IBI Group and NRCan

CanFlood 0.4

User Manual

Seth Bryant

December 8, 2020

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Notes and Acknowledgements

CanFlood is an Open Source experimental flood risk modelling platform. Natural Resources Canada and IBI Group assume no liability for any errors or inaccuracies. The tools provided in CanFlood are for convenience only, and the user is responsible for developing their own tests and confidence in any model results.

For the latest manual and software version, please visit the project page:

https://github.com/IBIGroupCanWest/CanFlood

Development Acknowledgements

The CanFlood plugin and this user's manual were developed by IBI Group under contract with Natural Resources Canada (NRCan).

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Glossary

Annual Recurrence Intervals (ARI)	The statistical expectation of time between events derived from some observed time-series (e.g. a 100 ARI magnitude flood or larger has occurred 10 times in the past 1000 years). The inverse of an event's ARI is the annual exceedance probability of that event (e.g. a 100 ARI flood has a 1% chance of occurring each year). Often, the suffix 'ARI' is replaced with '-year' (e.g. a 100 ARI flood is equivalent to a 100-year flood).
Annual Exceedance Probabilities (AEP)	The inverse of ARI.
Estimated Annualized Damages (EAD)	Expected value of impacts. See Section 5.3.1.

1. Introduction

CanFlood is an object-based, transparent, open-source flood risk modelling QGIS plugin built for Canada. CanFlood facilitates flood risk calculations with three 'toolsets':

1) Building the model
2) Running the model
3) Visualizing and analyzing the results

Each of these steps has a suite of tools designed to assist the flood risk modeller in a wide range of flood risk modelling tasks.

CanFlood is NOT a flood risk model, instead it is a modelling platform with a suite of tools to aide users in building, executing, and analyzing their own models. CanFlood requires users to pre-collect and assemble the datasets that describe flood risk in their study area (see Section 3). Once analysis in CanFlood is complete, users must apply their own professional judgement and experience to attach the necessary context and advice to any reporting before communicating results to decision makers. CanFlood results should not be used to *make* decisions, instead they should be used to *inform* decisions along with all the other dimensions and criteria relevant to the community at risk.

1.1. Intended Users

The CanFlood plugin is for users with spatial and vulnerability data desiring to perform an object-based flood risk assessment (FRA) in Canada. CanFlood is meant for flood risk practitioners with the following expertise:

- Object-based flood risk analysis
- QGIS (novice)

See Section 1.4.2 for a summary of guidelines and procedures related to FRAs in Canada.

1.2. Control Files

CanFlood models are designed to write and read from small 'Control Files'. These make it easy to build and share a specific model or scenario, and to keep a record of how the results set were generated. These also facilitate making a small change to a common input file (e.g. inventory), and having this change replicated across all scenario runs. Control Files don't contain any (large) data, only parameter values and pointers to the datasets required by a CanFlood model. All CanFlood filepaths are absolute, so moving or renaming files/folders will break a control file. Diligent and consistent file storage and naming conventions are essential for a pleasant modelling experience. Most Control File parameters and Data Files can be configured in the 'Build' toolset; however, some advanced parameters must be configured manually (see Section 5 for a full description of the Control File Parameters)[1]. The collection of model inputs and configured control file is called a 'model package' as shown in Figure 1.1.

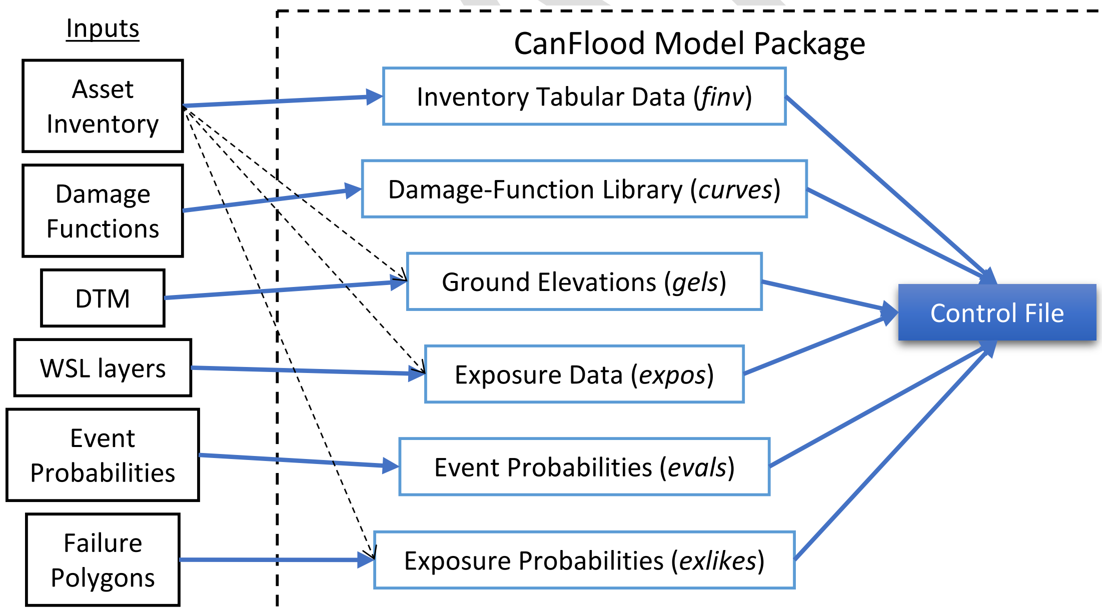


Figure 1.1: CanFlood model package summary diagram.

[1] All SOFDA inputs must be built and configured manually.

1.3. Analysis Levels

Flood risk analysis objectives and applications are as diverse as the communities they serve. To accommodate this wide range, CanFlood contains 3 separate modelling tools or tiers as summarized in Table 1.1.

Table 1.1 - CanFlood Analysis level summary.

Analysis Level:	**L1: Overview**	**L2: Initial**	**L3: Full-Scale**
Guidance[1]	Rapid FRA. desktop type appraisals: first approximations to identify areas where more detailed work is required	More detailed appraisals where further assessment of loss potential is warranted	Detailed study of potential losses/benefits and robust uncertainty quantification
Data requirements	low	medium	high
Level of modelling effort (per asset)	low	medium	high
Model complexity	low	medium	high
Vulnerability Functions	none (inundation only)	site-specific	site-specific, un-compiled
Uncertainty quantification	none	none	stochastic modelling
Property Level Protection Measures (PLPMs)	no	no	yes
Risk Dynamics	no	no	yes
Asset geometry	point, polygon	point, polygon	point
Inputs	asset inventory, hazard raster set, DTM (optional), conditional exposure polygons (optional)	asset inventory, hazard raster set, DTM (optional), vulnerability functions, conditional exposure polygons (optional)	asset inventory, WSL tables, vulnerability functions (un-compiled), dynamic parameters, others
Outputs	impacts table, annualized impacts (summary and per asset), summary plot,	impacts table, annualized impacts (summary and per asset) summary plot,	impacts table, annualized impacts (summary and per asset) summary plot, others
CanFlood tool names	Risk (L1)	Impacts (L2) and Risk (L2)	Risk (L3) (aka SOFDA)

1. Adapted from Penning-Rowsell et al. (2019)

1.4. Background

The devastation of the 2013 Southern Alberta and Toronto Floods triggered a transition in Canada from the traditional standards-based approach, where flood protection is designed for a single level-of-safety, towards a risk-based approach. This new risk-based approach recognizes that robust planning must consider vulnerability and the full range of floods that may harm a community rather than focus on a single, subjective, design event. Further, a risk-based view allows decision makers to quantitatively optimize mitigations for their community, helping jurisdictions with shrinking budgets spread protections further. The foundation of decisions under a risk-based flood management is a risk assessment, which is:

> *A methodology to determine the risk by analyzing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend (UNISDR 2009).*

To quantify risk, modern risk assessments integrate data on the natural and built environment with predictive models. Applied in flood risk management, a risk analysis is highly sensitive to the spatial components of risk: vulnerability (what has been built where and how harmful are flood waters?) and hazard (where and how intense can flooding be?). Evaluating these components is typically accomplished with a chain of activities (e.g. data collection, processing, modelling, and post-processing) to arrive at the desired risk metrics. The core components of a typical flood risk assessment are the hazard assessment (synthesize spatial exposure-likelihood data sets) and a damage assessment (estimate damage to assets from the hazard assessment results), followed by the risk quantification (use event probabilities to estimate average damages).

1.4.1. Motivation

Considering the limitation of existing tools, and the growing need to minimize flood harm in Canada through a better understanding of flood risk, NRCan sought to develop and maintain a flexible open source tool tailored to Canada. Such a standardized tool would:

- Reduce the cost of individual flood risk assessments (FRA) by consolidating software development and maintenance costs;
- Increase the transparency and standardization of FRAs for improved cross study-area comparisons of risk and updating;
- Encourage communities to perform additional FRAs by reducing opacity and cost and increasing awareness;
- Facilitate and motivate the standardization and collection of flood risk related datasets;
- Facilitate more sophisticated and stream-lined modelling in the future.

1.4.2. Guidelines

Users should be familiar with the following additional references and guidelines before using CanFlood.

Federal Flood Mapping Guidelines Series
"The Federal Flood Mapping Guidelines Series was developed under the leadership of the Flood Mapping Committee, a partnership between Public Safety Canada, Natural Resources Canada, Environment and Climate Change Canada, National Research Council of Canada, Defence Research and Development Canada, Canadian Armed Forces, Infrastructure Canada, and Crown Indigenous Relations and Northern Affairs Canada." These "are a series of evergreen guidelines that will help advance flood mapping activities across Canada" (Public Safety Canada 2018). Published documents can be found with a web search for "Federal Flood Mapping Guidelines Series". The following are particularly relevant to CanFlood:

- Federal Flood Damage Estimation Guidelines (in development)
- Federal Flood Risk Assessment Procedures (in development)

2. Getting Started

This section provides installation information and a few tutorials to get a user started in CanFlood. We suggest working through the tutorials sequentially. More detailed information on the tools in CanFlood is presented in later sections.

2.1. Installation

All installation instructions can be found on GitHub:

https://github.com/IBIGroupCanWest/CanFlood

Once installed, you should see the three CanFlood buttons on your QGIS toolbar:

2.2. Tutorial 1a: Risk (L1)

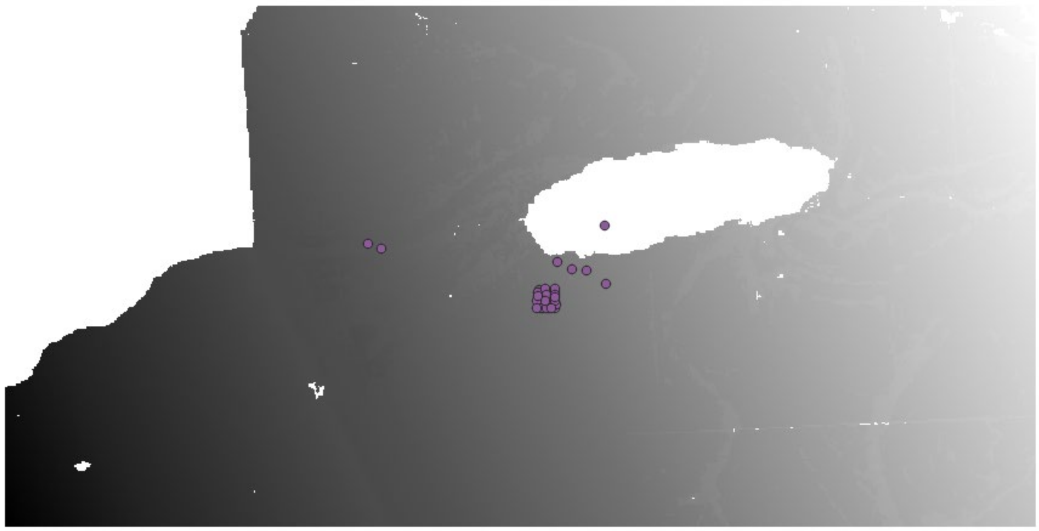
This tutorial guides the user through the simplest application of a risk analysis in CanFlood, called a level 1 (L1) analysis, where only binary or exposure impacts are calculated. This 'exposed vs. not exposed' analysis can be useful for preliminary analysis where there is insufficient information to model more complex object vulnerability.

2.2.1. Load data to the project

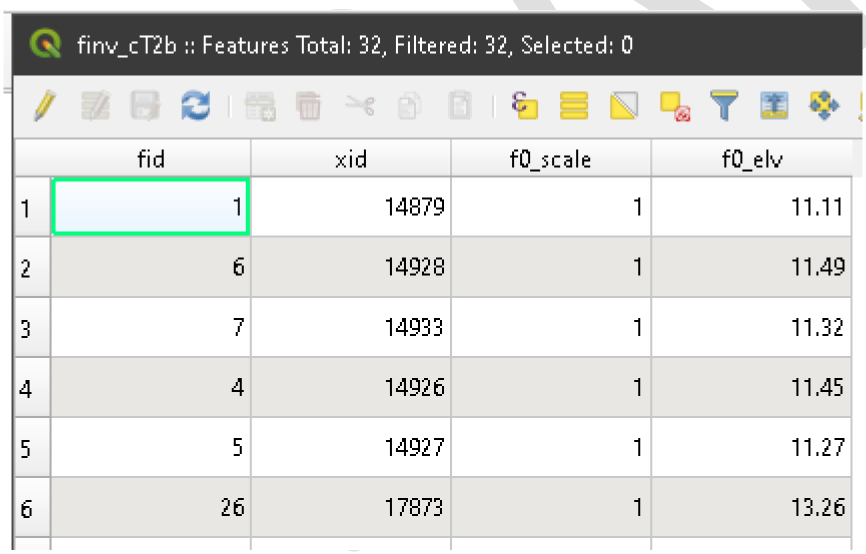
Download then add the data layers for Tutorial 1 from CanFlood's tutorial page (CanFlood\tutorials\1\data\) into a QGIS project:

- *haz_1000yr_cT2.tif:* Hazard event raster with WSL value predictions for the study area during a 1000-yr event;
- ~~haz_1000yr_fail_cT2.tif~~ (not used in Tutorial 1a)
- *haz_100yr_cT2.tif:* Hazard event raster;
- *haz_200yr_cT2.tif:* Hazard event raster;
- *haz_50yr_cT2.tif:* Hazard event raster;
- ~~exlikes_1000yr_cT2.gpkg~~ (not used in Tutorial 1a)
- *finv_cT2b.gpkg*: flood asset inventory (*finv*) spatial layer.

Your map canvas should look something like this:



Explore the *finv* layer's attributes. You should see something like this:



finv_cT2b :: Features Total: 32, Filtered: 32, Selected: 0

	fid	xid	f0_scale	f0_elv
1	1	14879	1	11.11
2	6	14928	1	11.49
3	7	14933	1	11.32
4	4	14926	1	11.45
5	5	14927	1	11.27
6	26	17873	1	13.26

The 4 fields are:

- *fid*: built-in feature identifier (not used);
- *xid*: Index FieldName, unique identifier for the asset[2];
- *f0_scale*: value to scale the results of the 'f0' calculation for this asset;
- *f0_elv*: height (above the project datum) at which the asset is vulnerable to flooding;

For this example, each inventory entry or 'asset' could represent a home with the main floor elevation entered into 'f0_elv'. Any flood waters above this elevation will be tabulated as an impact for that asset. For CanFlood's L1 analysis, based on the user supplied likelihood of each event, the total 'risk of inundation' for each asset and for the full study area will be computed.

[2] Any field with unique integer values can be used as the FieldName Index (except built-in feature identifiers).

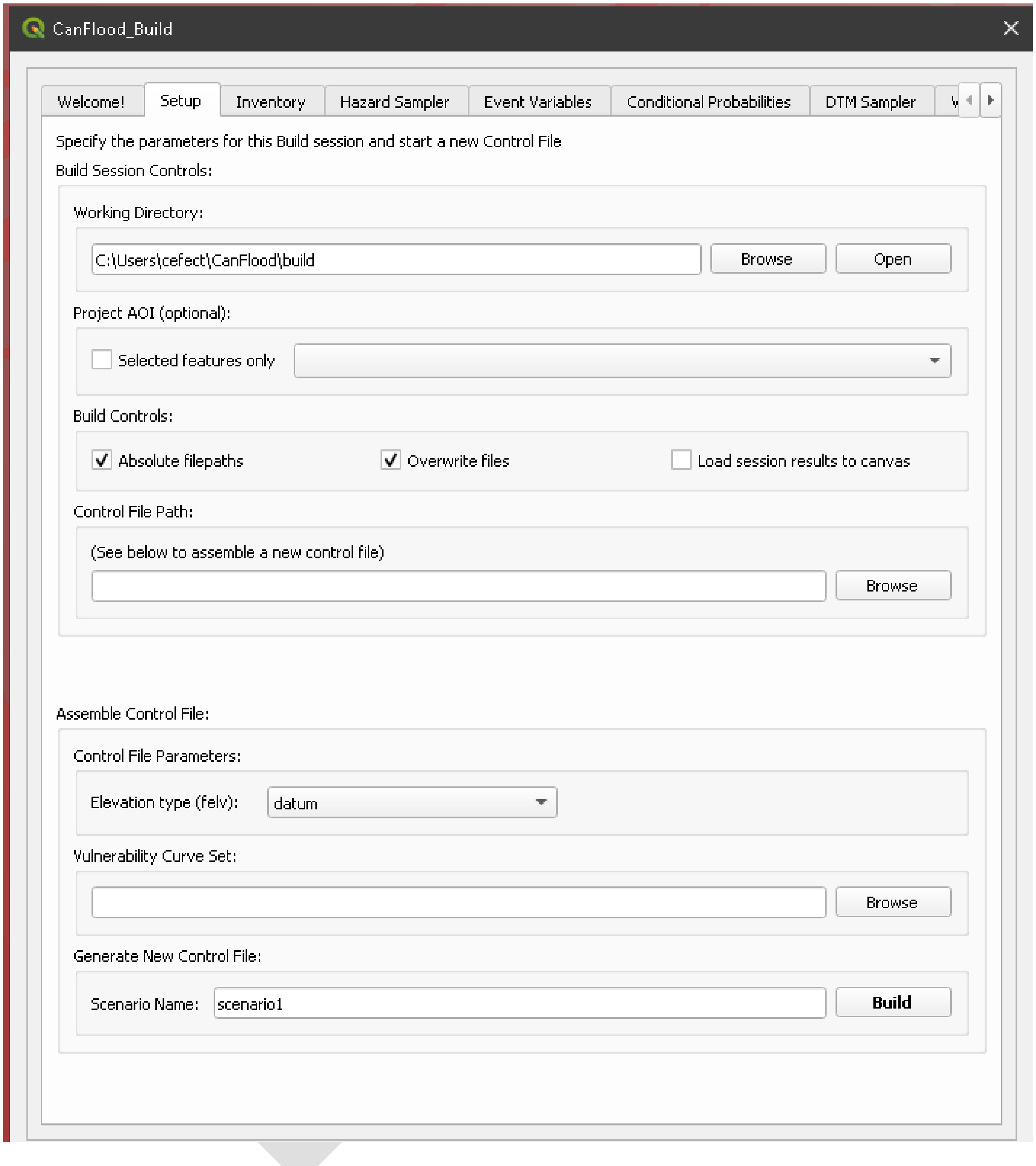
2.2.2. Build the Model

Press the 'Build' button to begin building a CanFlood model.

