IBI Group and NRCan

CanFlood 0.4

User Manual

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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

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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 4.2.3.
Coordinate Reference System (CRS)	
water surface level (wsl)	
Area of Interest (AOI)	

1. Introduction

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

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

Each of these has a suite of tools to assist the flood risk modeller in a wide range of tasks common in developing flood risk assessments in Canada.

CanFlood flood risk models are object-based, where consequences from flood exposure are calculated for each asset (e.g., a house) using a one-dimensional user-supplied vulnerability function (i.e., depth-damage function) before summing the consequences on each asset and integrating a range of events to obtain the total flood risk in an area. To support the diversity of flood risk assessment needs and data availability across Canada, CanFlood supports three modelling frameworks of increasing complexity, data requirements, and effort (see Table 1-1). Each of these frameworks was designed to be flexible and agnostic, allowing modellers to implement a single software tool and data structure while maintaining flood risk models that reflect the heterogeneity of Canadian assets and values. Recognizing the significance of flood protection infrastructure on flood risk in many Canadian communities, CanFlood models can incorporate failure potential into risk calculations. To make use of Canada's growing collection of hazard modelling datasets, CanFlood helps users connect with and manipulate such data into flood risk models.

The CanFlood plugin 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 4.2 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.

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

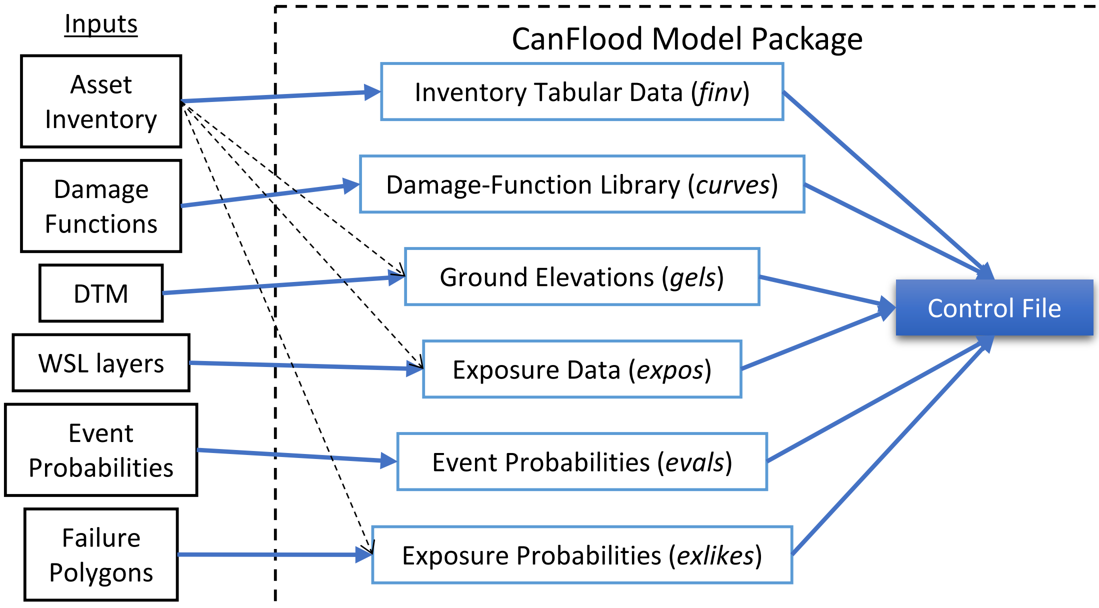


Figure 1-1: CanFlood model package summary diagram.

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: Initial**	**L2: Intermediate**	**L3: Detailed**
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 req.	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,	exposure table, annualized impacts (summary and per asset) summary plot,	exposure 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)

1.5. Defense Failure

Many developed areas in Canada rely on some form of flood defense infrastructure (e.g. levees or drainage pumps) to reduce the exposure of built assets. 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 assumption 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's calculated risk metric useless. Recognizing the importance of flood protection infrastructure in Canadian flood risk management, CanFlood Risk (L1) and Risk (L2) workflows facilitate the incorporation of defense failure into risk calculations.

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 a breach point anywhere along a 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 hazard rasters for the breach conditions. Qualified hydrotechnical and geotechnical professionals should be engaged to perform this analysis and generate the inputs required by CanFlood and summarized in Section 3.2.

Workflow

Defense failure is incorporated into risk calculations during CanFlood's Risk (L1) and Risk (L2) workflows with the following basic steps:

1) Collect and assemble reliability analysis data (see Section 3.2 *companion failure events*)
2) Extract, resolve, and assign conditional failure probabilities for each failure event in the resolved exposure probabilities ('exlikes') dataset using the 'Conditional P' tool (Section 4.1.5)
3) Execute the Risk (L1) or Risk (L2) model to employ CanFlood's algorithms to calculate expected values with defense failure (Section 4.2.3 *Events with Failure*)

Figure 1-2 summarizes CanFlood's full expected value algorithm.

