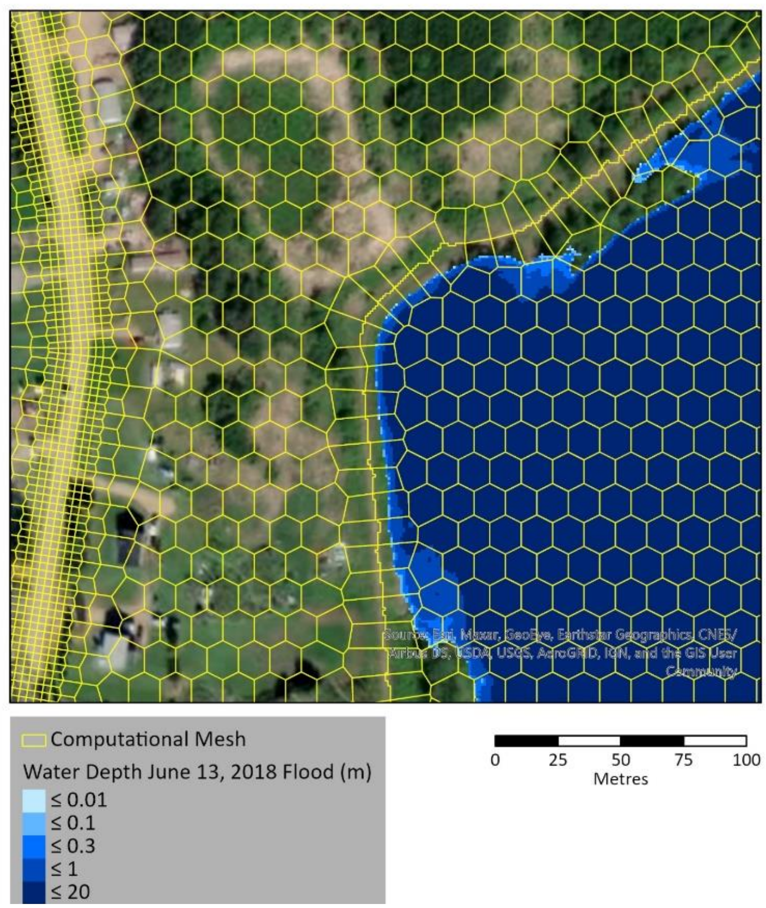


Figure 6: Water depth and velocities are calculated at the mesh resolution and are then distributed for each time interval according to the terrain within each mesh area, resulting in realistic water depth mapping at a 1m² resolution.

This resulted in 600,000 computational mesh grids (Figure 6) and 100 million grid cells. First, HEC-Ras was run for the last large flood (1918) for verification analysis through photographs and anecdotal knowledge. This was when the demand for a 1-sec simulation interval was discovered.

## 3. Results

The results included a series of inundation maps for flooding depth at a 1m² resolution for return periods 1:5, 1:10, 1:20, 1:50, 1:100 and 1:200-years. Overlay analysis resulted in shapefiles with of infrastructure (individual houses and roads) with fields for water depth for all return periods. The maximum flood values for each m² were extracted (Figure 7) and overlain with local infrastructure (Figure 8) to create a spatial flood database (Figure 9).