Setup

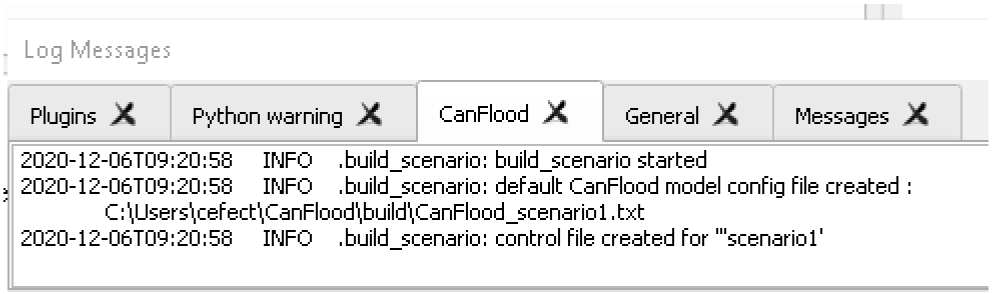
On the 'Setup' tab, configure your Build session by first creating or selecting an easy to remember working directory using the 'Browse' button. CanFlood will place all the data files assembled with the Build toolset in this directory. Ensure the remaining 'Build Controls' are specified as shown below.

Now use the lower portion of the dialog to specify the parameters CanFlood should use to assemble your new Control File as shown below. For this L1 analysis, no 'Vulnerability Curve Set' is required. Ensure 'elevation type' is set to 'datum' to reflect that the inventory's 'f0_elv' values are measured from the project's datum.



Once the parameters are correctly entered, click ‘Build’ to create your Control File in the working directory. There should be a message on the Qgis Toolbar indicating the process ran successfully.

If you view the ‘CanFlood’ Log Messages Tab (View > Panels > Log Messages), you can see the detailed log messages for the process you just completed. It should look something like this:

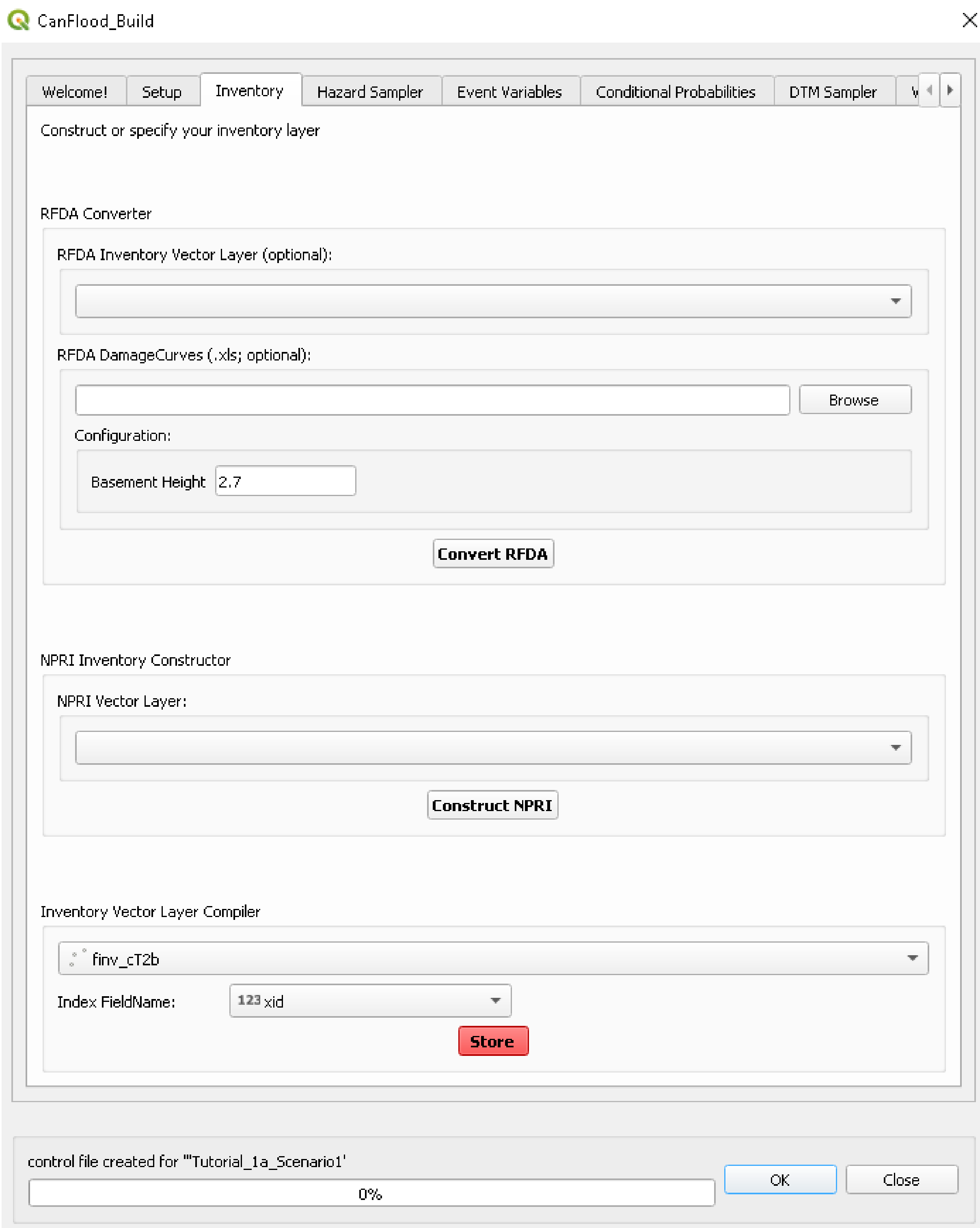


On the ‘Setup’ tab, next to the working directory file path, click ‘Open’ to open the specified working directory, you should see the Control File ‘CanFlood_scenario1.txt’ created in your working directory. This is a template with some blank, default, and specified parameters. As you work through the remainder of this tutorial, blank parameters will be filled in by the CanFlood tools.

Open the Control File. Notice the ‘#’ comment letting you know how and when this control file was created (#comment lines are ignored by the program).

Store Inventory

Move to the ‘Inventory’ tab, select the inventory vector layer and the appropriate Index FieldName as shown, then click ‘Store’.

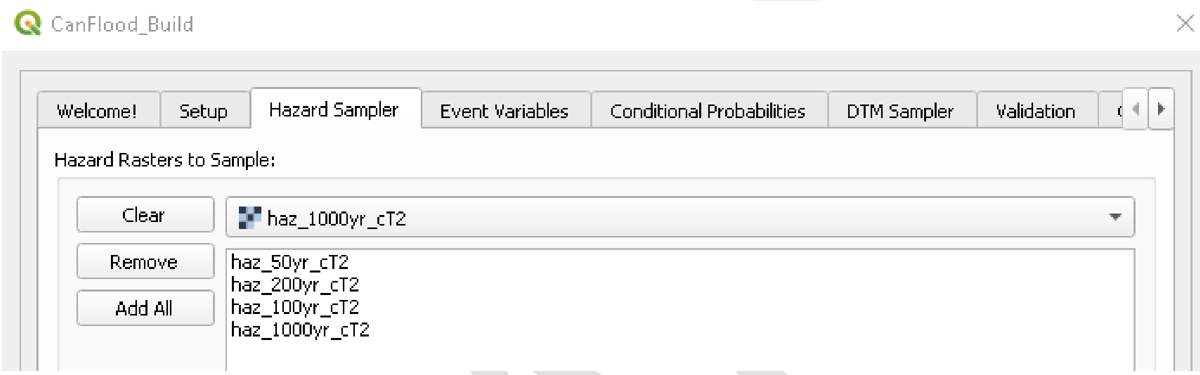


You should see the inventory csv stored into the working directory. This is simplified version of the inventory layer with all of the spatial data removed.

Now open the Control File again. You should notice that *finv* parameter has been populated with the file name of the newly created csv *finv*.

Hazard Sampler

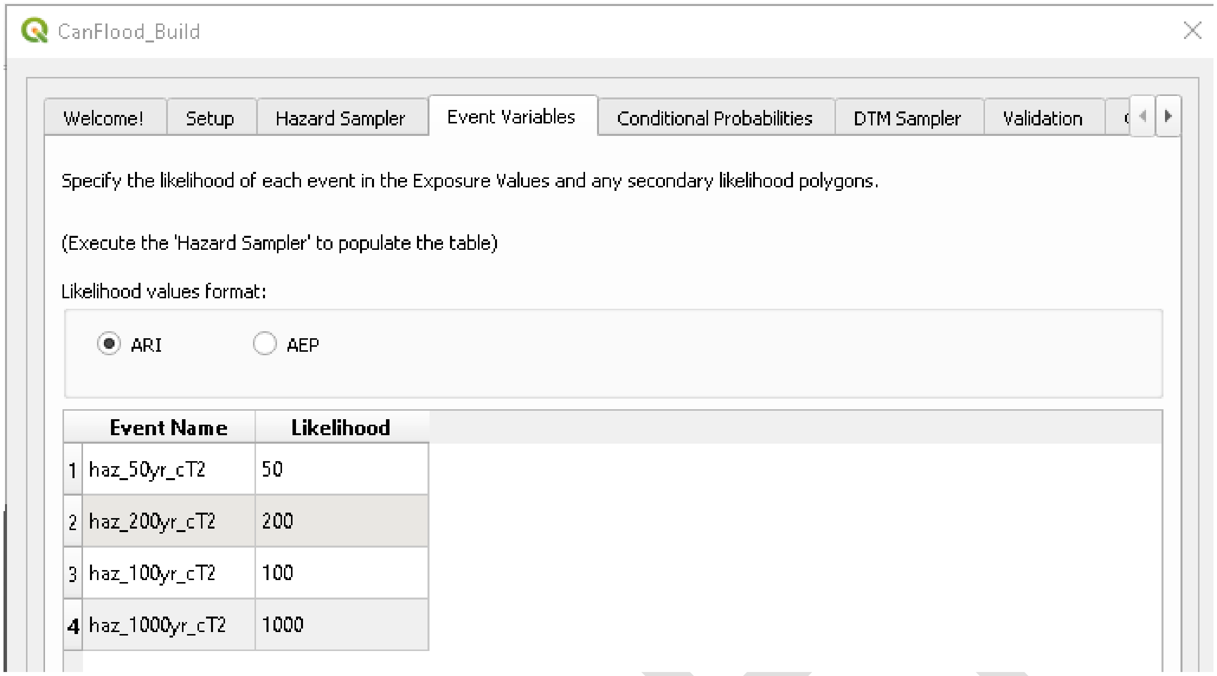
Move to the 'Hazard Sampler' tab. Add all the hazard rasters to the display box as shown, leaving the remaining parameters blank or untouched:



Click 'Sample' to generate the exposure dataset. You should see a new file in the working directory called 'expos_tutorial1_4_32.csv, and its filepath added to the control file under 'expos'. These are the WSLs sampled at each asset from each hazard event raster.

Event Variables

Now that the WSLs have been stored, we need to tell CanFlood what the probability of realizing each of these events is. Move to the 'Event Variables' tab. Specify the correct values for each event's likelihood (from the event names) as shown:



Press ‘Store’. The file ‘evals_4_tutorial1.csv’ should have been created and its filepath written to the Control File under ‘evals’.

Validation

Move to the ‘Validation’ tab, check ‘Risk (L1)’, then push ‘Validate’. This will check all the inputs in the control file and set the ‘risk1’ validation flag to ‘True’. Without this flag, the CanFlood model will fail.

The model control file should now be fully built. Navigate to the Control File, open and inspect the file. It should look similar to this (but with your directories):

```
CanFlood_scenario1.txt - Notepad
File  Edit  Format  View  Help
[parameters]
name = scenario1
cid = xid
prec = 6                    #float precision for calculations
ground_water = True         #whether to allow wsl < gel
felv = datum
event_probs = ari
ltail = extrapolate         #EAD extrapolation: left tail treatment code (low prob high damage)
rtail = 0.5                 #EAD extrapolation: right trail treatment (high prob low damage)
drop_tails = True           #whether to remove the extrapolated values from the results
integrate = trapz           #integration method to apply: trapz, simps
as_inun = False

[dmg_fps]
curves = #damage curve library filepath
finv = C:\Users\cefect\CanFlood\build\finv_scenario1_finv_cT2b.csv
expos = C:\Users\cefect\CanFlood\build\expos_scenario1_4_32.csv
gels = #ground elevation data filepath

[risk_fps]
dmgs = #damage data results filepath
exlikes = #secondary exposure likelihood data filepath
evals = C:\Users\cefect\CanFlood\build\evals_4_scenario1.csv

[validation]
risk1 = True
dmg2 = False
risk2 = False
risk3 = False
```

2.2.3. Run the Model

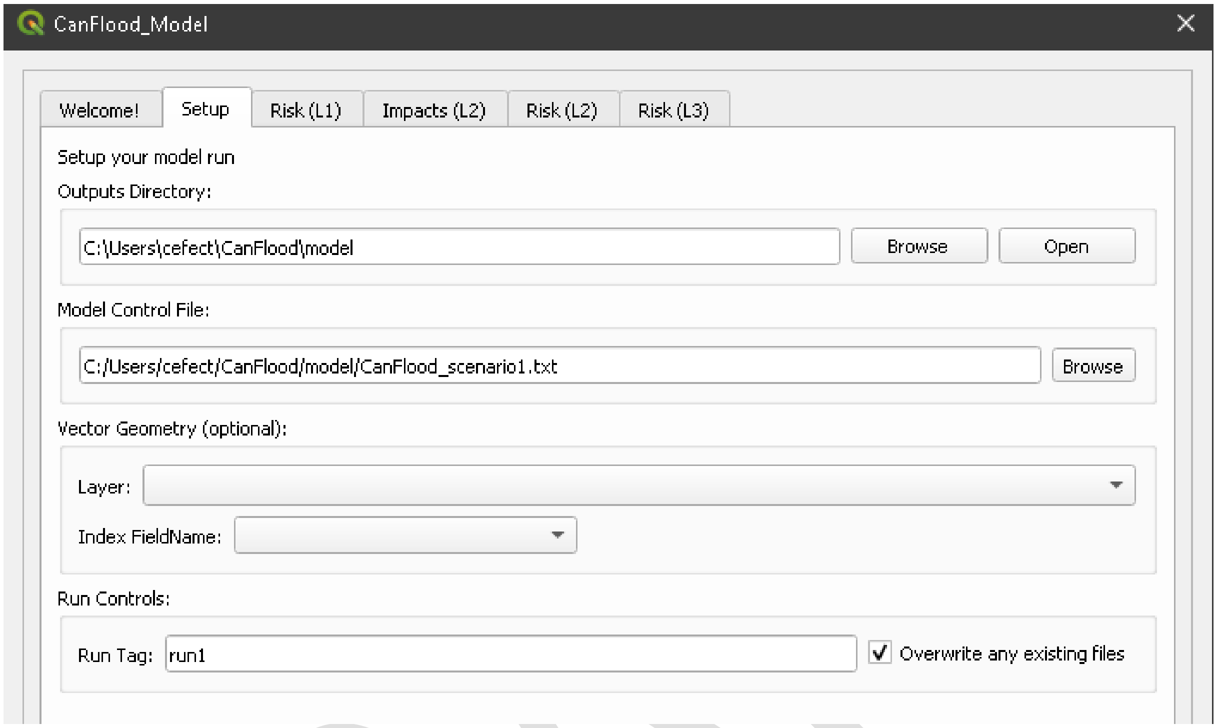
Click the 'Model' button to launch the Model toolset dialog.

Setup

On the 'Setup' tab, select a working directory[3] where all your results will be stored. Also select your Control File created in the previous section.

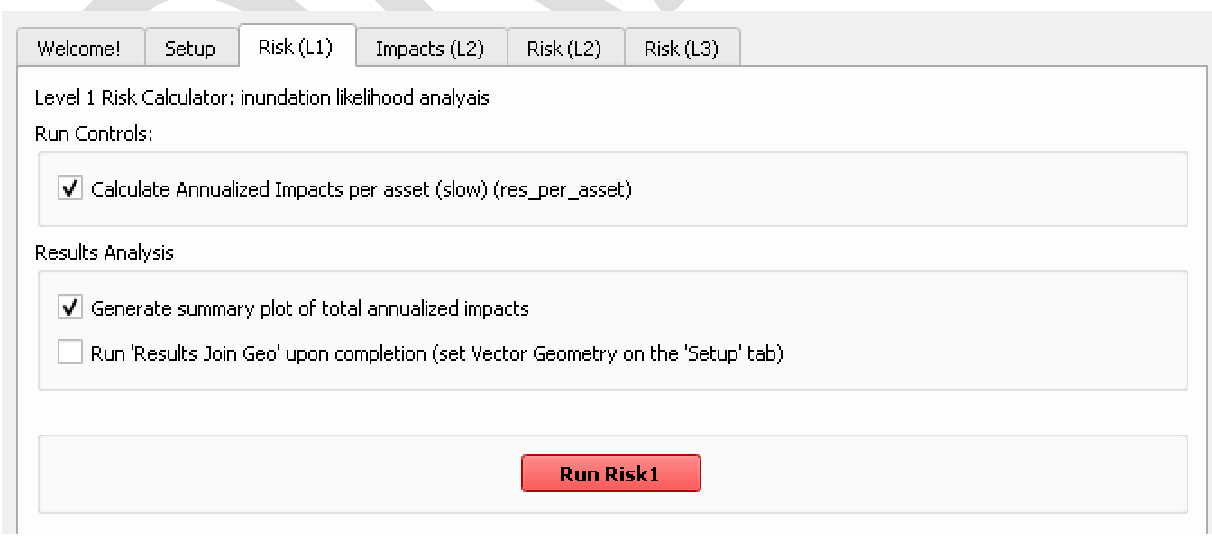
[3] does not have to match the directory from the previous step

Your dialog should look like this[4]:



Execute

Navigate to the 'Risk (L1)' tab. Check the first two boxes as shown below and press 'Run Risk1':

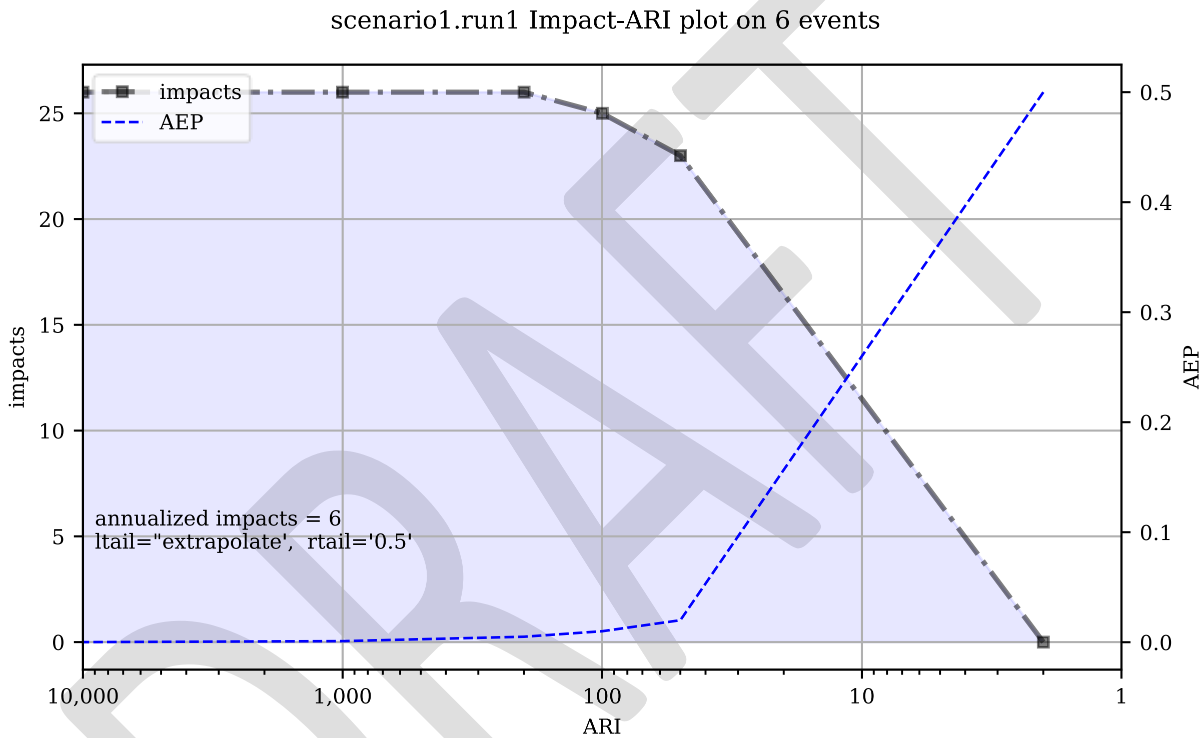


[4] CanFlood will attempt to automatically identify the Inventory Vector Layer; however, this tutorial does not make use of this layer so the selection here can be ignored.