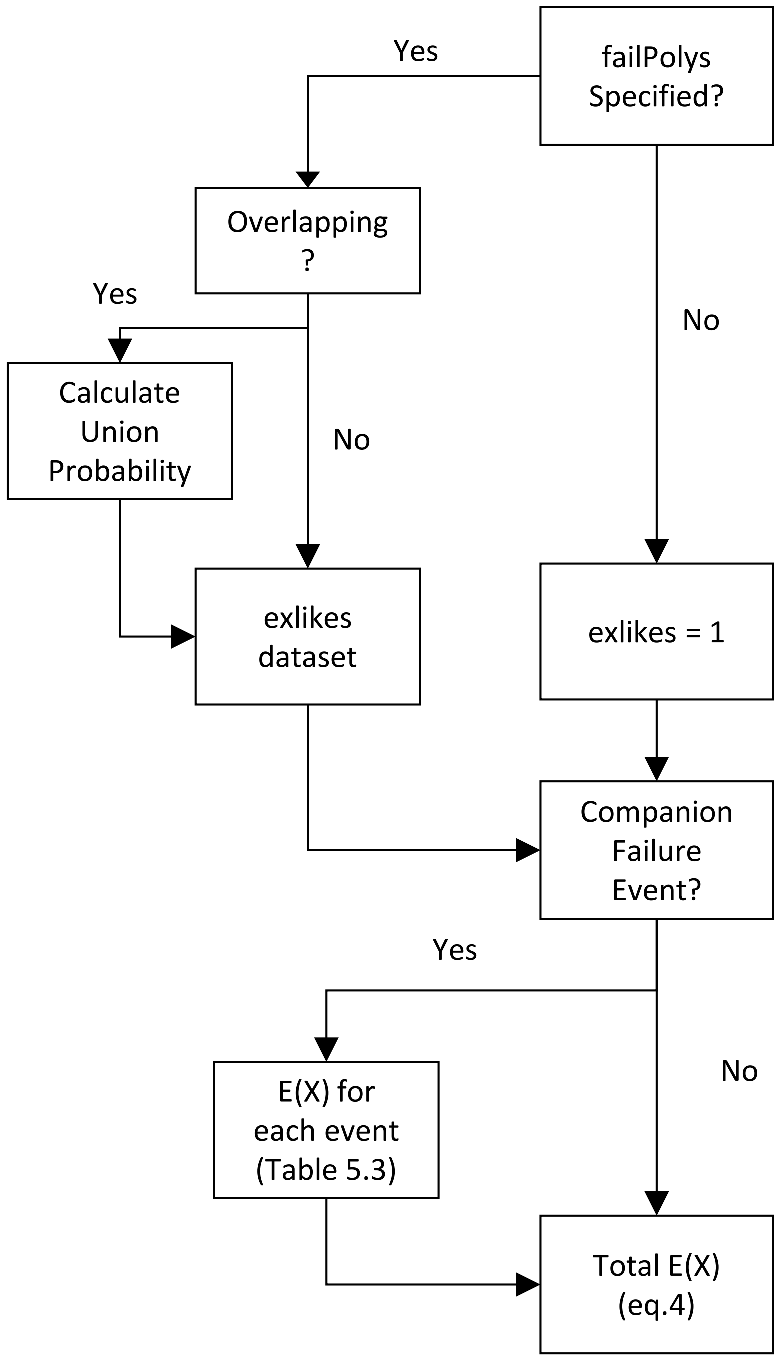


Figure 1-2: CanFlood's Risk (L1 and L2) tool expected value (E(X)) calculation algorithm

Event Relations

To calculate these expected values (in more complex models), the application of both the 'Conditional P' tool and the risk models requires accounting for the relationship between the events supplied by the user. In other words, when multiple failures are specified, we must specify how those failures should/should-not be combined. Calculating and incorporating failure correlations between elements in a defense system requires a sophisticated and mechanistic understanding of the system that is beyond the scope of CanFlood. As an alternative approximation, CanFlood includes two basic assumptions for the relationship between failure elements summarized in Figure 1-3. These alternate assumptions are provided to allow the user to test the sensitivity of the model to failure element correlations; if the model is found to have a high sensitivity to this parameter, more sophisticated defense system analysis should be pursued.

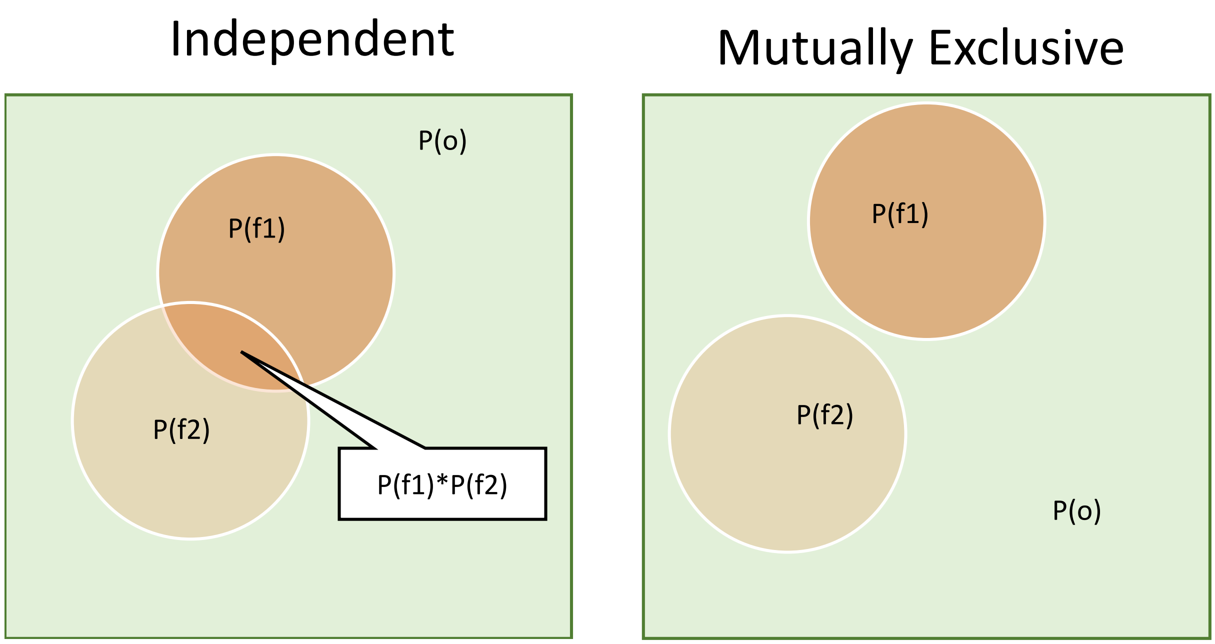


Figure 1-3: Example probability space diagram showing two events either [left] independent or [right] mutually exclusive where 'P(o)' is the probability of no failures.

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. For all tutorials, the project CRS can safely be set from any of the data layers, unless otherwise specified.

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)