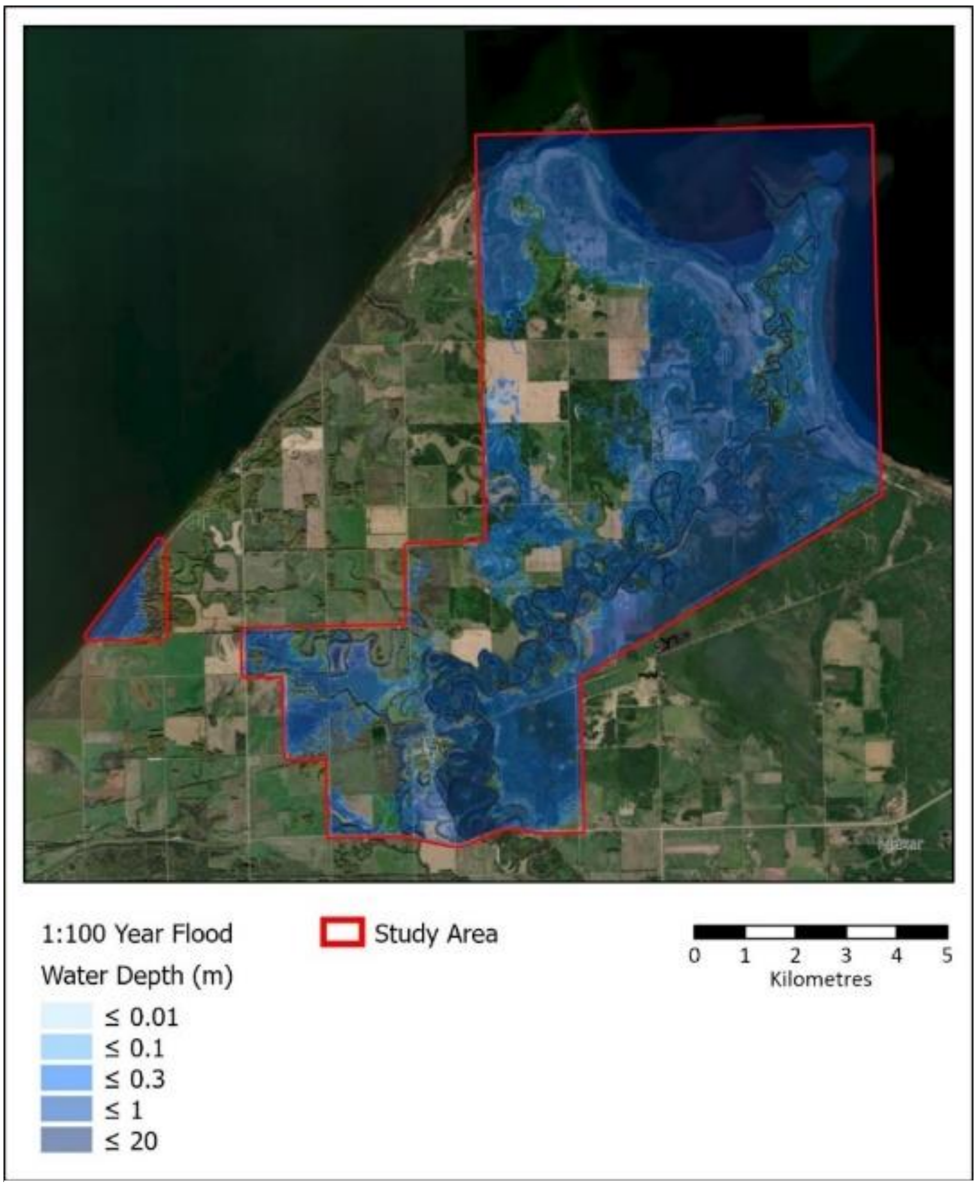


Figure 7: Maximum future 100-year flood level overlain over a base map.

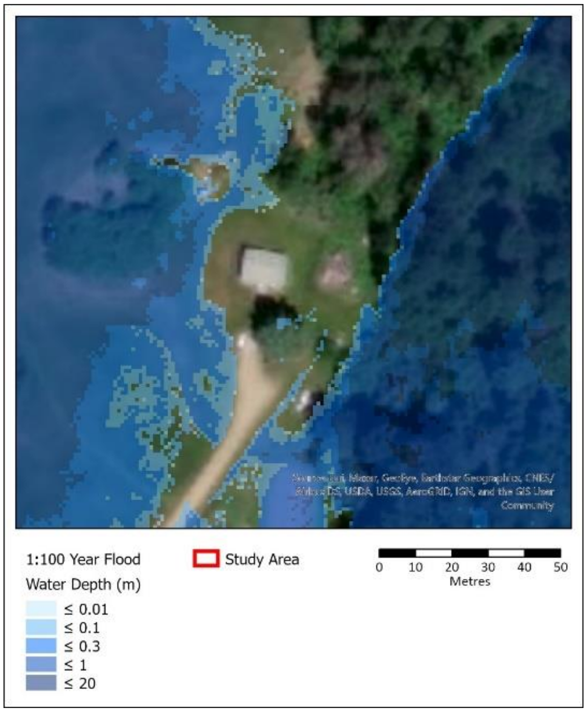


Figure 8: Example of flood levels at a map scale of 1:100, where individual 1m² pixels become visible.


Figure 9: A partial view of the shapefile containing road flooding depths, sampled at least every 10m. Here, the road location highlighted in red is flooded during the 1:100-year flood to a depth of 17cm, and during a 1:200-year flood to a depth of 22cm.

## 4. Discussion & Conclusion

Without spatial knowledge across a large range of spatial scales, ranging in this analysis from 44km for RCMs to 1m for DSMs, flood inundation maps could not be meaningfully carried out. As a flood depends on local topography, represented by high-resolution terrain data, and the hydrological conditions of the watershed upstream of the study area, represented by HRUs's at a one to 10skm² range, fed by climate data at a 100km² scale, and altered by RCM projections in the 500 to 2000km² scale. Detailed knowledge of the bio-physical and hydro-climatological conditions of the watershed are required at the HRU scale. The modelling procedure demonstrated here is based on spatially distributed physically-based modelling, integrating rigorous statistical and spatial analyses, to provide a time series of future flood events. The flood representing a given return period was fed into a spatially distributed hydraulic model with a spatial resolution of 1m². The hydraulic model simulated the flood wave for each grid cell for each second, and the maximum water depth values were extracted and mapped.

The procedure provided here is robust and is suited to be applied in similar studies. A project of this nature is limited by the availability, quality, and spatial resolution of all input data.

## Acknowledgments

This project was funded by Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC) and managed by MSES Inc.

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