2.2.4. View Results

Navigate to the selected working directory. You should see 3 files created:

- *risk1_run1_scenario1_passet.csv:* Expected value of inundation per asset;
- *risk1_run1_scenario1_ttl.csv*: Total results, expected value of total inundation per event (and for all events);
- *scenario1.run1 Impact-ARI plot on 6 events.svg*: a plot of the total results (see below)

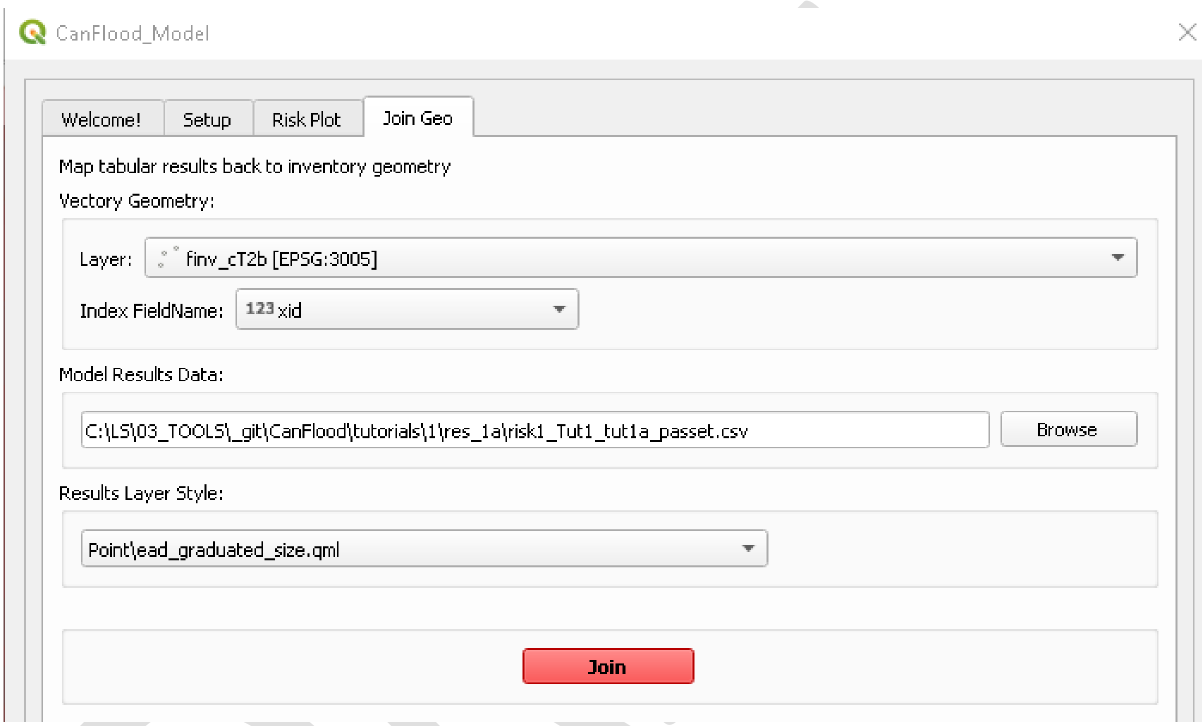


These are the non-spatial results which are directly generated by CanFlood's model routines. To facilitate more detailed analysis and visualization, CanFlood comes with a third and final 'Results' toolset.

Open this toolset by clicking the 'Results' button.

Join Geometry

The CanFlood models are designed to run independent of Qgis's spatial API. Therefore, if you would like to view the results spatially, additional actions are required to re-attach the tabular model results to the *finv* vector geometry. To do this, move to the 'Join Geo' tab, select the *finv* layer and Index FieldName. Then select the per asset results ('passet') filepath generated in the previous step. Finally, select a Results Layer Style as shown:



Click 'Join'. A new layer 'run1_risk1_Tut1_tut1a_passet_djoin' should have been loaded onto the map canvas. Try re-classifying the layer styling[5] and hiding all other layers[6]. The result should be a points layer where the size of each point is relative to the magnitude of the expected value of inundation (i.e. the average number of inundations per year) similar to this:

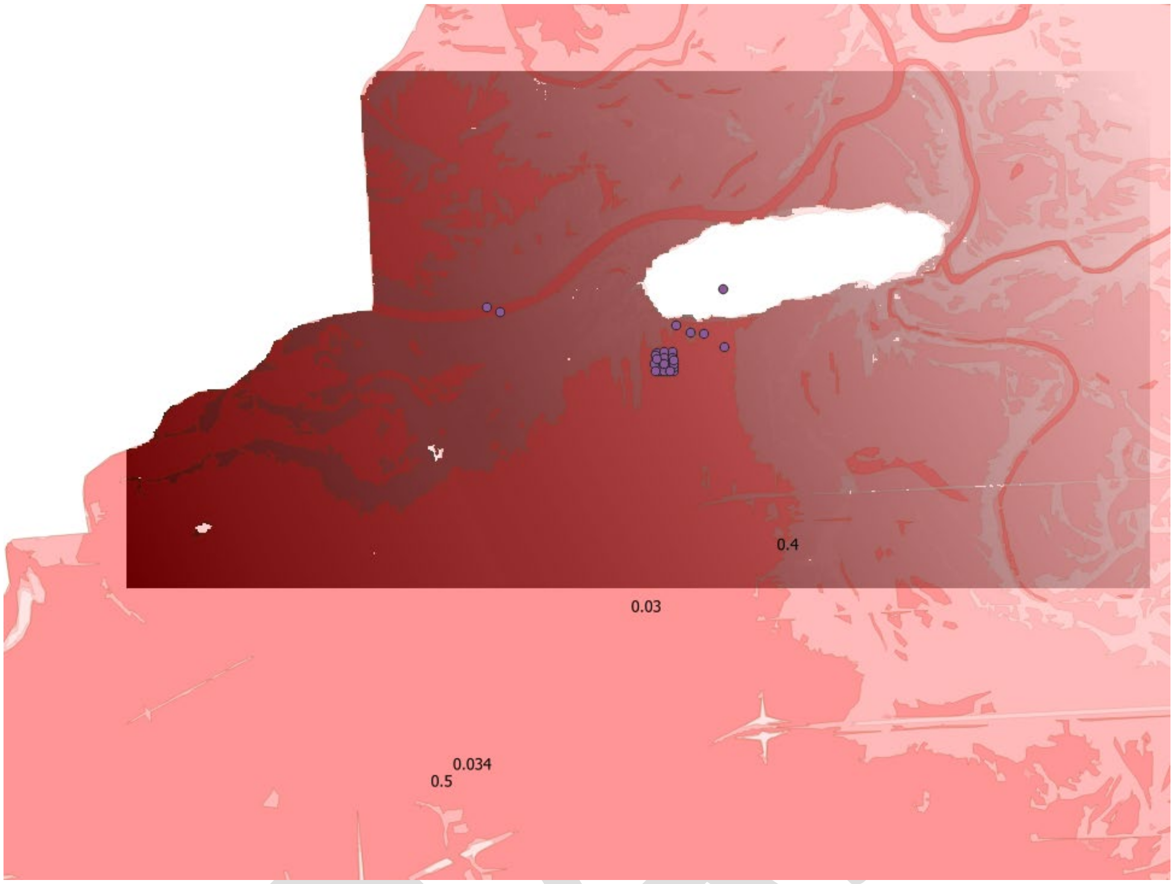
Congratulations on your first CanFlood run!

2.3. Tutorial 1b: Risk (L1) With Conditional Probabilities

We recommend users first complete Tutorial 1a. Tutorial 1b uses the same input data and expands the analysis to demonstrate conditional probabilities of levee failure.

In the same project as was used for Tutorial 1a, ensure the 'exlikes_1000yr_cT2.gpkg' polygons and 'haz_1000yr_fail_cT2' raster are added to the project. Stylize these polygons by adding 30% transparency, a red fill, a single label for 'p_fail', and moving them just beneath the *finv* points. Your project should now look like this:

[5] Right click the layer > Properties…, click 'Control Feature Symbology' on the left, click 'Classify' at the bottom.
[6] Select the layer in the 'Layers pane', click the 'Manage Map Themes' eyeball at the top of the Layers Pane, select 'Hide Deselected Layers'



Notice that two '1000yr' rasters are provided: one for the exposure that would occur if the levees perform as intended (haz_1000yr_cT2), and the other for levee breach or failure (haz_1000yr_fail_cT2). Explore the 'exlikes_1000yr_cT2' layer. This is a layer with 5 overlapping polygon features. Each feature corresponds to a levee segment during the 1000yr event and quantifies: 1) influence area of a breach at the corresponding segment; and 2) the conditional probability of that segment breaching. This layer will be used to tell CanFlood when and how to sample the levee failure raster (haz_1000yr_fail_cT2).

2.3.1. Build the Model

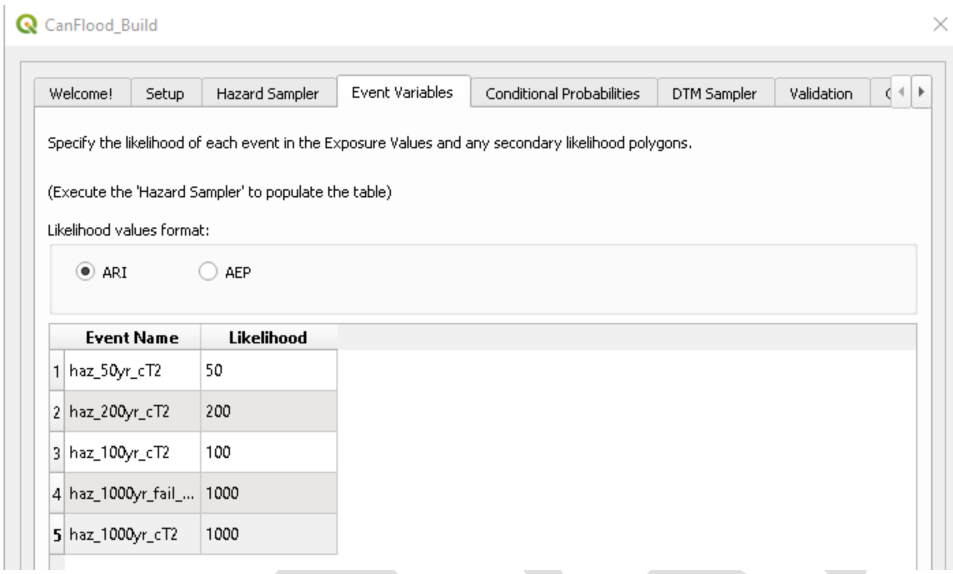
In a new working directory, follow the steps under 'Setup' and 'Store Inventory' described in Section 2.2.2.

Hazard Sampler

Move to the 'Hazard Sampler' tab, add all 5 rasters to the list, then generate the 'expos' dataset by pressing 'Sample'.

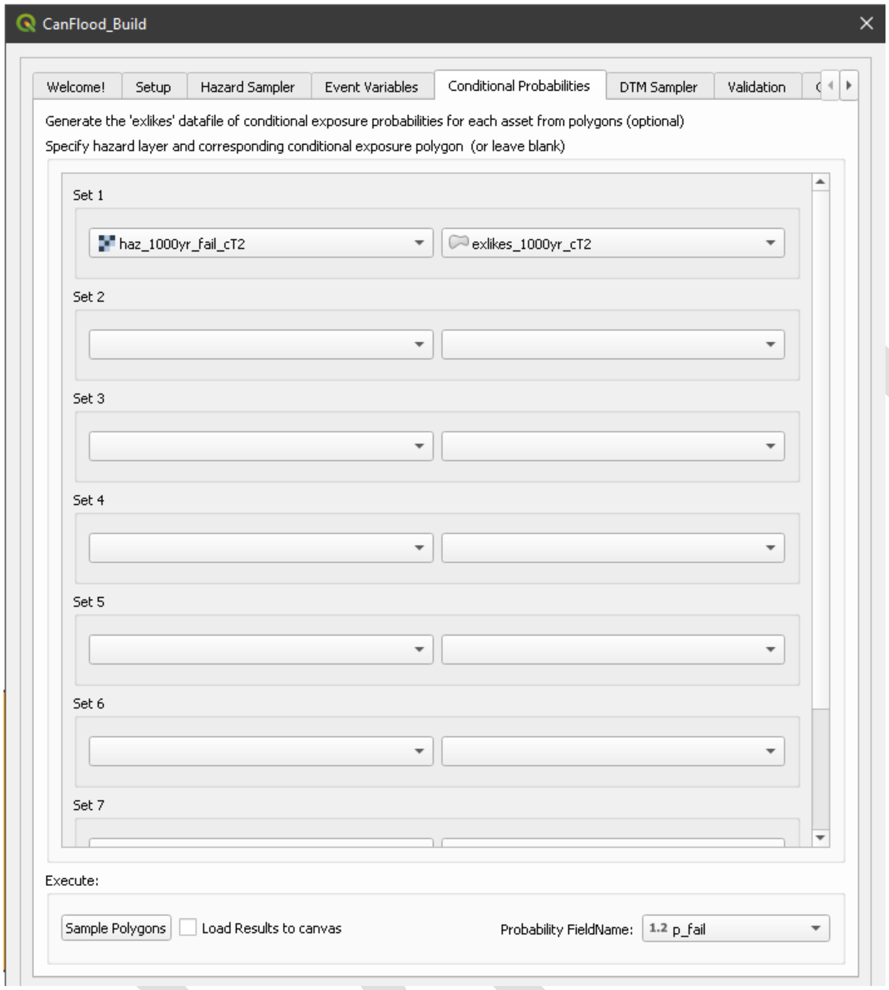
Event Variables

Move to the ‘Event Variables’ tab. Specify the correct values for each event’s likelihood (from the event names) as shown, then press ‘Store’ to generate the ‘evals’ dataset. Ensure the two 1000-yr events are given the same likelihood (this tells CanFlood to look for conditional probabilities on these layers).



Conditional Probabilities

Move to the 'Conditional Probabilities' tab. Clear all rasters from the first column except the 1000yr failure raster, then select the conditional probability polygon layer as shown:



Ensure 'p_fail' has been selected for the 'Probability FieldName', then click 'Sample Polygons' to generate the 'exlikes' dataset.

Validation

Move to the ‘Validation’ tab, check ‘Risk (L1)’, then push ‘Validate’. The Control File should look like this:

CanFlood_scenario1.txt - Notepad

File Edit Format View Help

```
[parameters]
name = scenario1
cid = xid
prec = 6                #float precision for calculations
ground_water = True     #whether to allow wsl < gel
felv = datum
event_probs = ari
ltail = extrapolate     #EAD extrapolation: left tail treatment code (low prob high damage)
rtail = 0.5             #EAD extrapolation: right trail treatment (high prob low damage)
drop_tails = True       #whether to remove the extrapolated values from the results
integrate = trapz       #integration method to apply: trapz, simps
as_inun = False

[dmg_fps]
curves = #damage curve library filepath
finv = C:\Users\cefect\CanFlood\build\t1b\finv_scenario1_finv_cT2b.csv
expos = C:\Users\cefect\CanFlood\build\t1b\expos_scenario1_5_32.csv
gels = #ground elevation data filepath

[risk_fps]
dmgs = #damage data results filepath
exlikes = C:\Users\cefect\CanFlood\build\t1b\exlikes_scenario1.csv
evals = C:\Users\cefect\CanFlood\build\t1b\evals_5_scenario1.csv

[validation]
risk1 = True
dmg2 = False
risk2 = False
risk3 = False
```

And your working directory should look like this:

Name	Date modified	Type	Size
CanFlood_scenario1.txt	2020-12-08 6:02 PM	TXT File	2 KB
evals_5_scenario1.csv	2020-12-08 5:57 PM	Microsoft Excel C...	1 KB
exlikes_scenario1.csv	2020-12-08 5:59 PM	Microsoft Excel C...	1 KB
expos_scenario1_5_32.csv	2020-12-08 5:57 PM	Microsoft Excel C...	4 KB
finv_scenario1_finv_cT2b.csv	2020-12-08 5:57 PM	Microsoft Excel C...	1 KB

2.3.2. Run the Model

Push the ‘Model’ button to open the Model dialog.

Setup the Risk (L1) model by pointing to the new control file, then execute the model as described in Tutorial 1a.

2.3.3. View Results

Navigate to the selected working directory. You should see the same 3 results files as tutorial 1a. Open the annualized results per asset file 'risk1_run1_tutorial1_passet.csv', The first few rows should look like this:

xid	0.001	0.005	0.01	0.02	ead
14879	0.7712	0	0	0	0.002
14880	0.7712	0	0	0	0.002
14925	0.7712	0	0	0	0.002
14926	0	0	0	0	0
14927	1	1	1	1	0.26

This output table shows the impacts per asset per event (as AEP) and the expected value of impacts for all events for that asset (ead).

Notice that there are now impact values for the 1000yr event for the first 3 assets (these were all zeros in the tutorial 1a results). These are the expected value of impacts at these assets for the 1000yr event considering the conditional probabilities of levee failures captured in the 'exlikes' datafile.