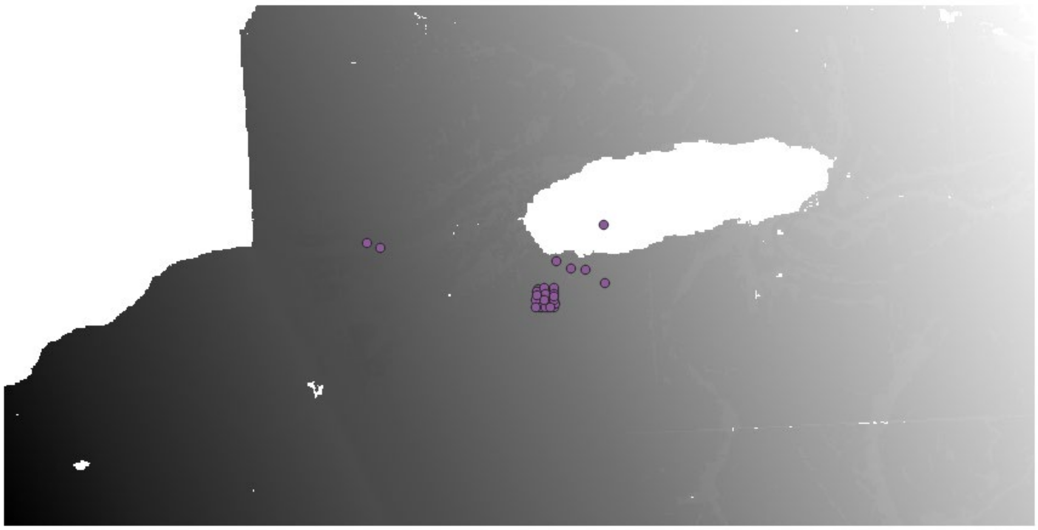
This tutorial guides the user through the simplest application of a risk analysis in CanFlood, called a level 1 (L1) analysis, where only binary exposure is calculated. This 'exposed vs. not exposed' analysis can be useful for preliminary analysis where there is insufficient information to model more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

2.2.1. Load data to the project

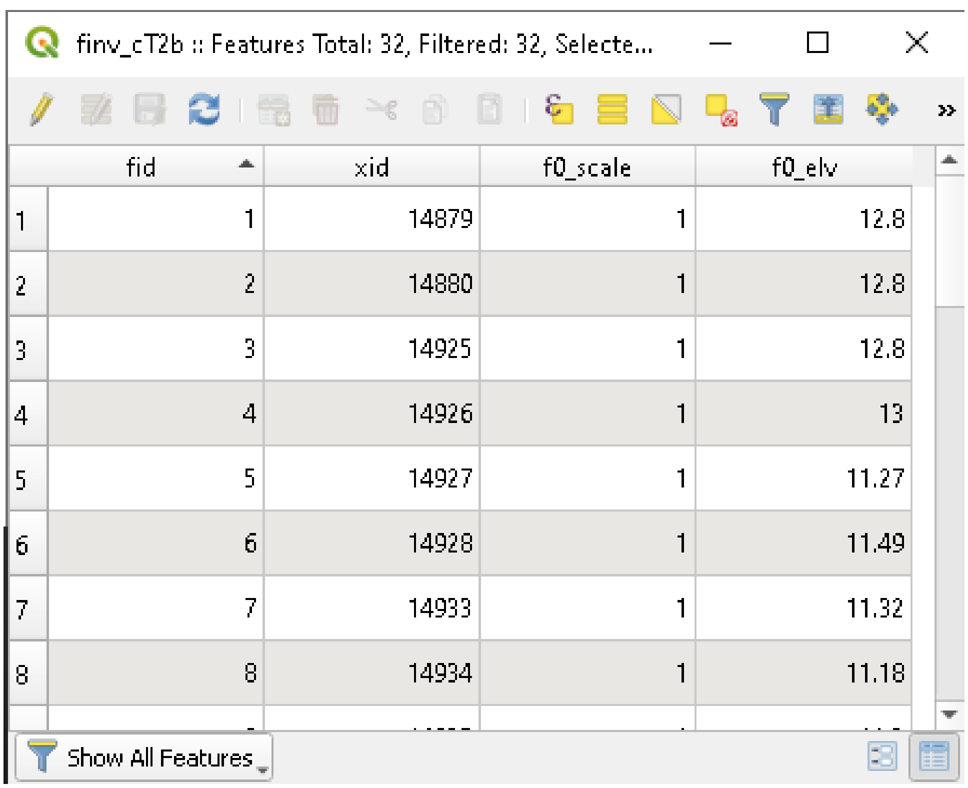
Download the data layers for Tutorial 1 from CanFlood's tutorial page (CanFlood\tutorials\1\data\):

- *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.

Ensure your project’s CRS is set to ‘EPSG:3005’[2] and load the downloaded layers into a new QGIS project[3]. Your map canvas should look something like this:



Explore the flood asset inventory (‘finv’) layer’s attributes (F6). You should see something like this:



finv_cT2b :: Features Total: 32, Filtered: 32, Selecte...

	fid	xid	f0_scale	f0_elv
1	1	14879	1	12.8
2	2	14880	1	12.8
3	3	14925	1	12.8
4	4	14926	1	13
5	5	14927	1	11.27
6	6	14928	1	11.49
7	7	14933	1	11.32
8	8	14934	1	11.18

Show All Features

The 4 fields are:

- *fid*: built-in feature identifier (not used);
- *xid*: Index FieldName, unique identifier for the asset[4];
- *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.