2.4. Tutorial 2a: Risk (L2) with Simple Events

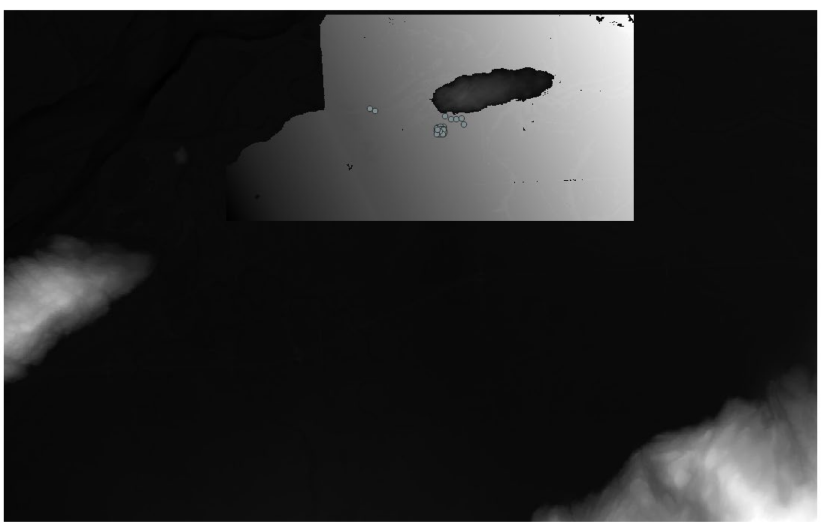
Tutorial 2 demonstrates the use of the Risk (L2) tool in CanFlood. This emulates a more detailed risk assessment where the vulnerability of each assets is known and described as a function of flood depth (rather than simple binary flood presence as in tutorial 1). This tutorial also demonstrates an inventory with 'relative' heights and CanFlood's 'nested vulnerability function' feature (multiple functions applied to the same asset).

2.4.1. Load data to project

Download the tutorial 2 data from the 'tutorials\2\data' folder. You should see the following datafiles:

- ~~*exlikes_1000yr_cT3.gpkg*~~: conditional failure probability polygon set (ignore for tutorial 2a);
- *finv_cT2.gpkg:* Flood Asset Inventory *(finv);*
- *dtm_cT1.tif:* example DTM raster showing ground elevations in the study area;
- *haz_1000yr_cT2.tif:* hazard event raster;
- ~~*haz_1000yr_fail_cT3.tif*~~: hazard failure event raster (ignore for tutorial 2a);
- *haz_100yr_cT2.tif:* hazard event raster;
- *haz_200yr_cT2.tif:* hazard event raster;
- *haz_50yr_cT2.tif:* hazard event raster;
- *CanFlood_curves_rfda_20200218.xls:* example vulnerability curve set. Each tab corresponds to one depth-damage curve and a 'tag' value in the *finv*;

Load these into a QGIS project, it should look something like this:

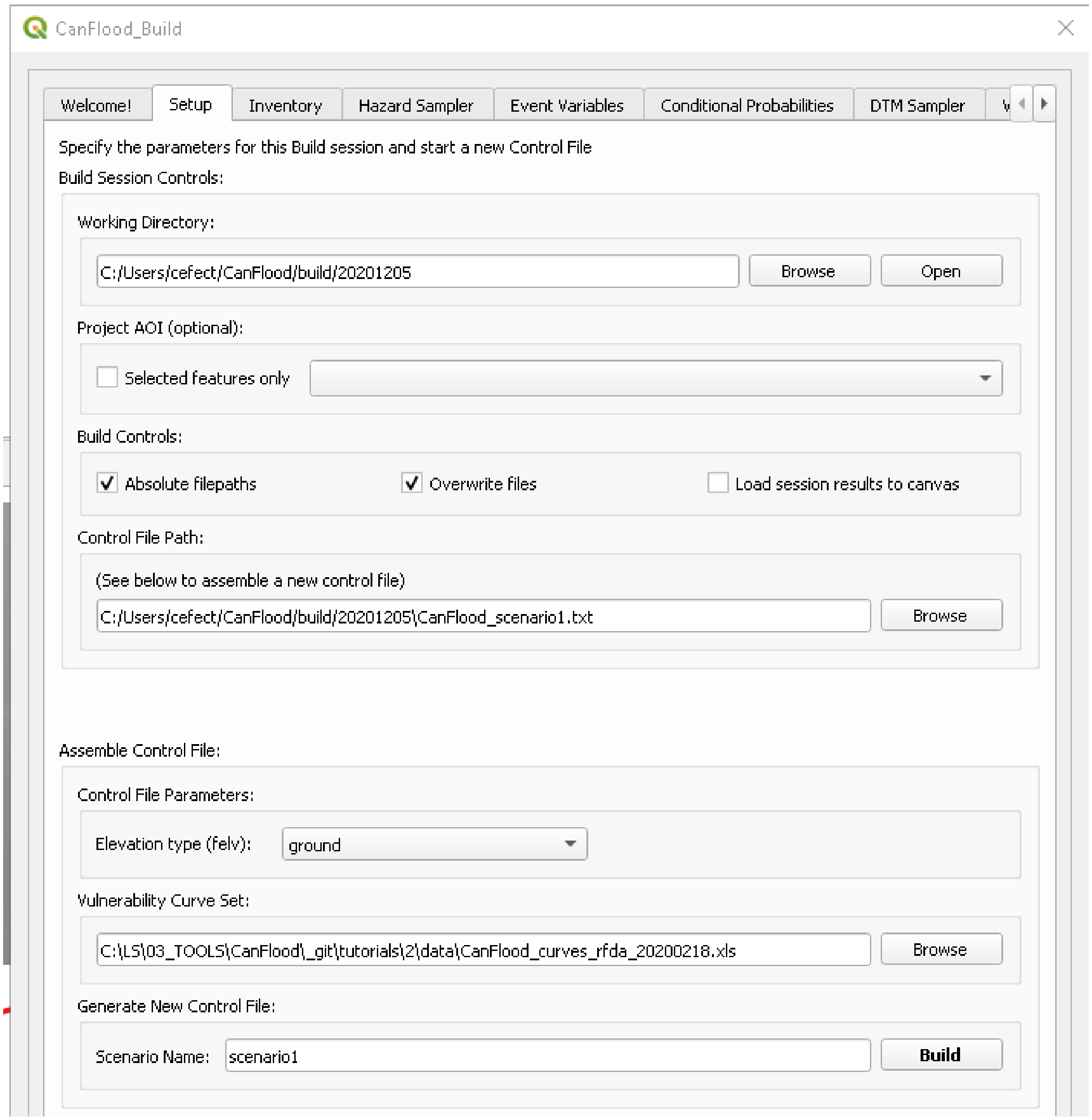


2.4.2. Build the Model

Open the 'Build' toolset.

Scenario Setup

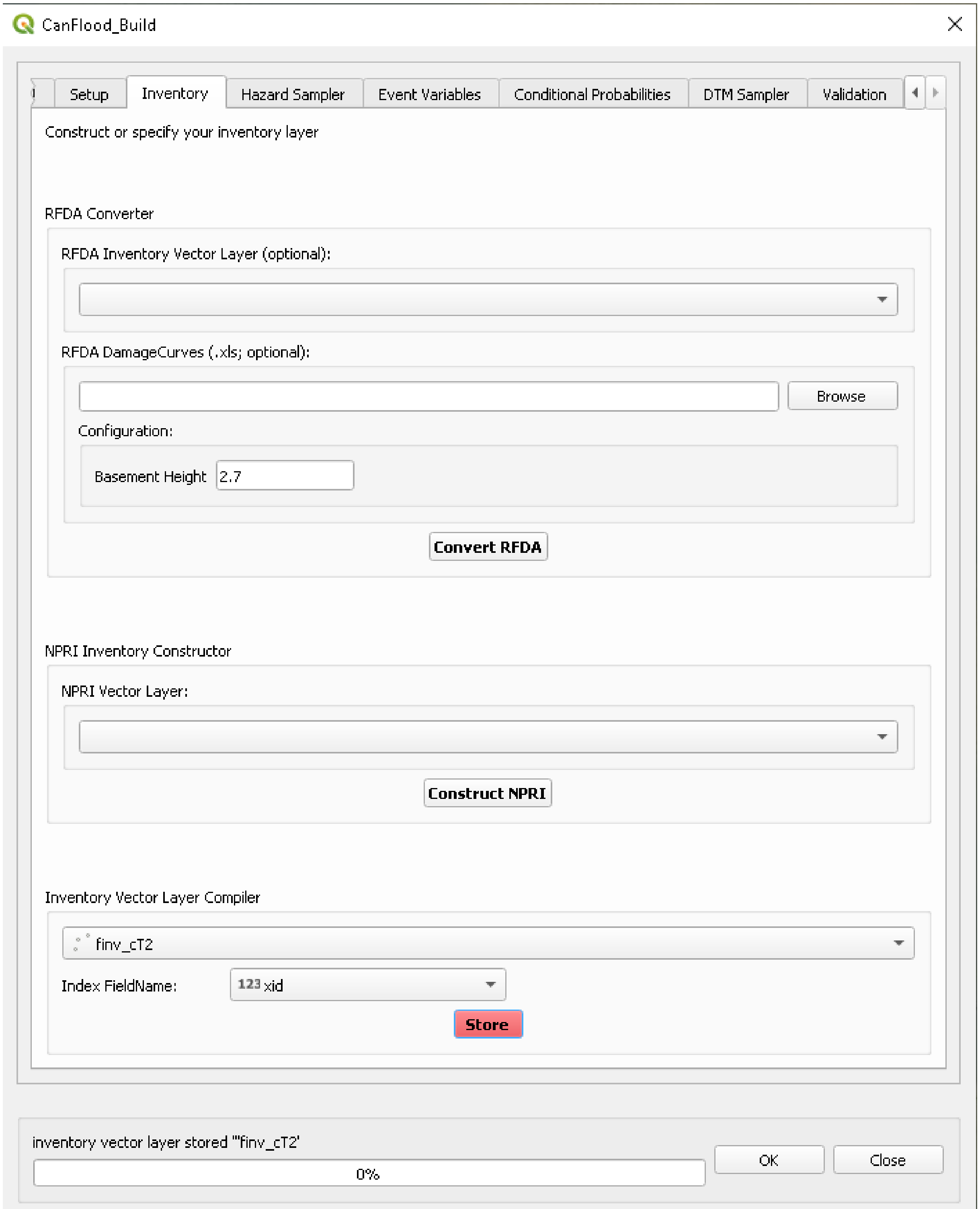
On the 'Setup' tab, configure the session as shown using your own paths, then click 'Build':



You should see the control file created in the selected directory.

Store Inventory

Move to the ‘Inventory’ tab, select the inventory vector layer and the appropriate Index FieldName as shown, then click ‘Store’.



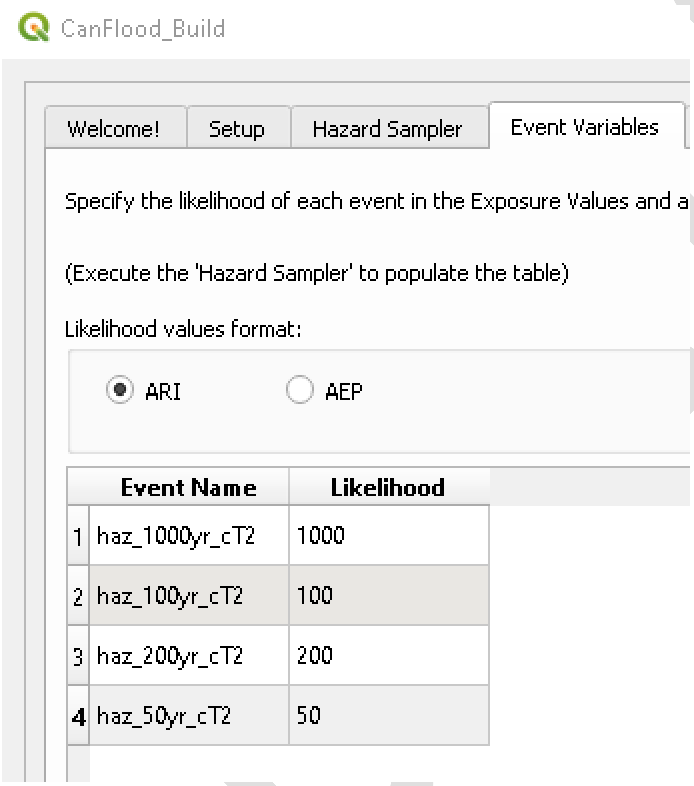
You should see the inventory csv stored into the working directory.

Hazard Sampler

Move to the ‘Hazard Sampler’ tab, ensure the four hazard rasters are shown in the window and all other fields are blank, then click ‘Sample’. You should see the ‘expos’ data file created in the working directory.

Event Variables

Move to the ‘Event Variables’ tab, you should now see the 4 hazard events from the previous task populating the table. Fill in the ‘Likelihood’ values as shown, then click ‘Store’ to generate the ‘evals’ dataset.



DTM Sampler

Move to the ‘DTM Sampler’ tab. Select the ‘dtm_cT1’ raster then click ‘Sample DTM’ to generate the ground elevation (‘gels’) dataset.

Validation

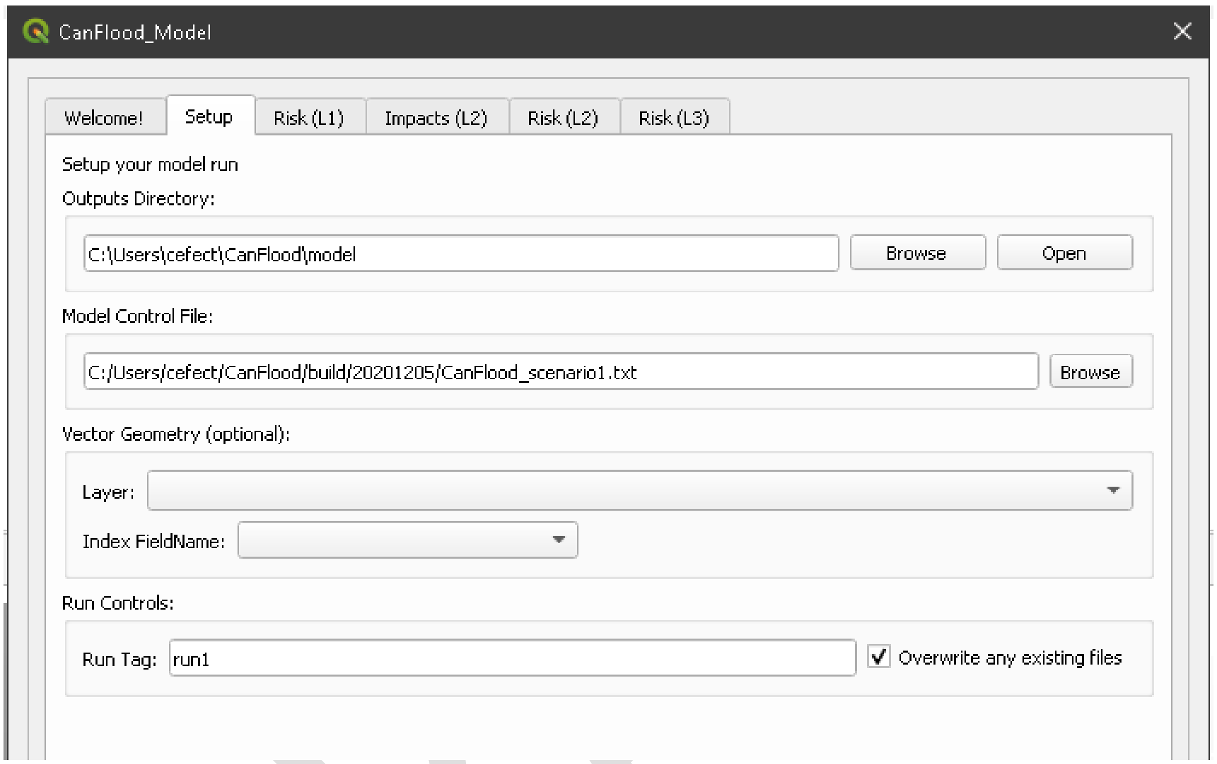
Move to the ‘Validation’ tab, check the boxes for both L2 models, then click ‘Validate’. Your Control File should look similar to this:

```
CanFlood_scenario1.txt - Notepad
File  Edit  Format  View  Help
[parameters]
name = scenario1
cid = xid
prec = 6                #float precision for calculations
ground_water = True     #whether to allow wsl < gel
felv = ground
event_probs = ari
ltail = extrapolate     #EAD extrapolation: left tail treatment code (low prob high damage)
rtail = 0.5             #EAD extrapolation: right trail treatment (high prob low damage)
drop_tails = True       #whether to remove the extrapolated values from the results
integrate = trapz       #integration method to apply: trapz, simps
as_inun = False

[dmg_fps]
curves = C:\LS\03_TOOLS\CanFlood\_git\tutorials\2\data\CanFlood_curves_rfda_20200218.xls
finv = C:/Users/cefect/CanFlood/build/20201205\finv_scenario1_finv_cT2.csv
expos = C:/Users/cefect/CanFlood/build/20201205\expos_scenario1_4_32.csv
gels = C:/Users/cefect/CanFlood/build/20201205\gels_scenario1_1_32.csv

[risk_fps]
dmgs = #damage data results filepath
exlikes = #secondary exposure likelihood data filepath
evals = C:/Users/cefect/CanFlood/build/20201205\evals_4_scenario1.csv

[validation]
risk1 = False
dmg2 = True
risk2 = True
risk3 = False
```

You’re now ready to run the Impacts and Risk (L2) models.

2.4.3. Run the Model

Open the ‘Model’ dialog. Configure the ‘Setup’ tab as shown below (using your own directories):



Impact (L2)

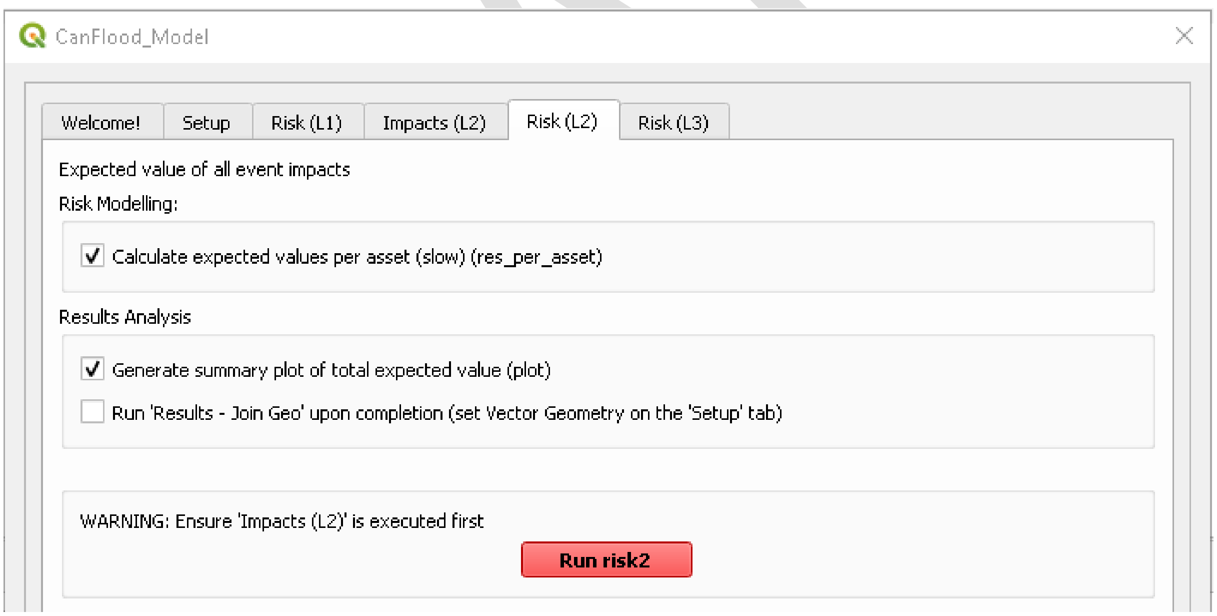
Move to the ‘Impacts (L2)’ tab. Ensure the ‘Run Risk Model’ box is **not** checked (we’ll execute the risk model manually in the next step). Click ‘Run dmg2’. This should create a ‘dmgs’ datafile and fill in the corresponding entry on the Control File. Navigate to this csv. It should look something like this:

xid	haz_1000yr_cT2_dmg	haz_100yr_cT2_dmg	haz_200yr_cT2_dmg	haz_50yr_cT2_dmg
14879	58996.91423	56812.88	57473.624	51146.88221
14880	72203.79659	64997.94133	66620.9408	63854.72
14925	56468.0522	55071.92	55135.619	20000
14926	49325.312	47297.36192	48753.92	20000
14927	68574.40663	66581.6	66785.64333	54765.2515
14928	72634.722	68649.1894	71826.32	20000
14933	60156.07535	58477.45219	58840.88	20000
14934	116561.9533	62504.6336	111354.2895	57716.08533
14935	100143.0633	54499.39472	89346.2504	31660.664
14936	119196.446	62039.45201	65764.93787	39767.52
14937	100259.1255	55052.33489	96340.66645	51442.248

These are the raw impacts per event per asset calculated with each vulnerability function, the sampled WSL and the sampled DTM elevation. Now you're ready to calculate flood risk!