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

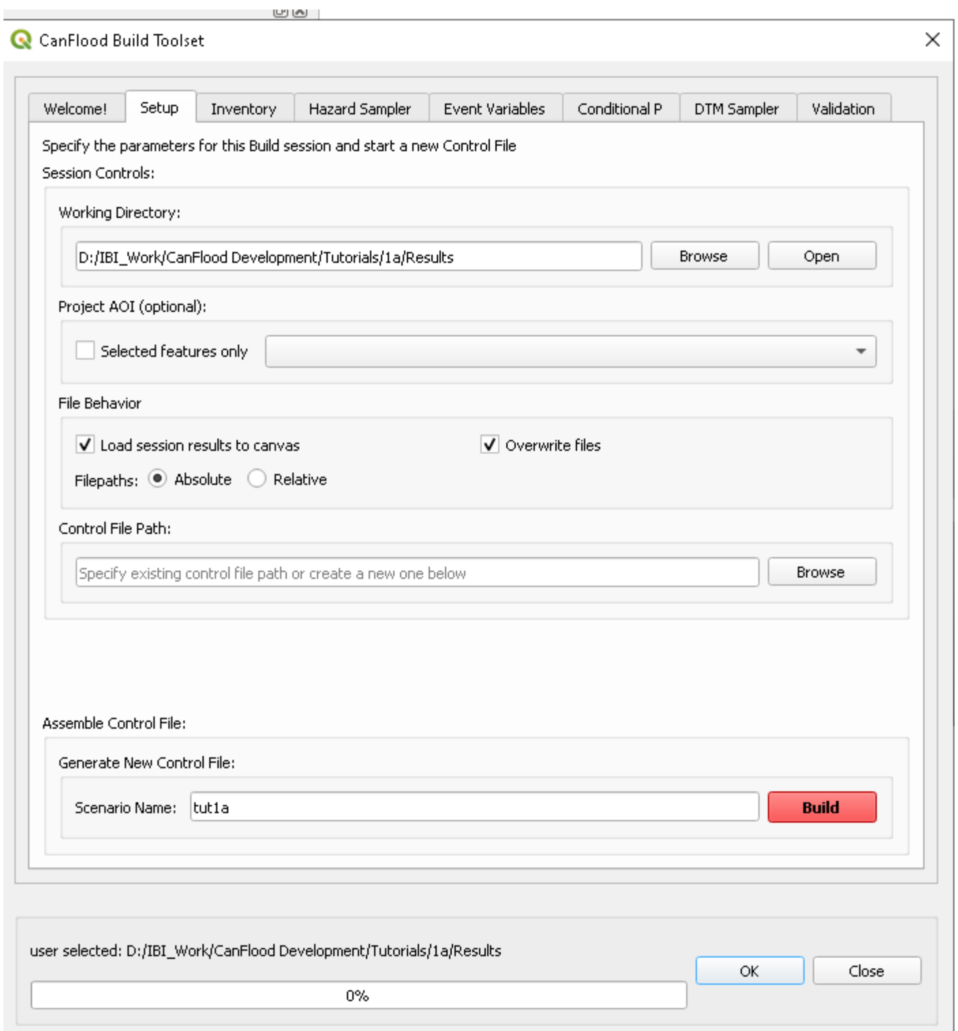
2.2.2. Build the Model

Press the ‘Build’ button to begin building a CanFlood model.

Setup

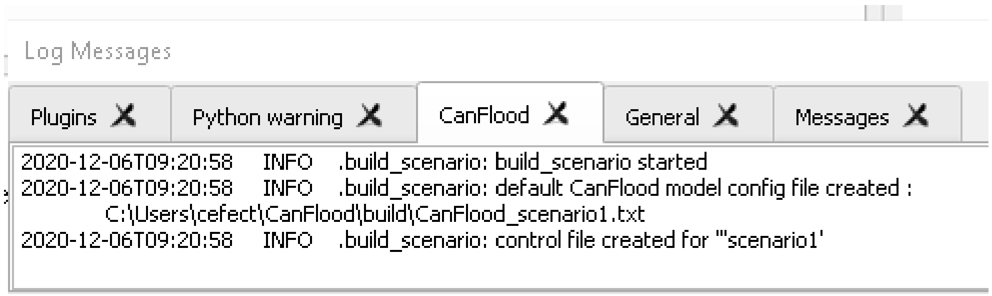
On the ‘Setup’ tab, configure your ‘Build Session’ by first creating or selecting an easy to locate working directory using the ‘Browse’ button. CanFlood will place all the data files assembled with the ‘Build’ toolset in this directory. Ensure the remaining ‘Build Controls’ are specified as shown below.

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.



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:

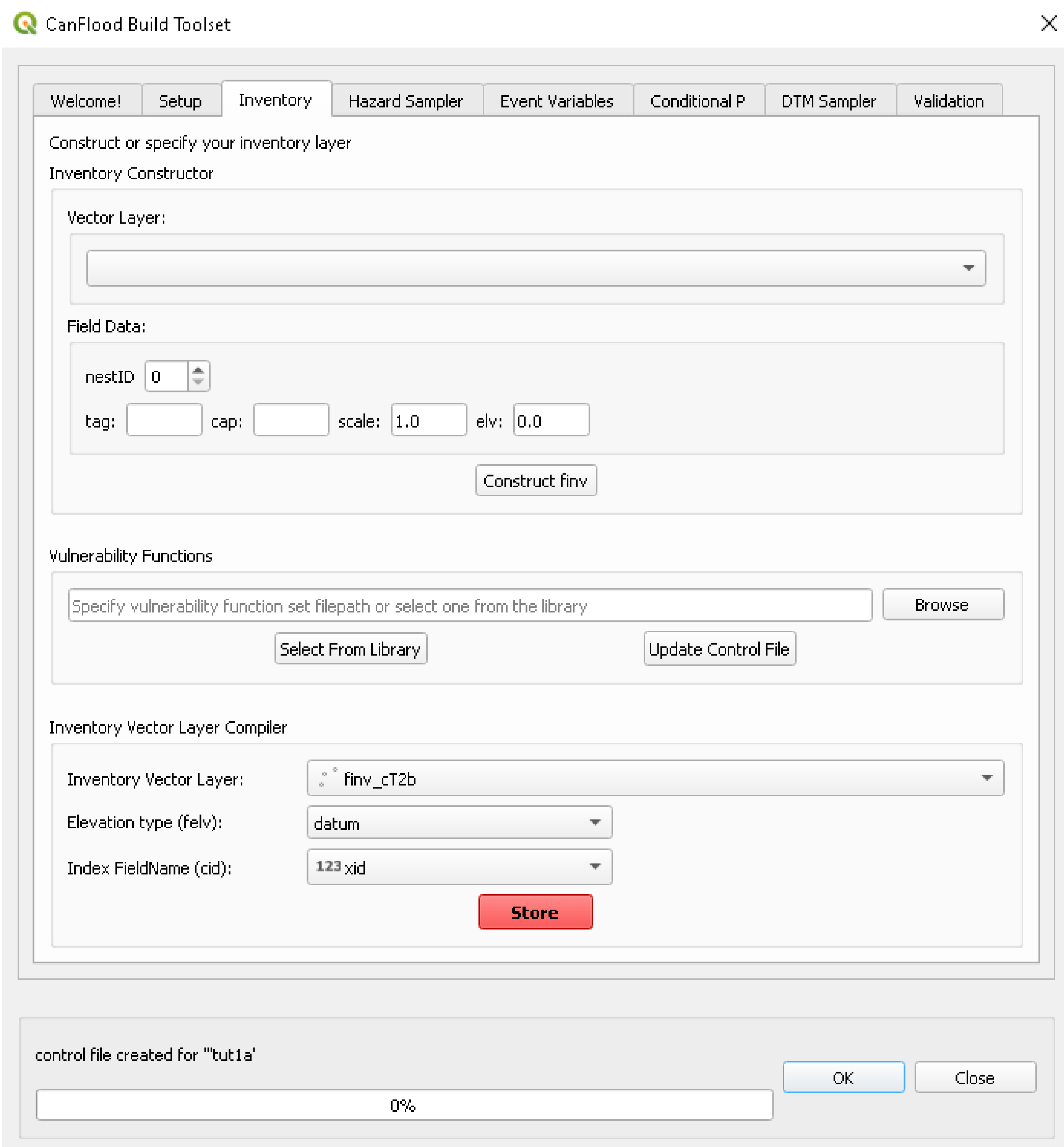


On the 'Setup' tab, next to the working directory file path, click 'Open' to open the specified working directory, you should see the Control File 'CanFlood_scenario1.txt' created in your working directory. This is a template with some blank, default, and specified parameters. As you work through the 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. Under the Inventory Vector Layer Compiler section, select your inventory layer and ensure 'elevation type' is set to 'datum' to reflect that the inventory's 'f0_elv' values are measured from the project's datum. Now select the inventory vector layer and the appropriate 'Index FieldName' as shown, then **click 'Store'**.