Risk (L2)

Move to the 'Risk (L2)' tab. Check all the boxes shown, and click 'Run risk2':

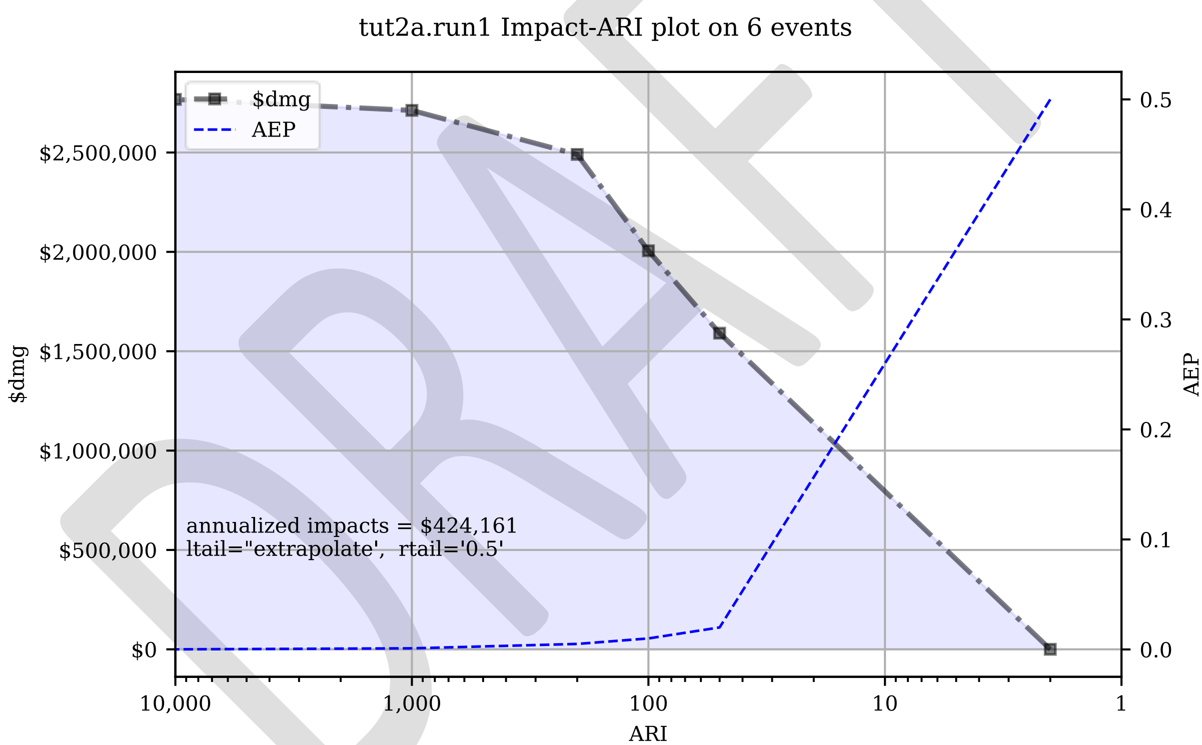


Three results files should have been generated (discussed below). For a complete description of the Risk (L2) module, see Section 5.3.

2.4.4. View Results

After completing the Risk (L2) run, navigate to your working directory. It should now contain these files:

- *dmgs_tutorial2_run1.csv*: impact results per asset (from Impact (L2) run)
- *risk2_run1_tutorial2_passet.csv*: expected value per asset ('passet')
- *risk2_run1_tutorial2_ttl.csv*: total expected value for all events.
- *scenario1.run1 Impact-ARI plot on 6 events.svg*: summary plot of inventory totals, see below figure.



Congratulations! The 'Join Geo' tool can be used, as demonstrated in Tutorial 1a, to generate the results geometry.

2.5. Tutorial 2b: Risk (L2) with Conditional Probabilities

We recommend users first complete Tutorials 1a, 1b, and 2a. Tutorial 2b uses the same input data as 2a but expands the analysis to demonstrate conditional probabilities of levee failure.

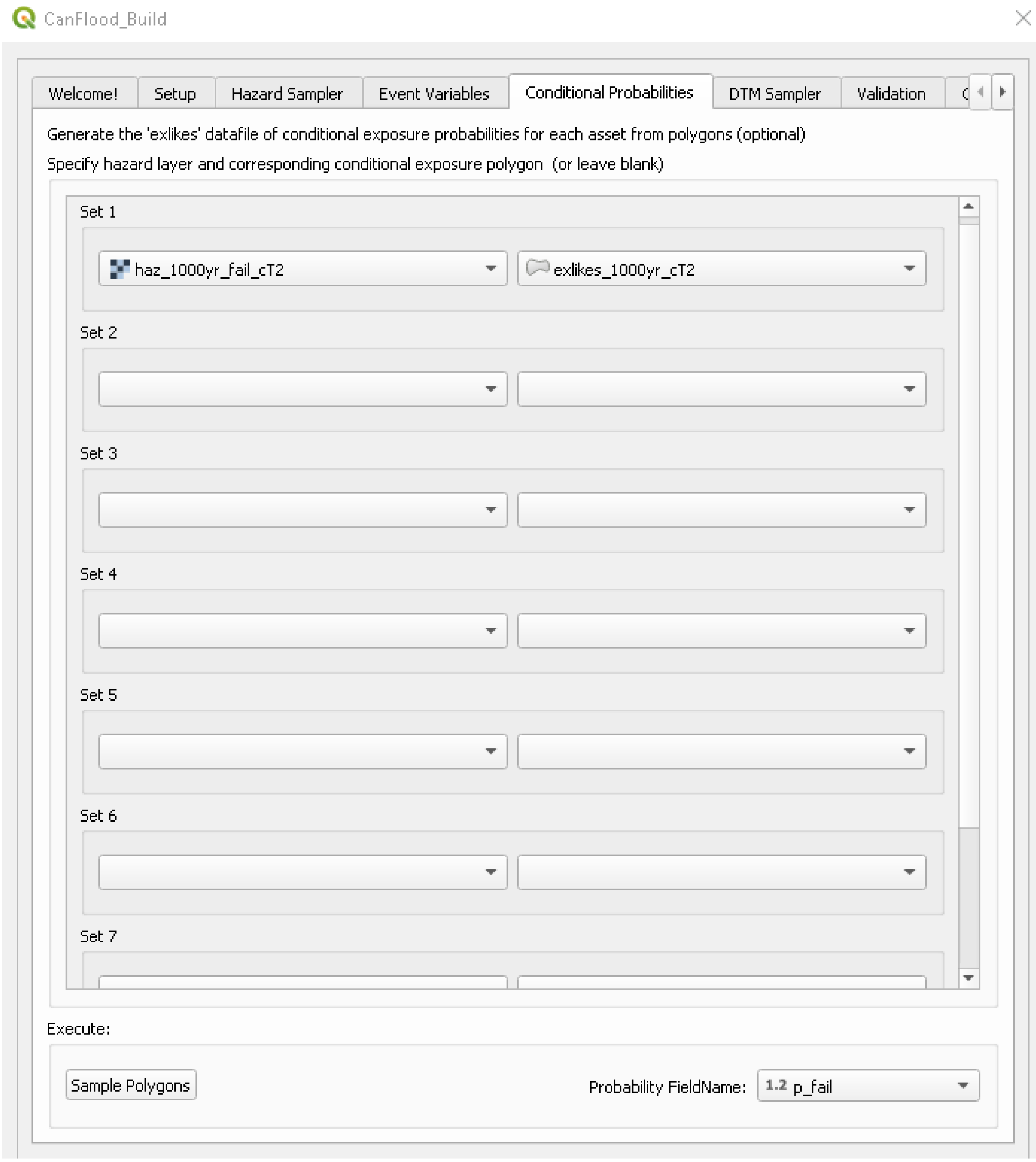
In the same QGIS project as was used for Tutorial 2a, ensure the 'exlikes_1000yr_cT2.gpkg' polygons and 'haz_1000yr_fail_cT2' raster are added to the project.

2.5.1. Build the Model

Follow the steps in Tutorials 2a 'Build the Model' but with including the failure raster layer 'haz_1000yr_fail' in the Hazard Sampler and Event Variables steps.

Conditional Probabilities

Navigate to the ‘Conditional Probabilities’ tab. Pair the failure polygons with the failure raster, and select the Probability FieldName as shown, then click ‘Sample Polygons’:



An ‘exlikes’ data file should have been created in your working directory with entries like this:

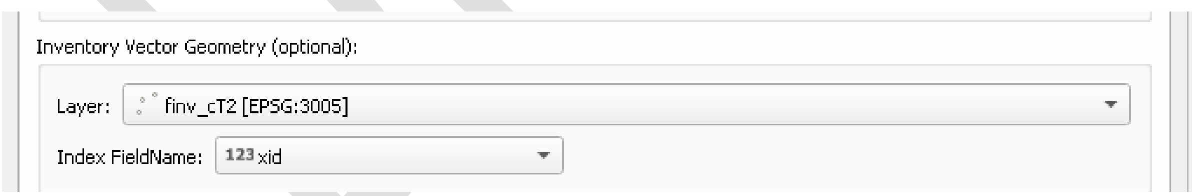
xid	haz_1000yr_fail_cT2
14879	0.7712
14880	0.7712
14925	0.7712
14926	0.7712
14927	0.7712
14928	0.5263
14933	0.7712
14934	0.7712
14935	0.7712
14936	0.7712
14937	0.7712

These are the conditional probabilities of each asset realizing the haz_1000yr_fail WSLs (all other hazard rasters have a conditional probability of 1.0). See Section 5.3 for a complete description of this tool.

Run the Validation tool for the L2 models.

2.5.2. Run the Model

Open the ‘Model’ dialog and follow the steps in Tutorial 2a to setup this model run. Ensure your *finv* layer is properly configured in the ‘Vector Geometry’ box.



Impacts and Risk

Navigate to the ‘Impacts (L2)’ tab, check the ‘Run Risk’ box to execute the impact and risk models in sequence from your Control File. Navigate to the ‘Risk (L2)’ tab to setup your risk model. Check all the boxes. Now move back to the ‘Impacts (L2)’ tab and click ‘Run dmg2’.

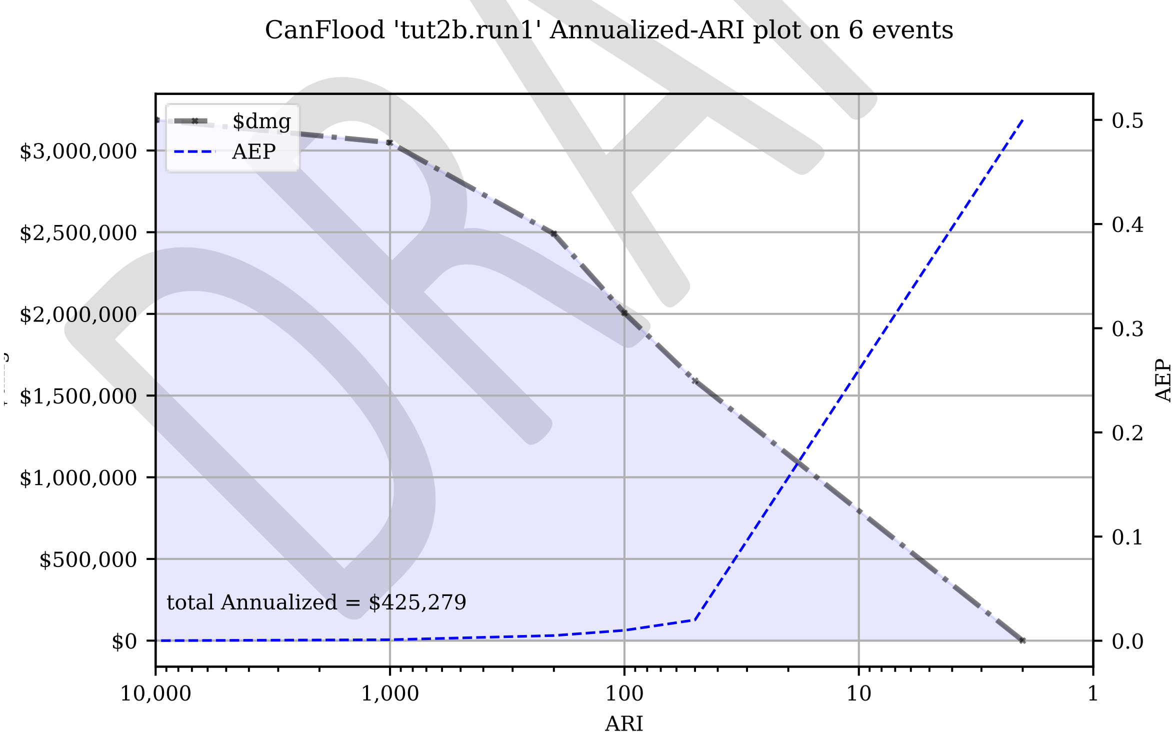
2.5.3. View Results

After executing the Impacts (L2) model linked with the Risk (L2) model and the 'Join Geo' tool, the following data files should have been created in your working directory (see Tutorial 2a for descriptions):

- dmgs_tut2b_run1.csv
- risk2_run1_tut2b_passet.csv
- risk2_run1_tut2b_ttl.csv
- tut2b_smry_plot.svg

A vectorized results data memory layer should have also been loaded to your canvas (with a default style).

Compare the results plot from tutorial 2a with 2b, notice the increase in risk once levee failure is incorporated.



2.6. Tutorial 3: Risk (L3) SOFDA research model

Sample inputs for the SOFDA research model are provided in the tutorials\3\ folder. Refer to the 'SOFDA_UsersManual' for more information.

2.7. Tutorial 4a: Risk (L1) with Percent Inundation

This tutorial demonstrates a risk analysis of polygon type assets (e.g. census geographies) where the impact metric is percent inundated rather than depth.

Load the following data layers from the 'tutorials\4\data\' folder:

- dtm_cT1.tif
- haz_1000yr_cT2.tif
- haz_100yr_cT2.tif
- haz_200yr_cT2.tif
- haz_50yr_cT2.tif
- finv_tut4.gpkg

Your project should look similar to this:

2.7.1. Build the Model

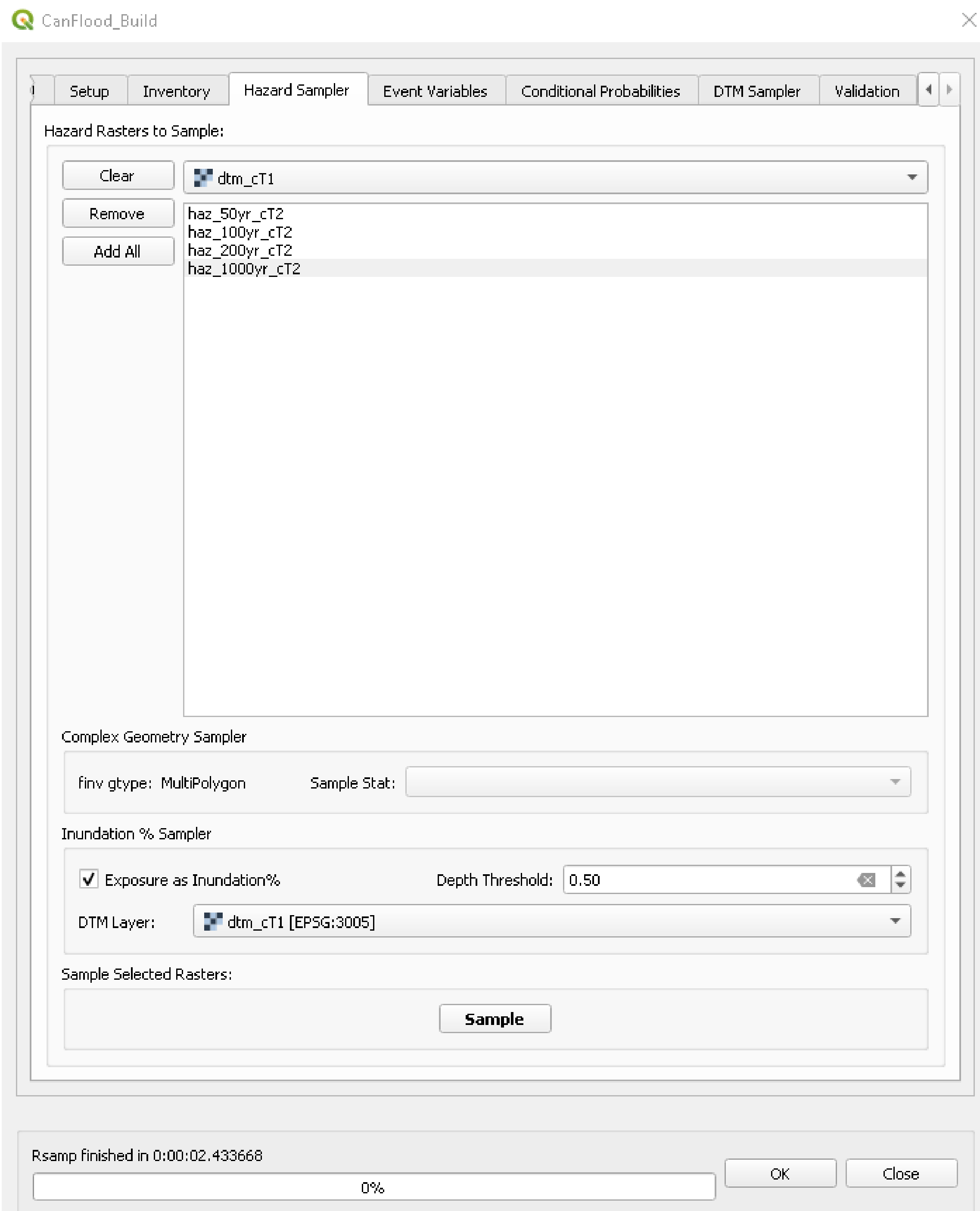
Setup

Setup your scenario for both the 'Setup' tab and 'Inventory' tab as instructed in Tutorial 1a. Ensure 'Elevation type' is set to 'datum'[7] before selecting 'Build Scenario'.

[7] Risk (L1) inundation percentage runs can not use asset elevations; therefore, this input variable is redundant. When as_inun=True CanFlood model routines expect an 'elv' column with all zeros.

Hazard Sampler

Move to the 'DTM Sampler' tab and ensure the DTM raster is selected. Then move to the 'Hazard Sampler' tool and load the four hazard rasters into the dialog window, check 'Exposure as Inundation%', and set the Depth Threshold to 0.5 as shown:



Click ‘Sample’. Navigate to the ‘expos_tut4_4_169_d0.50.csv’ file this created in your working directory. You should see a table like this:

xid	haz_1000yr_cT2	haz_50yr_cT2	haz_200yr_cT2	haz_100yr_cT2
1	1	0.0162	0.0162	0.0162
2	0.9792			
3	0.967	0.1994	0.1994	0.1994
4	1	0.4647	0.4647	0.4647
5	1	0.2921	0.2933	0.2933
6	0.9981	0.9702	1	1
7	1	0.648	0.6567	0.656
8	1	0.9894	0.9894	0.9894
9	1	0.9829	0.9985	0.9985
10	0.9995	0.994	1	1
11	0.9986	1	1	1
12	1	0.9996	0.9996	0.9996

These values are the calculated percent of each polygon with inundation greater than the specified depth threshold (0.5m).

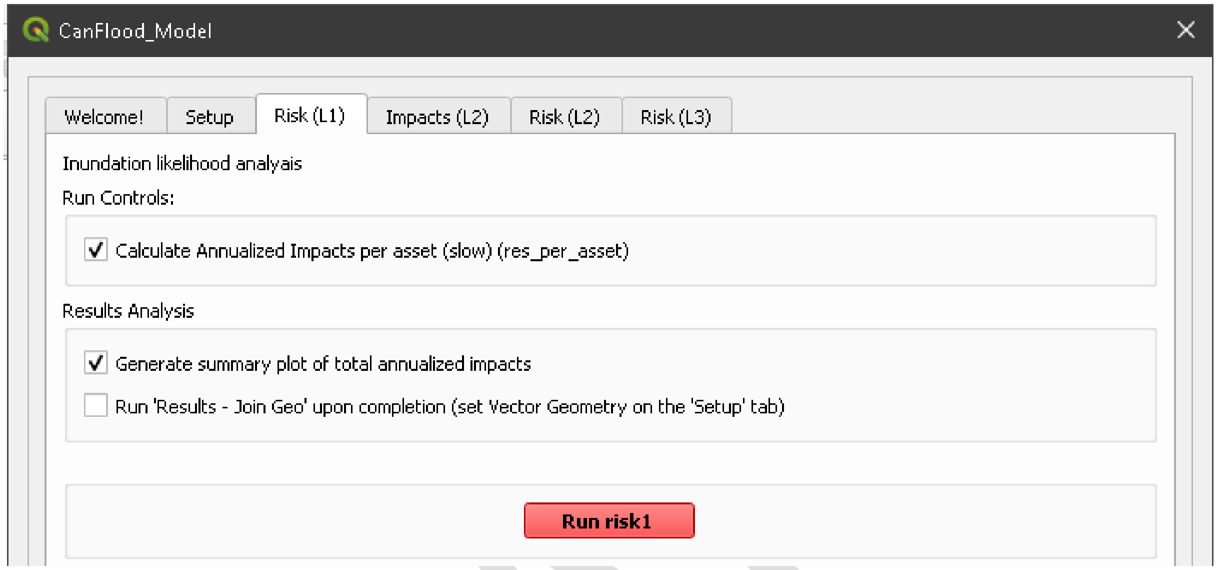
Event Variables and Validation

Run the Event Variables and Validation tools as instructed in Tutorial 1a.

Open the control file. Under ‘[parameters] prec’, change the value to 4. This sets the model precision to 4 decimal places. This is important for inundation percent analysis which deals with small fractions.

2.7.2. Run the Model

Open the ‘Model’ dialog and follow the steps in Tutorial 1a to setup this model run. Navigate to the ‘Risk (L1)’ tool, check the boxes shown, and click ‘Run risk1’:



2.7.3. View the Results

Navigate to your working directory. You should see the following results files have been generated:

- *risk1_run1_tut4_passet.csv*: per asset results
- *risk1_run1_tut4_ttl.csv*
- *tut4_smry_plot.svg*

Open the ‘passet’ results data file, it should look like this:

xid	0.001	0.005	0.01	0.02	ead
1	2577188	41750.45	41750.45	41750.45	18778.36
2	2507731	0	0	0	7836.66
3	19261920	3971900	3971900	3971900	1080475
4	947000	440070.9	440070.9	440070.9	116002.6
5	35253081	10339729	10339729	10297425	2755819
6	1892398	1896000	1896000	1839499	479106
7	15173865	9964677	9954055	9832664	2574672
8	1025000	1014135	1014135	1014135	263709.1
9	34643240	34591276	34591276	34050841	8861488

The first four non-index columns are simply the inundation percentage (from the 'expos' data file) multiplied by the asset scale attribute (from the 'finv' data file). The final 'ead' column is the expected value of these four columns.

2.8. Tutorial 4b: Risk (L1) with Percent Inundation (Lines)

Like Tutorial 4a, this tutorial demonstrates a risk analysis where the impact metric is percent inundated, but with line geometries (e.g. roads) rather than polygons.

Load the same data layers from the 'tutorials\4\data\' folder, with the addition of:

- finv_tut4b_lines.gpkg

Follow all the steps described in Tutorial 4a, but with this new *finv* layer.

The per-asset results should look like this:

xid	0.001	0.005	0.01	0.02	ead
1	91.972	0	0	0	0.287
2	21.669	0	0	0	0.068
3	105.07	0	0	0	0.328
4	216.571	0	0	0	0.677
5	167.26	0	0	0	0.523
6	75.795	75.795	56.846	0	0.995
7	77.712	0	0	0	0.243
8	215.041	0	0	0	0.672
9	410.144	104.997	104.997	104.997	28.253

The first four columns represent hazard events, with values showing the %inundation of each segment multiplied by its 'f0_scale' value. This could represent the meters inundated (above the 0.5m depth threshold) per segment, if the f0_scale value is set to the segment length (as is the case with the tutorial inventory). Alternatively, the f0_scale value could be set to '1' for all features which would cause the first 4 column values to simply reflect the % inundation of each segment (mirrors the output of the Hazard Sampler tool) and the last column would calculate the expected percent annual inundation of the segment.

2.9. Tutorial 5a: Risk (L1) from NPRI data

This tutorial demonstrates how to construction a CanFlood L1 inventory from the National Pollutant Release Inventory (NPRI).

2.9.1. Load Data to Project

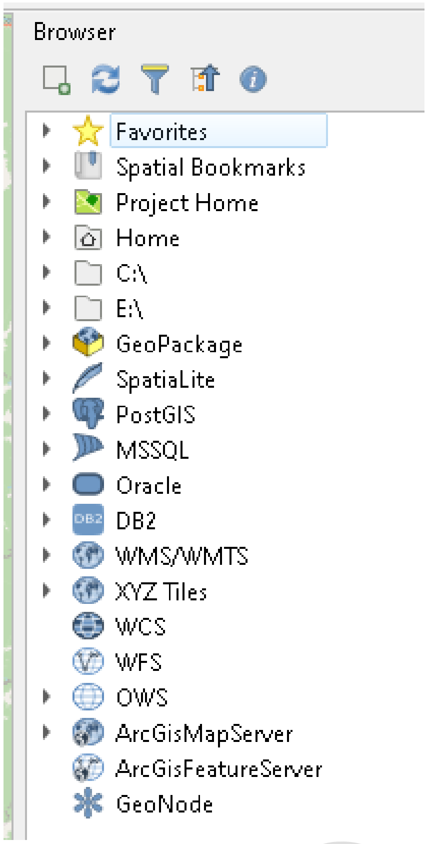
Begin by downloading, then adding, the data layers for Tutorial 5 from CanFlood's tutorial page (CanFlood\tutorials\5\data\) into a QGIS project:

- *tut5_aoi.gpkg*: Area of interest polygon for tutotial

Before inventory construction can begin, the user must add the NPRI raw data to their Qgis project. While many options are possible for accessing and importing NPRI data, this tutorial will demonstrate how to use CanFlood's built-in 'Add Connections' feature to first add a connection to the profile, then download the 'Location of 2017 NPRI facilities' layer.

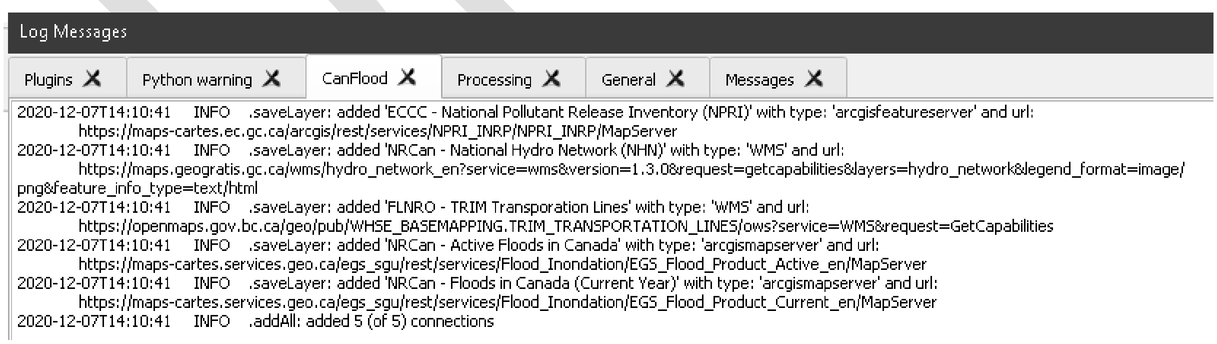
Connect to NPRI Data

Begin by expanding Qgis' 'Browser Panel' (Ctrl + 2) then clicking 'Refresh' on the panel. It should look similar to this:



This shows all the connections added to your Qgis profile.

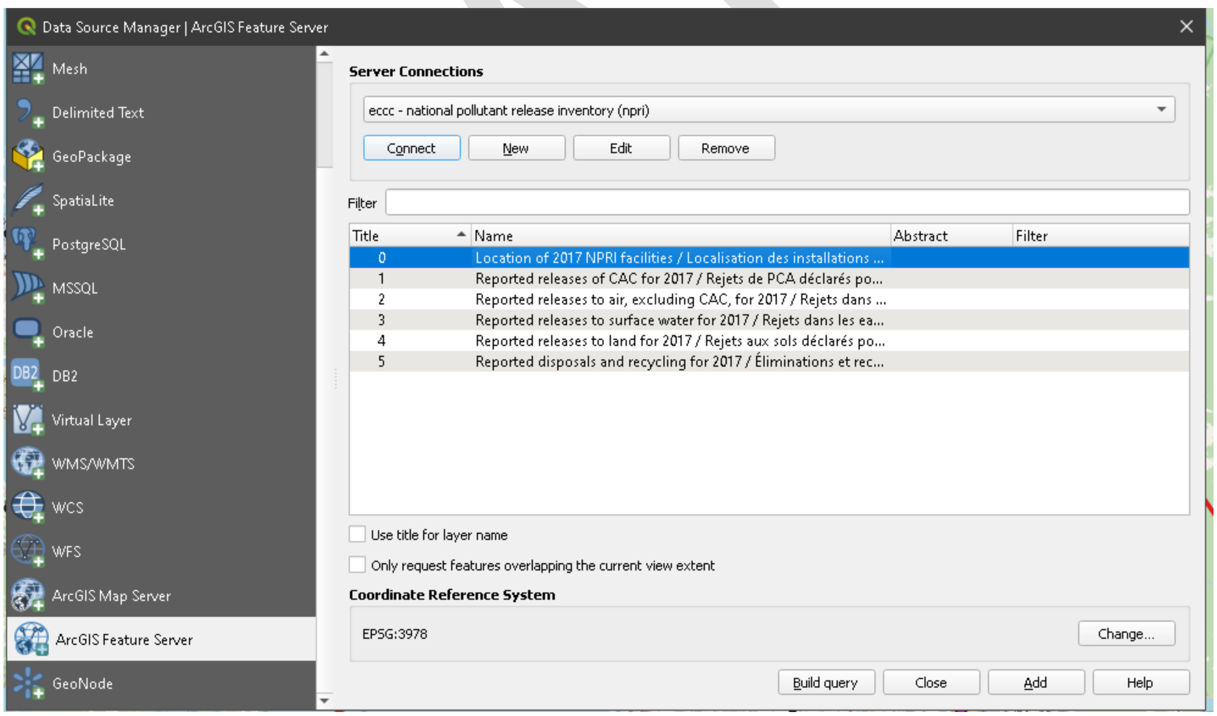
Next, execute 'Add Connections' (Plugins > CanFlood) to run a script that will attempt to add a set of additional connections to your profile. The 'Log Messages' CanFlood panel should look similar to this:



This describes each of the connections that CanFlood added to your Qgis profile. To verify this, navigate back to the 'Browser Panel' and hit the refresh button. You should see 'eccc - national pollutant release inventory (npri)' now listed under 'ArcGisFeatureServer'. Note that this connection will remain in the user's profile for future Qgis sessions, meaning the 'Add Connections' tool should only be required once per install.

Download NPRI Data

Now that the connection has been added to your profile, you're ready to download the layer. To limit the data request, ensure your map canvas matches the extents of the AOI. Now navigate to Qgis' 'Data Source Manager' (Ctrl + L) and select 'ArcGIS Feature Server'. You should see 'eccc – national pollutant release inventory (npri)' listed under server connections. Click 'Connect' to display the layers available on the server. Select the 'Location of NPRI facilities' layer, check 'Only request features…', then click 'Add' to add the layer to the project.



You should now see a vector points layer added to your project with information on each facility reported to the NPRI (within you canvas view).

2.9.2. Build the Model

This section describes how to complete the construction of an L1 inventory from the downloaded NPRI data. For instructions on the remainder of the L1 modelling process, see Section 2.2.

Setup

Follow the instructions in Section 2.2.2 *Setup*; however, ensure 'tut5_aoi' is selected under 'Project AOI'.

Construct and Store Inventory

Navigate to the 'Inventory' tab. Under 'NPRI Vector Layer', select the points vector layer added in the previous section, click 'Construct NPRI'. You should see a new points layer added to the canvas, trimmed to the AOI, and two new fields added: 'f0_scale' and 'f0_elv'. This new layer can be used as a Flood Asset Inventory (Section 3.1) from which to construct a CanFlood L1 model[8].

[8] When storing the this inventory to CSV, the 'OBJECTID' field can be used as the 'Index FieldName'

3. Data Requirements

CanFlood models are only as useful as the datasets they are built with. Below is a summary of the main datasets the user must collect and compile prior to building a CanFlood model.

3.1. Flood Asset Inventory (*finv*)

The asset inventory is a comprehensive list of the objects or assets whose impacts will be evaluated by the CanFlood model. The asset inventory is a spatial dataset with these attributes:

- *fX_tag*: value telling the model which vulnerability function to assign to this asset;
- *fX_scale*: value to scale the vulnerability function by (e.g. floor area);
- *fX_cap*: value to cap vulnerability prediction by (e.g. improvement value);
- *fX_elv*: elevation to anchor the vulnerability function (e.g. first floor height + DTM);
- *geometry*: geospatial data used to locate the asset for sampling;
- *FieldName Index (cid)*: unique asset identifying integer used to link datasets.

To facilitate complex assets (e.g. a house vulnerable to structural and contents damages), CanFlood asset inventories support nesting of the 4 key attributes (tag, scale, cap, elv) with the 'f' suffix numerator (e.g. f0, f1, f2, etc.). In this way, CanFlood can simulate a complex vulnerability function combining the set of simple nested functions to estimate flood damage. An example entry for a single-family dwelling may look like:

xid	f0_tag	f0_scale	f0_cap	f0_elv	f1_cap	f1_elv	f1_scale	f1_tag
14879	BA_S	117.99	91300	11.11	20000	11.11	117.99	BA_C

Where BA_S corresponds to a vulnerability function for estimating structural cleanup/repair, and BA_C estimates household contents damages (both scaled by the floor area). Additional fX columns could be added to nest vulnerability functions for basements, garages, and so on.

3.2. Hazard Events

CanFlood requires a set of 'hazard events' to calculate flood impacts and risk. For a risk calculation, each event must have:

Single Probability value: communicates the likelihood of the event occurring. This can be input as Annual Exceedance Probabilities (AEP) or Annual Recurrence Intervals (ARI). Often these are developed using statistical analysis of past flood events. As this information is not contained in the raster data file itself, best practice is to include it in the layer name.

Water level values: communicates the location and level of the flood event. CanFlood's Build toolset expects this as a raster data file, but CanFlood's Model routines only require tabular data. These values must be relative to the project datum (WSLs). These datasets are typically developed using hydraulic modelling software.

3.3. Impact Function Sets

For the Impacts (L2) model, CanFlood requires an impact function library with a function for each asset tag in the inventory. The datafile is a .xls spreadsheet, where each tab corresponds to a separate impact function. Each tab contains:

- metadata about the function (not used by CanFlood); and
- a 1D function translating exposure to impact.

An example is provided below with a description. During the Impacts (L2) model, each asset interpolates its vulnerability function at the exposure value (from the 'expos' data set) to estimate the impact value. Typically, the exposure variables are depth and the impact variables are damages, but the user can customize the model by populating the 'expos' data set with alternative exposure variables and developing vulnerability functions with alternative outputs (e.g. persons displaced = f(percent inundated)).

Table 3.1: CanFlood impact function format requirements and description.

CanFlood Impact Function		**description**	**required**
tag	02Office.inEq.comp	Linking variable used to assign this function to an asset in the inventory	TRUE
desc	some description	Long form description of the impact function.	FALSE
source	BCStats NRP Survey (2020)	Primary data source for the impact function.	FALSE
location	BCs LowerMainland	Geographic location of applicable assets	FALSE
date	2020	Applicable period	FALSE
impact_units	$CAD	Units of impact output (after scaling)	FALSE
exposure _units	m	Units of expected impact input	FALSE
scale_units	m2	Units of expected scale input	FALSE
exposure_var	water height from main floor	Variable of expected exposure input	FALSE
impact_var	building repair and restoration cost estimate	Variable of impact output (after scaling)	FALSE
scale_var	main floor area	Description of expected scale variable	FALSE
exposure	impact	Header for exposure-impact function	TRUE
0	0	First exposure-impact entry	TRUE
0.305	394.56	…	TRUE
0.914	543.05	Last exposure-impact entry	TRUE

3.4. Digital Terrain Model (DTM)

A project DTM is only required for those models with relative asset heights (elv).

3.5. Conditional Probability Polygons

See Section 4.5.

4. Build Toolset

The build toolset contains a suite of tools intended to aide the flood risk modeller in their construction of CanFlood L1 and L2 models.

- *Scenario Setup*: This is a mandatory tab for starting the control file (and converting the inventory to csv format).
- *Hazard Sampler*: This tab facilitates sampling the different flood event WSL rasters with the inventory geometry. This results in an exposure table of WSL per event per asset.
- *Event Variables*: This tab is used to assign variables (e.g. event likelihoods) to the different events sampled by the Hazard Sampler.
- *Conditional Probabilities:* This tab is used to assign secondary or conditional event polygons to each event. This is useful for modelling flood protection failures during a flood event.
- *DTM Sampler:* Like the Hazard Sampler, this is used for sampling a DTM raster with the inventory geometry. This tool is only required if the elevations provided in the inventory are relative to ground.
- *Validation:* This should always be the last Build tool executed. Validation should also be executed before any Control File is loaded into a model (and after any subsequent changes). This tab ensures all of the inputs are in the proper format for the Level 1 and Level 2 models.
- *Other:* This tab provides some tools to aide in conversion from common legacy data formats to CanFlood data formats.