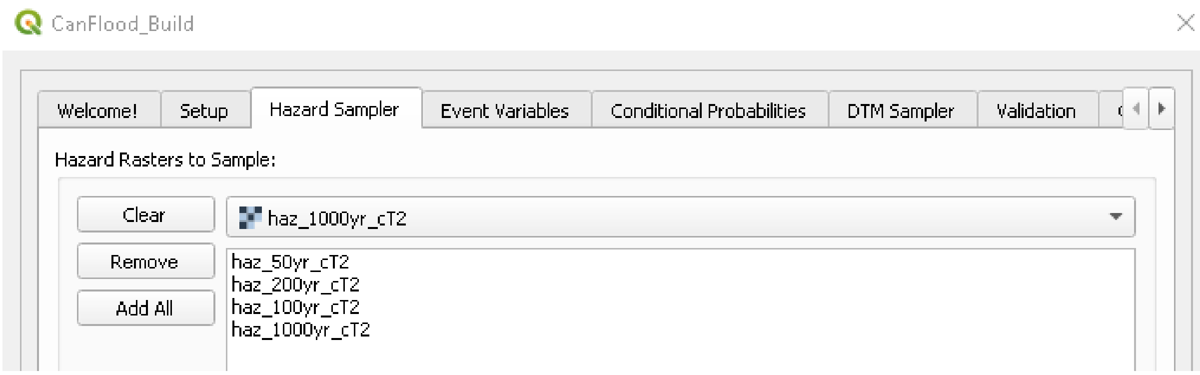


You should see the inventory csv stored into the working directory. This is a simplified version of the inventory layer with all of the spatial data removed.

Now open the Control File again. You should notice that asset inventory ('finv') parameter has been populated with the file name of the newly created csv.

Hazard Sampler

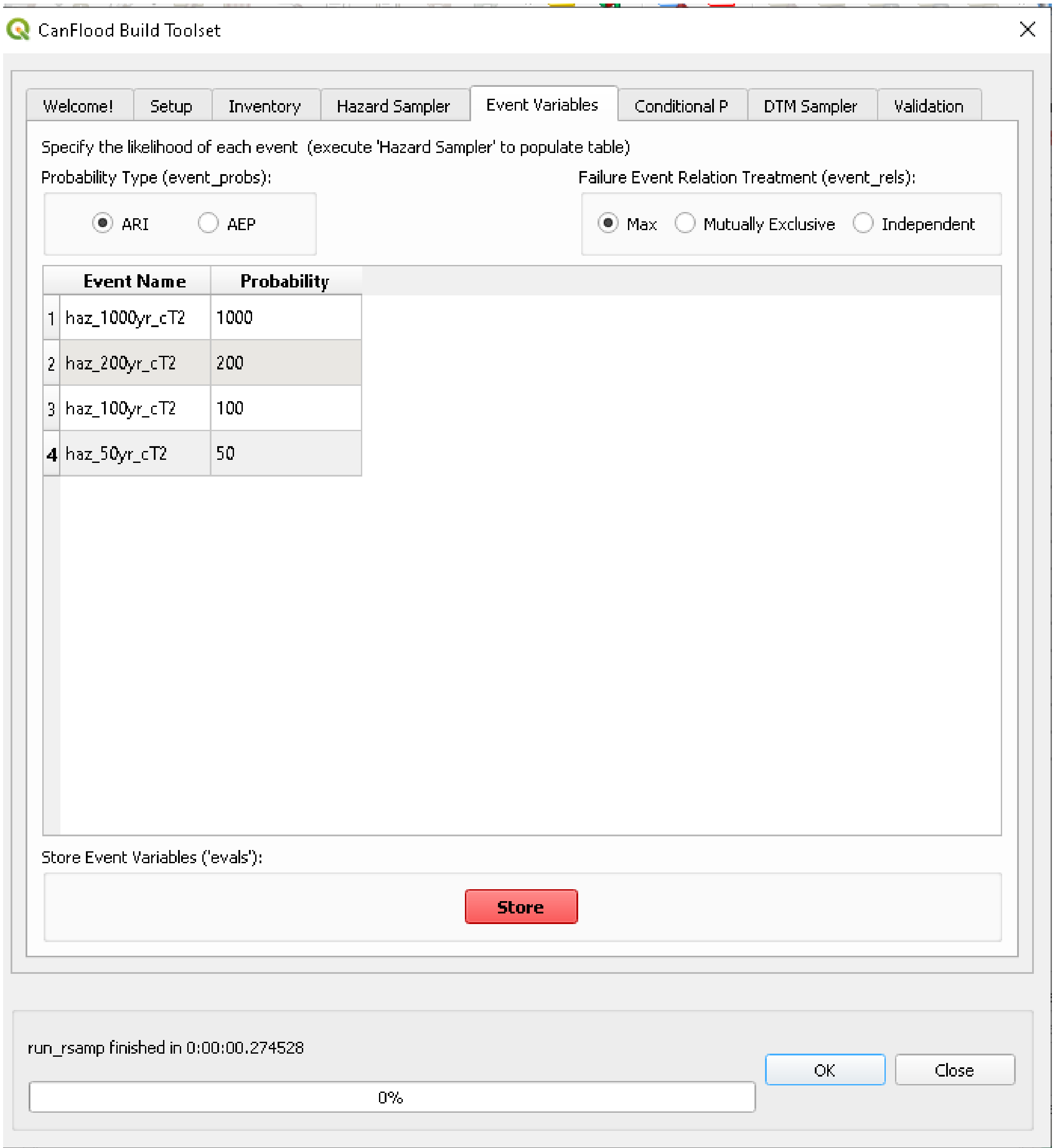
Move to the 'Hazard Sampler' tab. Add all the hazard rasters to the display box as shown, leaving the remaining parameters blank or untouched:



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_tut1a.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 **click 'Validate'**. This will check all the inputs in the control file and set the 'risk1' validation flag to 'True' in the control file. 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

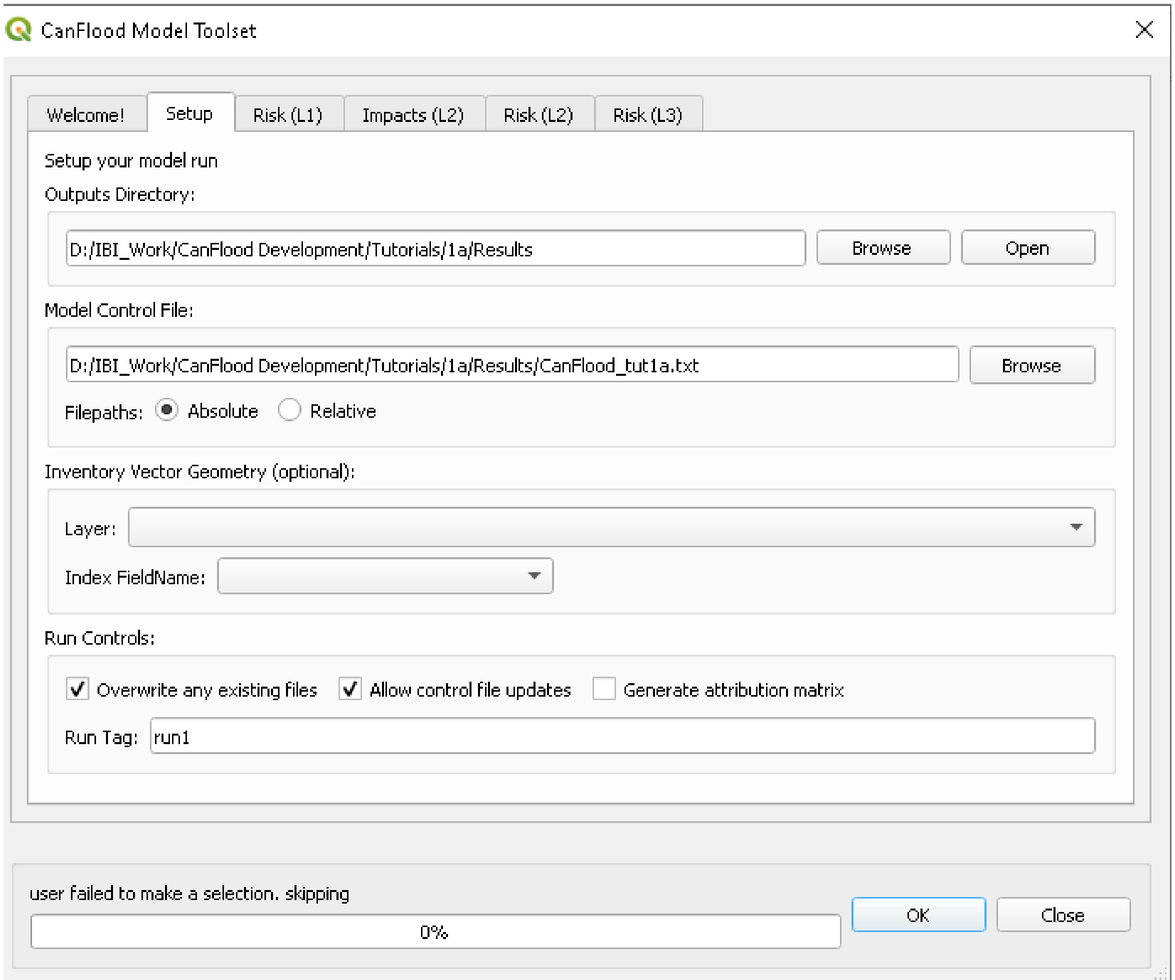
Click the 'Model' button to launch the Model toolset dialog.

Setup

On the 'Setup' tab, select a working directory[5] where all your results will be stored. Also select your Control File created in the previous section.

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

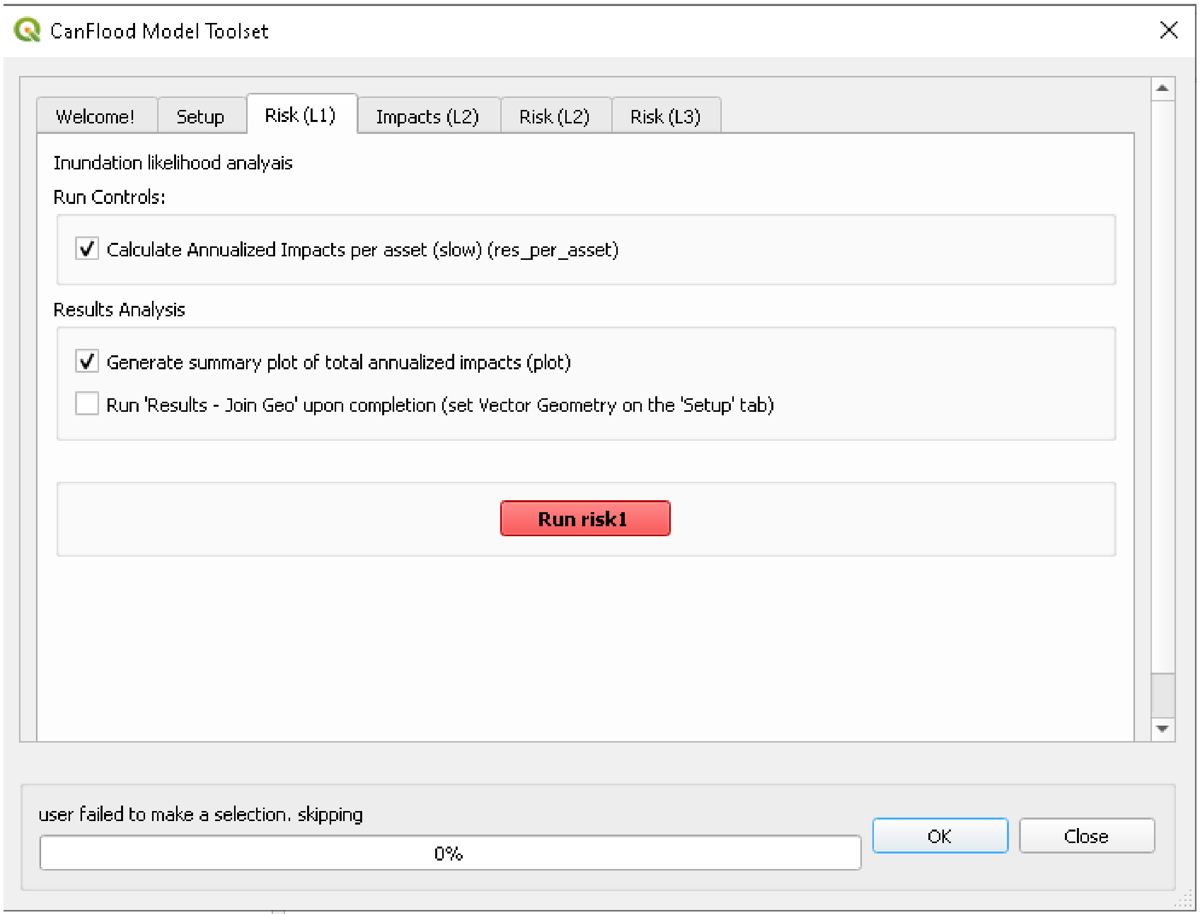
Your dialog should look like this[6]:



[6] 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.

Execute

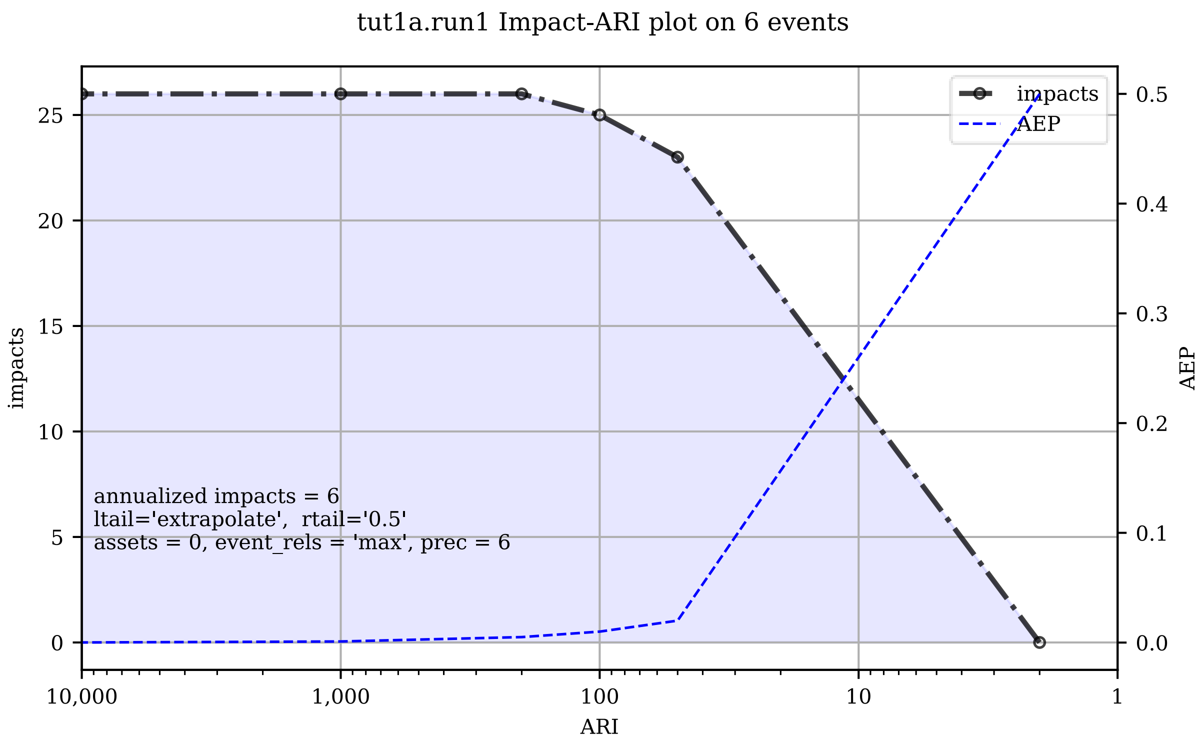
Navigate to the 'Risk (L1)' tab. Check the first two boxes as shown below and **press 'Run Risk1'**:



2.2.4. View Results

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

- *risk1_run1_tut1a_passet.csv:* expected value of inundation per asset;
- *risk1_run1_tut1a_ttl.csv*: total results, expected value of total inundation per event (and for all events);
- *tut1a.run1 Impact-ARI plot on 6 events.svg*: a plot of the total results (see below).