4.1. Setup

This tab facilitates the creation of a Control File from user specified parameters and inventory, as well as providing general file control variables for the other tools in the toolset.

4.2. Inventory

The inventory tab contains a set of tools for constructing and converting Flood Asset Inventories (finv; Section 3.1). The remainder of this section describes the available inventory tools.

4.2.1. Inventory Vector Layer Compiler

The Inventory Vector Layer Compiler is a simple tool used to prepare an inventory vector layer for inclusion in a CanFlood model using the following process:

1. Clip the selected vector layer by the AOI
2. Extract non-spatial data to the working directory as a csv
3. Write the file location of this csv and the Index FieldName to the control file

4.2.2. RFDA Converter

The Rapid Flood Damage Assessment (RFDA) tool was developed by the Province of Alberta in 2014 as a QGIS 2 plugin. RFDA did not include any spatial analysis or risk calculations. RFDA inventories are in spreadsheet format (.xls) indexed by column location (not labels). Curves are tagged to assets using a concatenation of columns 11 and 12. Many columns in the inventory are ignored in RFDA. These are the functional columns:

- 0:'id1',
- 10:'class',
- 11:'struct_type',
- 13:'area',
- 18:'bsmt_f',
- 19:'ff_height',
- 20:'lon',*
- 21:'lat', *
- 25:'gel'

*not used by RFDA, but necessary for spatial analysis.

RFDA uses a legacy format for reading damage functions based on alternating column locations. An example is provided below:

70																								
AA1	11	0.0	0.0	0.1	372.8	0.3	624.5	0.6	757.8	0.9	808.7	1.2	815.8	1.5	815.8	1.8	838.9	2.1	838.9	2.4	838.9	2.7	838.9	MC
AA2	11	0.0	0.0	0.1	588.2	0.3	594.2	0.6	674.1	0.9	847.9	1.2	847.9	1.5	847.9	1.8	847.9	2.1	847.9	2.4	847.9	2.7	847.9	MS
AA3	11	0.0	0.0	0.1	400.3	0.3	553.6	0.6	715.5	0.9	777.7	1.2	784.2	1.5	786.4	1.8	788.0	2.1	810.5	2.4	835.9	2.7	835.9	BC
AA4	11	0.0	0.0	0.1	231.5	0.3	271.4	0.6	299.4	0.9	299.4	1.2	305.4	1.5	335.4	1.8	335.4	2.1	356.2	2.4	357.2	2.7	365.2	BS
AD1	11	0.0	0.0	0.1	343.1	0.3	545.3	0.6	662.9	0.9	748.4	1.2	765.8	1.5	767.0	1.8	767.0	2.1	767.0	2.4	767.0	2.7	767.0	MC
AD2	11	0.0	0.0	0.1	664.5	0.3	675.8	0.6	825.8	0.9	1050.9	1.2	1050.9	1.5	1050.9	1.8	1050.9	2.1	1050.9	2.4	1050.9	2.7	1050.9	MS
AD3	11	0.0	0.0	0.1	226.0	0.3	354.1	0.6	395.5	0.9	436.6	1.2	440.0	1.5	441.9	1.8	444.0	2.1	474.7	2.4	522.9	2.7	522.9	BC
AD4	11	0.0	0.0	0.1	241.3	0.3	353.9	0.6	406.4	0.9	406.4	1.2	428.9	1.5	466.4	1.8	466.4	2.1	505.5	2.4	507.4	2.7	522.4	BS
BA1	11	0.0	0.0	0.1	220.9	0.3	384.1	0.6	430.7	0.9	492.0	1.2	494.1	1.5	494.1	1.8	495.1	2.1	495.2	2.4	495.2	2.7	495.2	MC
BA2	11	0.0	0.0	0.1	400.3	0.3	407.0	0.6	457.2	0.9	577.7	1.2	577.7	1.5	577.7	1.8	577.7	2.1	577.7	2.4	577.7	2.7	577.7	MS
BA3	11	0.0	0.0	0.1	226.4	0.3	338.9	0.6	375.4	0.9	400.7	1.2	410.3	1.5	411.0	1.8	411.7	2.1	426.0	2.4	503.7	2.7	503.7	BC
BA4	11	0.0	0.0	0.1	231.6	0.3	281.8	0.6	312.0	0.9	312.0	1.2	322.0	1.5	334.1	1.8	334.1	2.1	361.8	2.4	363.5	2.7	373.5	BS
BC1	11	0.0	0.0	0.1	107.7	0.3	194.1	0.6	216.5	0.9	251.6	1.2	252.6	1.3	360.4	1.5	441.3	1.8	462.9	2.1	493.6	2.4	494.7	MC
BC2	11	0.0	0.0	0.1	210.4	0.3	216.9	0.6	242.0	0.9	302.2	1.2	302.2	1.3	502.4	1.5	502.4	1.8	527.5	2.1	587.7	2.4	587.7	MS
BC3	11	0.0	0.0	1.2	0.0	1.3	113.2	1.5	169.4	1.8	187.7	2.1	200.3	2.4	218.8	2.7	296.1	3.0	296.4	3.3	296.8	3.6	297.1	BC
BC4	11	0.0	0.0	1.2	0.0	1.3	115.8	1.5	140.9	1.8	156.0	2.1	156.0	2.4	161.0	2.7	184.7	3.0	184.7	3.3	189.7	3.6	190.6	BS
BD1	11	0.0	0.0	0.1	235.3	0.3	342.3	0.6	421.5	0.9	481.3	1.2	506.6	1.5	508.3	1.8	510.9	2.1	511.0	2.4	512.0	2.7	512.0	MC
BD2	11	0.0	0.0	0.1	523.7	0.3	535.6	0.6	624.9	0.9	791.5	1.2	791.5	1.5	791.5	1.8	791.5	2.1	791.5	2.4	791.5	2.7	791.5	MS
BD3	11	0.0	0.0	0.1	163.4	0.3	254.9	0.6	293.9	0.9	324.0	1.2	332.2	1.5	335.9	1.8	336.1	2.1	363.6	2.4	426.9	2.7	426.9	BC
BD4	11	0.0	0.0	0.1	241.7	0.3	331.0	0.6	384.6	0.9	384.6	1.2	402.4	1.5	420.3	1.8	420.3	2.1	469.7	2.4	472.6	2.7	490.5	BS
CA1	11	0.0	0.0	0.1	239.8	0.3	360.2	0.6	420.2	0.9	468.4	1.2	478.5	1.5	478.8	1.8	479.1	2.1	479.1	2.4	479.1	2.7	479.1	MC
CA2	11	0.0	0.0	0.1	466.8	0.3	478.8	0.6	556.7	0.9	671.6	1.2	671.6	1.5	671.6	1.8	671.6	2.1	671.6	2.4	671.6	2.7	671.6	MS
CA3	11	0.0	0.0	0.1	293.6	0.3	350.4	0.6	384.9	0.9	418.0	1.2	422.0	1.5	422.2	1.8	422.5	2.1	438.9	2.4	511.1	2.7	511.1	BC
CA4	11	0.0	0.0	0.1	236.7	0.3	308.6	0.6	356.5	0.9	356.5	1.2	374.5	1.5	383.4	1.8	383.4	2.1	424.1	2.4	427.1	2.7	439.1	BS
CC1	11	0.0	0.0	0.1	117.2	0.3	182.8	0.6	211.9	0.9	240.4	1.2	245.5	1.3	362.7	1.5	423.0	1.8	450.9	2.1	475.0	2.4	480.1	MC
CC2	11	0.0	0.0	0.1	245.4	0.3	257.4	0.6	296.3	0.9	353.8	1.2	353.8	1.3	587.2	1.5	587.2	1.8	626.1	2.1	683.6	2.4	683.6	MS

RFDA was developed in parallel with a set of 1D damage functions from building surveys of structures in Edmonton and Calgary, AB in 2014. Curves for building replacement/repair and contents damage were developed separately. Residential curves for main floor and basement were developed separately.

During a model run, RFDA applies a contents and structural curve to each asset, and the corresponding basement pair to those with 'bsmt_f'=True.

To facilitate converting from RFDA inventories to CanFlood format, two tools are provided:

1) Inventory converter; and
2) Damage Curve converter.

Inventory Conversion

The RFDA Inventory Conversion requires a point VectorLayer as an input[9]. For Residential Inventories (those with struct_type not beginning with 'S'), each asset is assigned a f0_tag with an '_M' suffix to denote this as a main floor curve (e.g. BD_M) based on the concatenated 'class' and 'struct_type' values in the inventory. Using the 'bsmt_f' value, the f1_tag is also assigned with a '_B' suffix. These suffixes correspond to the curve naming of the DamageCurves tool (described below). The f1_elv is assigned from: f0_elv – bsmt_ht.

[9] Can be built from an .xls file by exporting to csv then creating a csv layer in QGIS from the lat/long values

For Commercial Inventories (those with struct_type beginning with 'S'), the f0_tag and f1_tag fields are populated with the 'struct_type' and 'class' values separately. Where 'bsmt_f' = True, a third f2_tag=' nrpUgPark' is added to denote the presence of underground parking[10]. Once converted, the user can start the CanFlood model building process.

DamageCurves Converter

This tool converts the RFDA format curves into a CanFlood curve set (one curve per tab). The following combinations of RFDA curves are constructed:

- Individual (e.g. main floor contents)
- Floor combined (e.g. main floor structural and contents)
- Type combined (e.g. structural basement and mainfloor)
- All combined

This allows the user to customize which curves are applied and how to each asset (with CanFlood's nested curve capabilities).

4.2.3. NPRI Inventory Constructor

The National Pollutant Release Inventory (NPRI) Inventory Constructor constructs a L1 inventory from an NPRI points vector layer (Section 4.2.3).

The NPRI collects information on the release, disposal and transfer of more than 320 substances. NPRI's data is organized and provided in multiple sets covering multiple years in multiple formats. See Section 2.9 and Section 7.1 for guidance on importing NPRI data into your Qgis project.

[10] A corresponding simple $/m2 curve is created by the DamageCurves Converter

4.3. Hazard Sampler

The Hazard Sampler tool generates the exposure dataset ('expos') from a set of hazard event rasters. To support a wide range of vulnerability analysis, the Hazard Sampler tool is capable of developing depth and inundation exposure variables from the three basic geometry types as shown in the following Table. For *line* and *polygon* type geometries, the tool requires the user specify the sample statistic for WSL calculations, and a depth threshold for percent inundation calculations.

Table 4.1: Hazard Sampler configuration by geometry type and exposure type (and relevant Tutorial).

Geometry	WSL		Inundation	
	Parameters	**Exposure**	**Parameters**	**Exposure**
Point	Default (Tutorial 2a)	WSL	Default (Tutorial 1a)	WSL[1]
Line[4]	Sample Statistic[3, 5]	WSL Statistic	% inundation, Depth Thresh [2]	% inundation
Polygon[4]	Sample Statistic[3]	WSL Statistic	% inundation, Depth Thresh [2] (Tutorial 4a)	% inundation

1. To apply a threshold depth, the f_elv values can be manually manipulated.
2. Requires a DTM raster be specified on the 'DTM Sampler' tab. Model tools expect finv to contain a f_elv column with all zero values and parameter.felv='datum'. Respects NULL raster cell values as not inundated.
3. Ignores NoData values when calculating statistics.
4. M and Z values are not supported.
5. Throws 'feature(s) from input layer could not be matched' error when null values are encountered. Safe to ignore.

4.4. Event Variables

The Event Variables tool stores user specified event variables into the 'evals' dataset for each hazard event. The Hazard Sampler tool must be run first to populate the Event Variables table.

4.5. Conditional Probabilities

This tool generates the conditional probability data set ('exlikes') for each asset. This dataset tells the CanFlood L1 and L2 models when/where to sample a secondary failure raster, and what the likelihood is of realizing that failure raster. This is useful for incorporating failure influence polygons from flood protection infrastructure into your FRA (e.g. the likelihood of a levee failing during a given flood event) (see Section 5.3.2). The user can specify up to eight event-raster/conditional-probability-polygon pairings with the GUI.

Overlapping Conditional Probability Polygons

In some FRAs, assets are vulnerable to exposure from the failure of multiple flood protection failures during the same flood (e.g. levee rings). In these cases, the combined probability of exposure from each failure must be calculated. Where conditional probability polygons overlap, the 'union_probabilities' method is used to calculate the union probability of multiple events using the exclusion principle[11]. The formula for 3 overlapping polygons is:

$$\mathbb{P}(A_1 \cup A_2 \cup A_3) = \mathbb{P}(A_1) + \mathbb{P}(A_2) + \mathbb{P}(A_3) - \mathbb{P}(A_1 \cap A_2) - \mathbb{P}(A_1 \cap A_3) - \mathbb{P}(A_2 \cap A_3) + \mathbb{P}(A_1 \cap A_2 \cap A_3)$$

Where 'A' is the liklihood attribute value in each polygon feature.

[11] https://en.wikipedia.org/wiki/Inclusion%E2%80%93exclusion_principle#In_probability

5. Model Toolset

The ‘Model’ toolset provides a GUI to facilitate access to CanFlood’s 3 flood risk models. CanFlood’s L2 models are split between impacts and risk to facilitate custom applications (these can be linked using the ‘Run Risk Model (L2)’ checkbox). The following tabs are implemented in CanFlood’s Model toolset:

- *Setup*: Filepaths, run descriptions, and optional parameters used by all Model tools;
- *Risk (L1)*: Inundation likelihood analysis;
- *Impacts (L2)*: Part one of the L2 models, impacts per event calculated with vulnerability functions;
- *Risk (L2)*: Part two of the L2 models, expected value of all event impacts;
- *Risk (L3)*: SOFDA research model

Batch Runs

To facilitate batch simulations for advanced users, all CanFlood modelling modules have reduced dependency requirements (e.g. the QGIS API is not required).

Parameter Summary

The following table summarizes the relevant parameters for CanFlood’s model toolset that can be specified in the Control File:

```
[parameters]

event_probs -- format of event probabilities (in 'aeps' data file)
                (default 'ari')

    'aeps'            event probabilities in aeps file expressed as
                     annual exceedance probabilities
    'aris'            expressed as annual recurrance intervals


ltail -- zero probability event extrapolation handle
        (default 'extrapolate')
    'flat'            set the zero probability event equal to the most
                     extreme impacts in the passed series
    'extrapolate'     set the zero probability event by extrapolating from
                     the most extreme impact
    'none'            do not extrapolate (not recommended)
    float             use the passed value as the zero probability impact value


rtail -- zreo impacts event extrapolation handle    (default 0.5)
    'extrapolate'     set the zero impact event by extrapolating from the
```

```
                    least extreme impact
    'none'           do not extrapolate (not recommended)
    float           use the passed value as the zero impacts aep value

drop_tails -- flag to drop the extrapolated values from the results
                    (default True)

integrate -- numpy integration method to apply (default 'trapz')

res_per_asset -- flag to generate results per asset

ground_water -- flag to include negative depths in the analysis

[dmg_fps]


[risk_fps]
dmgs -- damage data results file path (default N/A)

exlikes -- secondary exposure likelihood data file path (default N/A)

evals -- event probability data file path (default N/A)

[validation]
risk2 -- Risk2 validation flag (default False)
```

Some of these can be configured with CanFlood's 'Build' toolset UI, while others must be specified manually in the Control File.

5.1. Risk (L1)

CanFlood's L1 Risk tool provides a preliminary assessment of flood risk with binary vulnerability: exposed or not-exposed. Because this level of analysis doesn't require object specific vulnerability functions (like the L2 and L3 modules), this type of model can be useful for performing preliminary FRAs to determine which areas should receive priority for more detailed FRAs.

This tool also supports conditional probability inputs to incorporate flood protection failures. When the 'scale' factor is set to 1, 'height' to zero, and no conditional probabilities are used (typical for inundation analysis), most of the calculation becomes trivial as the result is simply the impact values provided by the 'expos' table (with the exception of the expected value calculation).

Outputs provided by this tool are summarized in the following table:

Table 5.1: Risk model output file summary

output name	suffix	condition	description
total impacts	ttl	default	table of sum of impacts (for all assets) per event and expected value of all events (ead)
per asset impacts	passet	res_per_asset	table of impacts per asset per event and expected value of all events per asset
summary plot	smry_plot	plot	summary plot of total impacts

5.2. Impacts (L2)

CanFlood's L2 impacts tool is designed to perform a 'classic' object-based deterministic flood damage assessment using depth-damage curves, asset heights, and WSL values to estimate flood impacts from multiple events.

To improve performance, Impacts (L2) only evaluates assets with positive depths (when ground_water=False) and real depths. By specifying ground_water=True, negative depths (within the minimum depth found in all loaded damage functions) can be included.

5.3. Risk (L2)

CanFlood's L2 Risk tool is designed to perform a 'classic' object-based deterministic flood risk assessment using damage estimates and likelihoods to calculate annualized risk. Beyond this classical risk model, Risk (L2) also facilitates risk estimates that incorporate conditional hazard events, like levee failure during a 100-yr flood. This can be conceptualized with Sayers (2012)'s 'source-pathway-receptor' framework as shown in Figure 5.1, where:

- *Source*: WSL prediction (in raster format) for levels behind the defense (e.g. levee) of an event with a quantified likelihood.
- *Pathway*: The infrastructure element separating receptors (i.e. assets) from the raw WSL prediction. Typically, this is a levee, but could be any element where 'failure' likelihood and WSL can be quantified (e.g. stormwater outfall gates, stormwater pumps).

- *Receptor*: Assets vulnerable to flooding where location and relevant variables are catalogued in the inventory and vulnerability is quantified with a depth-damage function.

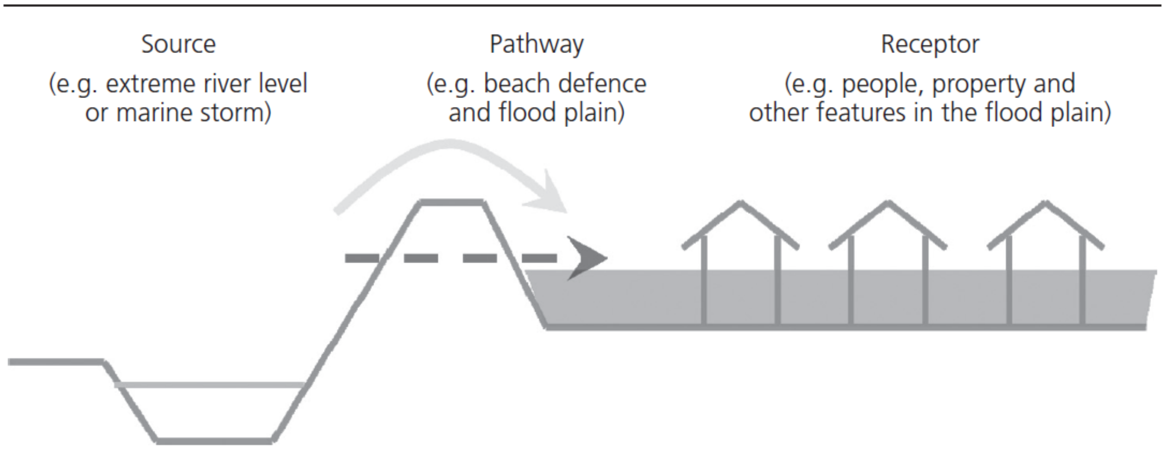


Figure 5.1: Sayers (2012)'s Source-Path-Receptor framework.

Outputs provided by this tool are summarized in table Table 5.1.

5.3.1. Simple Event

A simple application of the Risk (L1) model would be for a study area with no significant flood protection infrastructure (e.g. a floodplain with no levees).

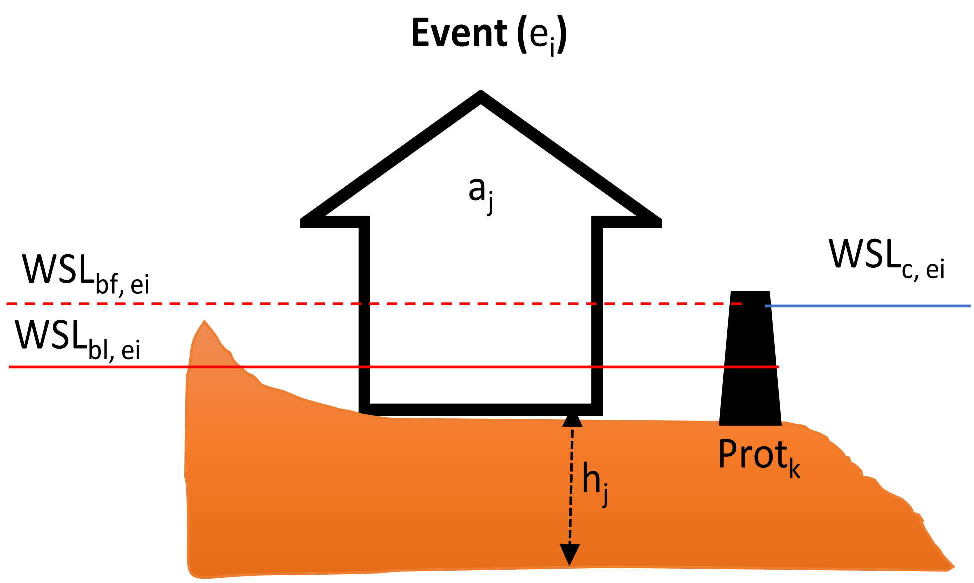


Figure 5.2: Risk calculation definition diagram where the dashed line is the WSL value of event ei

Using the definitions in Figure 5.2 the impact of an event e_i to a single asset a_j with height h_j is calculated as:

$$d_i = F(WSL_{\ bl,ei} - h_j, tag) \tag{1}$$

Where tag is the variable linking the asset to the corresponding vulnerability curve in the vulnerability curve set ('curves'), and $WSL_{bl,ej}$ is the WSL sampled at the asset location and contained in the exposure dataset ('expos')[12]. The total impact of an event x_i is the sum of impacts from all assets. The expected value of flood impacts *E[X]* (also called *Expected Annual Damages* (EAD), or *Average Annual Damages* (AAD), or *Annualized Loss*) is defined for discrete events as:

$$\mathrm{E}[X] = \sum_{i=1}^{\infty} x_i \, p_i \, .$$

[12] Risk (L2) will transfer any exposure variable to the damage function (adjusted by asset height). Typically, this is WSL (adjusted to water depth); however, the Hazard Sampler tool also facilitates calculating the hazard variable as percent inundated for polygon type inventories.

Where x_i is the total impact of the event i and p_i is the probability of that event occurring. While flood models discretize events out of necessity (e.g. 100yr, 200yr), real floods generate continuous hazard variables (e.g. 100- 200yr). Therefore, the continuous form of the previous equation is required:

$$\mathrm{E}[X] = \int_{\mathbb{R}} x f(x)\, dx.$$

Where *f(x)* is a function describing the probability of any event *x* (i.e. the probability density function) (USACE 1996). To align with typical discharge-likelihood expressions common in flood hazard analysis, the previous equation is manipulated further to:

$$E(X) = \int_0^\infty (1 - F_X(x))\, \mathrm{d}x \tag{4}$$

Where *Fx(x)* is the cumulative probability of any event *x* (e.g. cumulative distribution function). Recognizing that the complement of *Fx(x)* is the annual exceedance probability (AEP) (the probability of realizing an event of magnitude *x* or larger), this equation yields the classic 'Risk Curve' common in flood risk assessments shown in Figure 5.3.

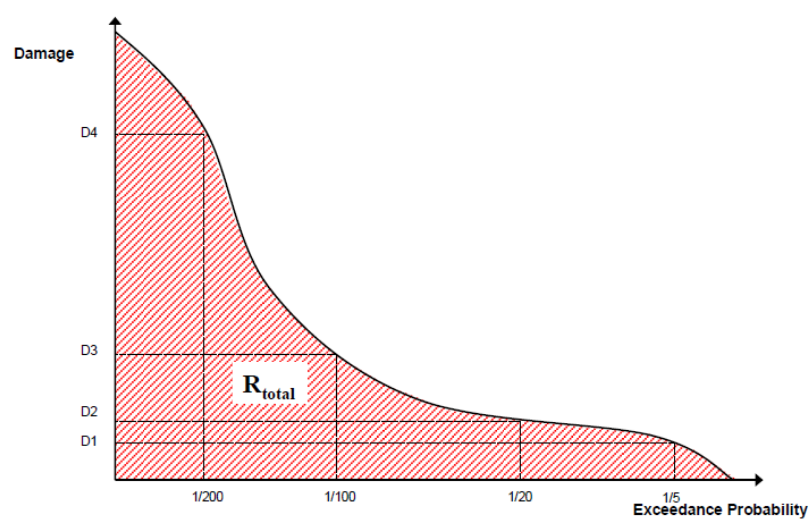


Figure 5.3: Damage-probability Curve from Messner(2007).

The following algorithm is implemented in CanFlood's Risk (L1 and L2) to execute the expected value formula:

1. Assemble a series of AEPs and total impacts for each event;
2. Extrapolate this series with the user provided extrapolation handles ('rtail', and 'ltail')
3. Use the [numpy integration]() method specified by the user to calculate the area under the series;

The same algorithm is used for calculating the total expected value across all assets and for the expected value of individual assets (if 'res_per_asset'=True).

5.3.2. With Flood Protection Infrastructure

Developed areas often rely on some form of flood protection infrastructure to reduce the exposure of built assets (e.g. levees or drainage pumps). Any such infrastructure has the potential to fail during a flood event. Ignoring this failure potential (p_{fail}=0) will underestimate the real flood risk in an area (negative model bias). Assuming such infrastructure will always fail (p_{fail}=1) can drastically overestimate flood risk (positive model bias). Either scenario will reduce confidence in the model and the quality of any flood management decisions made from it. In many areas in Canada, flood protection plays such a significant role in exposure mechanics that a binary treatment of failure probability (p_{fail} = 0 or 1) would render the model risk metric useless. Recognizing the importance of flood protection infrastructure in Canadian flood risk management, CanFlood facilitates the specification of conditional exposure probabilities for each asset, and companion hazard rasters.

A common application of this capability is the incorporation of levee fragility into a risk model. Often such study areas will have groups of levee-protected assets, where each asset is vulnerable to breaching along much of the levee ring. This situation can be analyzed by discretizing the levee into segments, estimating the influence area of a breach along each segment (for event j), estimating the conditional probability of that breach occurring (during event j), and developing a hazard raster for the breach condition. This process should yield one polygon for each breach segment (possibly overlapping), a failure probability value as an attribute in each polygon, and a raster layer with the corresponding failure WSL. Qualified hydrotechnical and geotechnical professionals should be engaged to develop these inputs. An example is provided below:

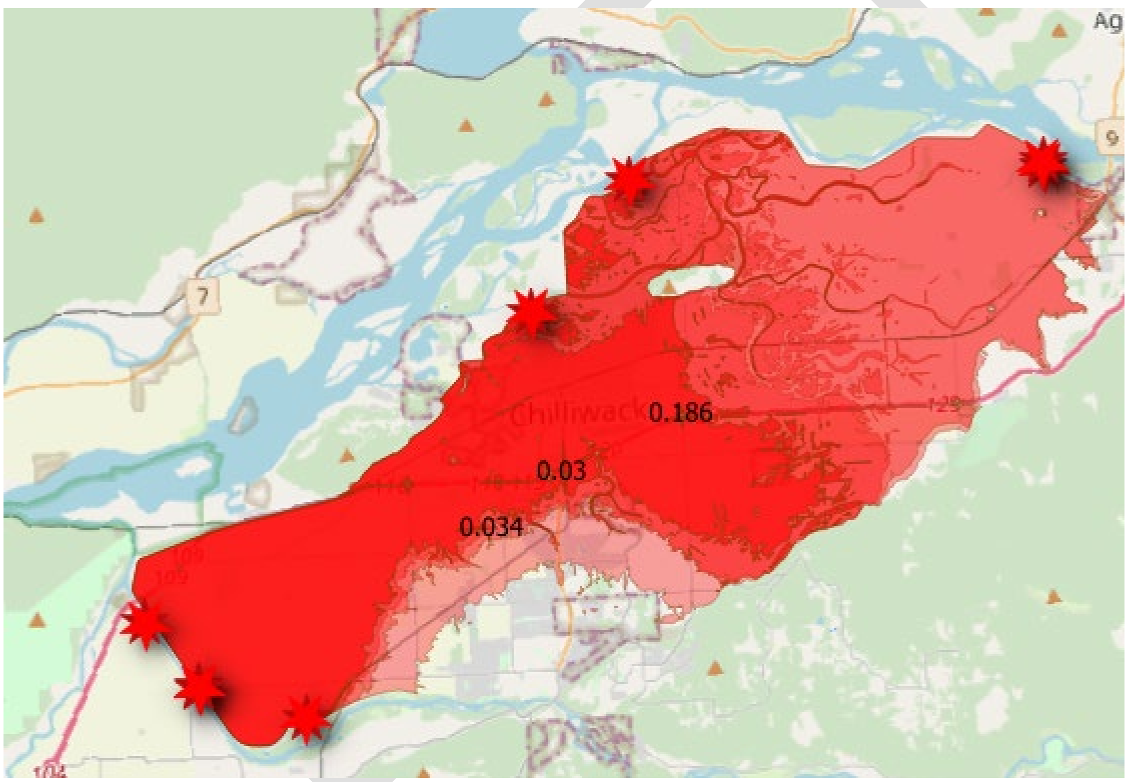


Figure 5.4: Example conditional exposure polygons showing breach locations and associated failure probabilities..

Conditional Probability Polygons

CanFlood facilitates the specification of conditional exposure probabilities with polygons that quantify: 1) the conditional probability of realizing the paired event raster; and 2) the area of influence of the specified conditional probability. Once these conditional exposure polygons are loaded into the project, the conditional exposure dataset ('exlikes') can be generated using the 'Conditional Probabilities' tool described in Section 4.5. Any unpaired hazard rasters will be assigned a conditional probability of 1.0. Assets in areas with any overlapping polygons (i.e. areas exposed to failure from multiple breach points) will have a single conditional probability value pre-calculated by the 'Conditional Probabilities' tool using the described exclusion principle.

Companion Rasters

In conjunction with facilitating the spatial specification of the conditional probability of realizing hazard variables, CanFlood also allows the user to specify companion hazard rasters for a single 'event'. A common application for this is a 'failure' and 'non-failure' hazard raster for a single hydraulic event (e.g. 100yr with levee failure and 100yr without levee failure)[13]. To specify companion rasters for the failure scenario, simply include the raster in the exposure data set[14] and ensure the event likelihood is specified[15] with the same value as the non-failure event. CanFlood selects the maximum expected value of impacts per asset from the duplicated events as shown in the following formula (see Figure 5.2 for variable definitions):

$$d_i = \max\left(F\left(WSL_{bl,ei} - h_j, tag\right) * P_{bl,.ei}\ ,\ F\left(WSL_{bf,ei} - h_j, tag\right) * P_{bf,.ei}\right) \qquad (5)$$

[13] Some flood risk studies refer to 'failure' and 'non-failure' events as 'scenarios', reporting a separate risk metric for each to decision makers. While this communicates model results transparently, it shifts the burden of estimating flood protection failure from the flood risk team onto decision makers. This implies decision makers are better suited at estimating flood protection failure (a f unction of hydraulic loading, geotechnical stability, and breach mechanics for levees) than the flood risk team. While it is possible to take this fail/no-fail scenario approach with CanFlood using separate scenarios/control-files for each, best-practice is for flood analysts to quantify protection failure in the model — rather than push that uncertainty onto decision makers.

[14] 'expos' dataset generated using the 'Hazard Sampler' tool

[15] 'aeps' dataset generated using the 'Event Likelihoods' tool

Where $WSL_{bf,ej}$ is the WSL sampled at the asset location from the companion raster ('failure' raster), $P_{bf,ei}$ is the conditional likelihood of realizing the companion raster (specified in the 'exlikes' datafile)[16]. Once a single impact value is obtained for each asset, the expected value algorithm proceeds as described in Section 5.3.1. Figure 5.5 summarizes CanFlood's full expected value algorithm.

[16] If no P value is specified, the default value of 1.0 is used.

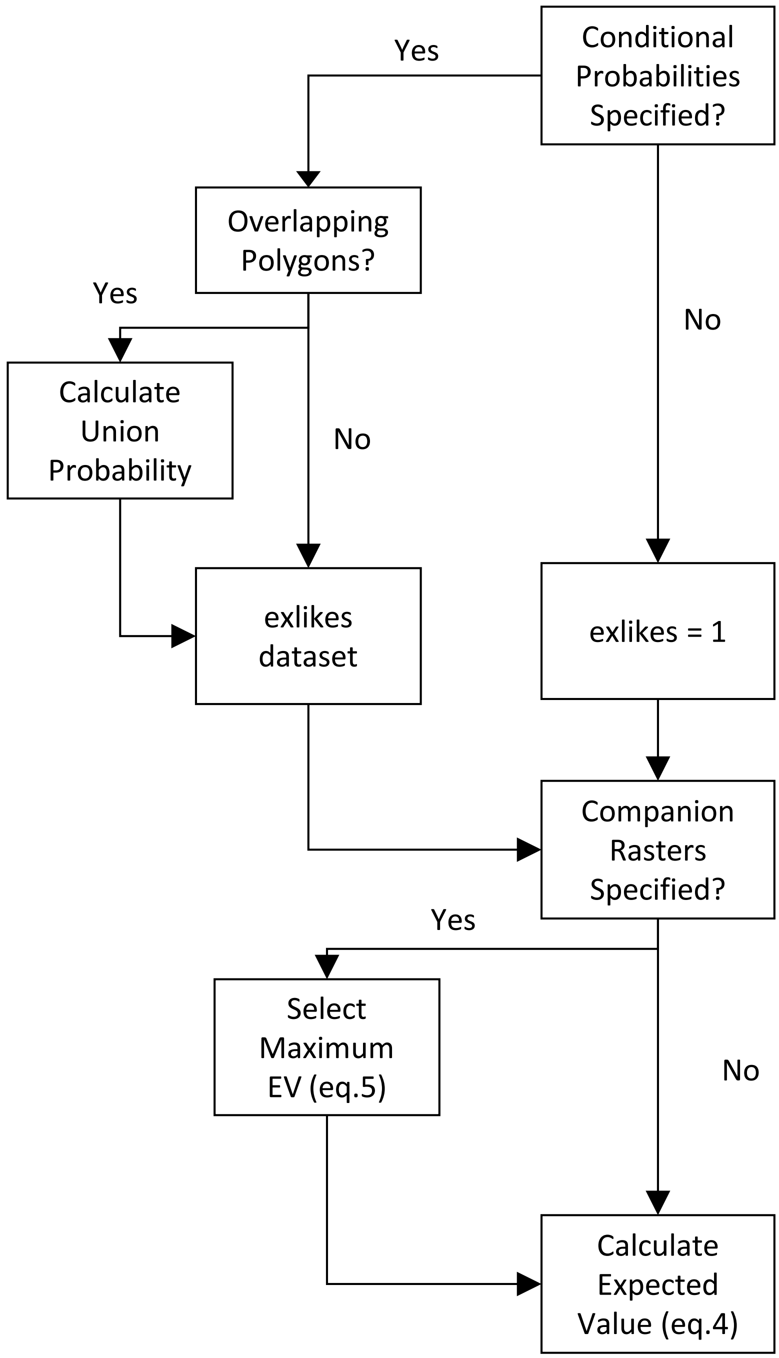


Figure 5.5: CanFlood's Risk (L1 and L2) tool expected value (EV) calculation algorithm

5.4. Risk (L3)

In response to the limitations of RFDA, and the desire to examine more complex elements of flood risk (e.g.; dynamics), Bryant (2019) developed the Stochastic Object-based Flood damage Dynamic Assessment model framework (SOFDA) to simulate flood risk over time using the Alberta Curves and a residential re-development forecast. Framework development was motivated by a desire to quantify the benefits of Flood Hazard Regulations (FHRs) and to help incorporate the dynamics of risk into decision-making. Like the precursor model RFDA, SOFDA quantifies flood risk of an asset through the use of direct-damage and depth-likelihood functions. In this way, flood risk can be quantified (e.g. monetized) at fine spatial resolutions for robust decision support.

SOFDA has the following capabilities:

- Estimate the vulnerability reduction of Flood Hazard Regulations;
- Estimate the vulnerability reduction of Property Level Protection Measures;
- Estimate the influence of elevating damage-features (e.g. raising water heaters);
- Simulate changes in relevant building typology brought about by re-development (e.g. larger homes with deeper basements);
- Dynamic and flexible modeling of many model components (e.g. more expensive water heaters)
- Provide some quantification of uncertainty (i.e. stochastic modeling);
- Provide detailed outputs to facilitate the analysis of underlying mechanisms.

For additional information and guidance, refer to the latest SOFDA Users Manual.

6. Results Toolset

The 'Results' toolset is a collection of tools to assist the user in performing secondary data analysis and visualization on CanFlood models. The following tools have been implemented in CanFlood's Results toolset:

- *Risk Plot*: Generate a risk summary plot from total results data
- *Join Geo*: Map tabular results back to inventory geometry

For more efficient applications, both tools can be linked to execute upon model completion on the Risk tabs in the 'Model' toolset.

7. Miscellaneous Tools

The following section describes some additional tools provided in the CanFlood platform that support flood risk modelling in Canada.

7.1. Add Connections

CanFlood's 'Add Connections' tool adds a pre-compiled set of web-resources to a user's Qgis profile for easy access. The set of web-resources attempted by this tool are included in the 'canflood_pars\WebConnections.ini' file (in the user's plugin directory). The QGIS User Guide explains how to manage and access these connections. Once the resources are added to a user's profile, two basic methods can be used to add the data to the project:

- **Browser Panel**: This is the simplest method but does not support any refinement of the data request. On the Browser Panel, expand the provider type of interest (e.g., ArcGisFeatureServer) > expand the connection of interest (e.g., 'eccc - national pollutant release inventory (npri)') > select the layer of interest > right click > Add Layer To Project.
- **Data Source Manager**: This is the recommended method as it provides more versatility when adding from data connections. Open the Data Source Manager (Ctrl + L) > select the provider type of interest > select the server of interest > select the layer of interest > specify any additional request parameters > 'Add' to the project.

8. Platform Validation

Preliminary CanFlood 0.3 validation exercises include:

- Manual spot checks of dmg2 model and conditional probabilities sampler.
- Dmg2 model results validation against RFDA.

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