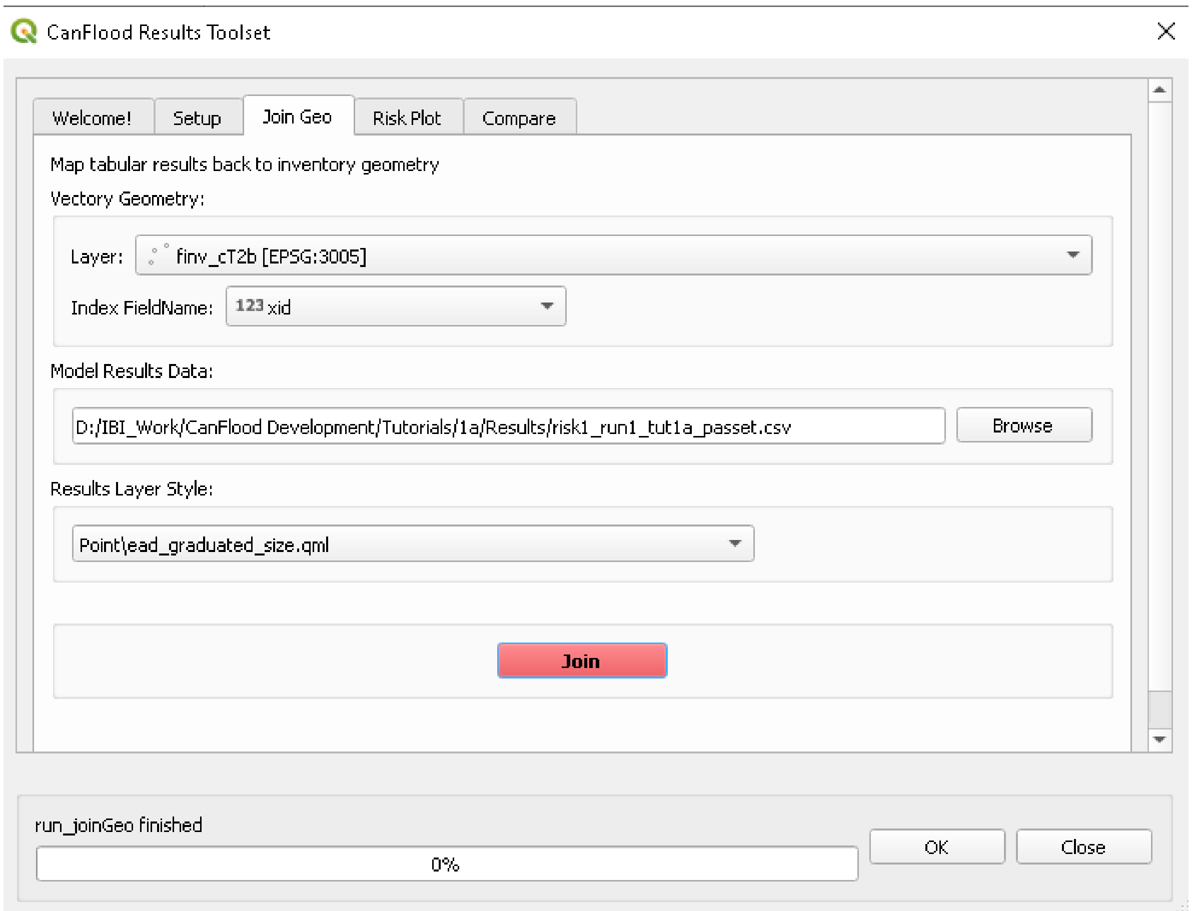


These are the non-spatial results which are directly generated by CanFlood's model routines. To facilitate more detailed analysis and visualization, CanFlood comes with a third and final 'Results' toolset.

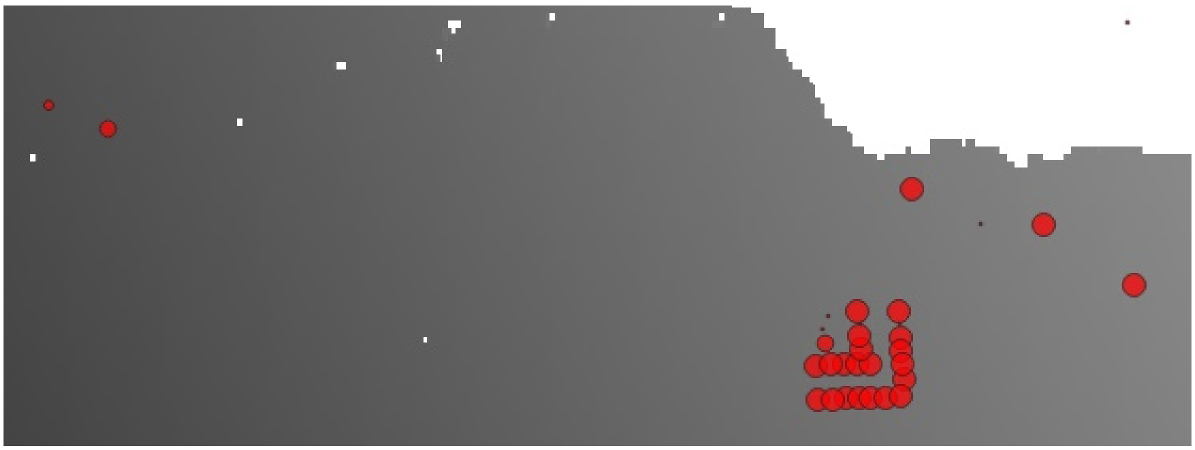
Open this toolset by **clicking the 'Results'**  **button**.

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 asset inventory ('finv') vector geometry. To do this, move to the 'Join Geo' tab, select the asset inventory ('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[7] and hiding all other layers[8]. 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 2a: Risk (L2) with Simple Events

Tutorial 2 demonstrates the use of CanFlood's 'Risk (L2)'model (Section 4.2.3). 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 'composite vulnerability function' feature where multiple functions are applied to the same asset.

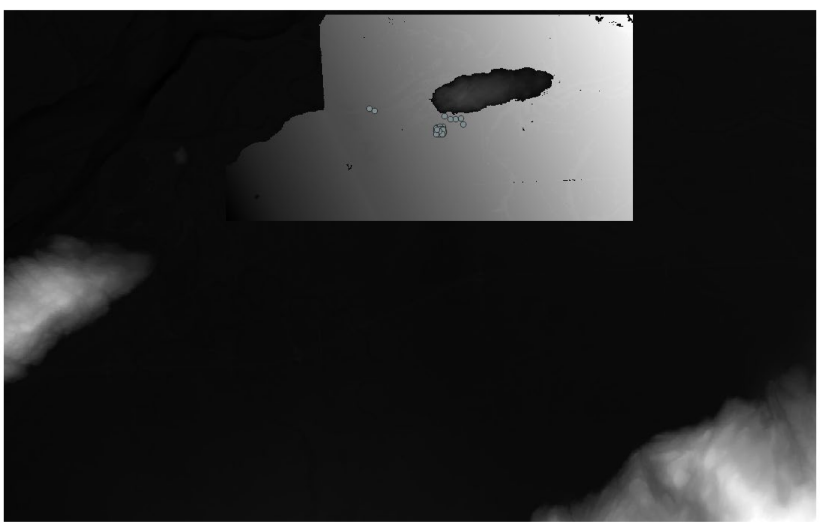
[7] Right click the layer > Properties…, click 'Control Feature Symbology' on the left, click 'Classify' at the bottom.
[8] Either uncheck each layer, or select the layer in the 'Layers pane', click the 'Manage Map Themes' eyeball at the top of the Layers Pane, select 'Hide Deselected Layers'

2.3.1. Load data to project

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

- ~~*expoProbPoly_1000yr_A_T2d.gpkg*~~: (ignore for tutorial 2a);
- ~~*expoProbPoly_1000yr_B_T2d.gpkg*~~: (…);
- *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_A_cT3.tif*~~: (ignore for tutorial 2a);
- ~~*haz_1000yr_fail_B_cT3.tif:*~~ (…)
- *haz_100yr_cT2.tif:* hazard event raster;
- *haz_200yr_cT2.tif:* hazard event raster;
- *haz_50yr_cT2.tif:* hazard event raster.

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

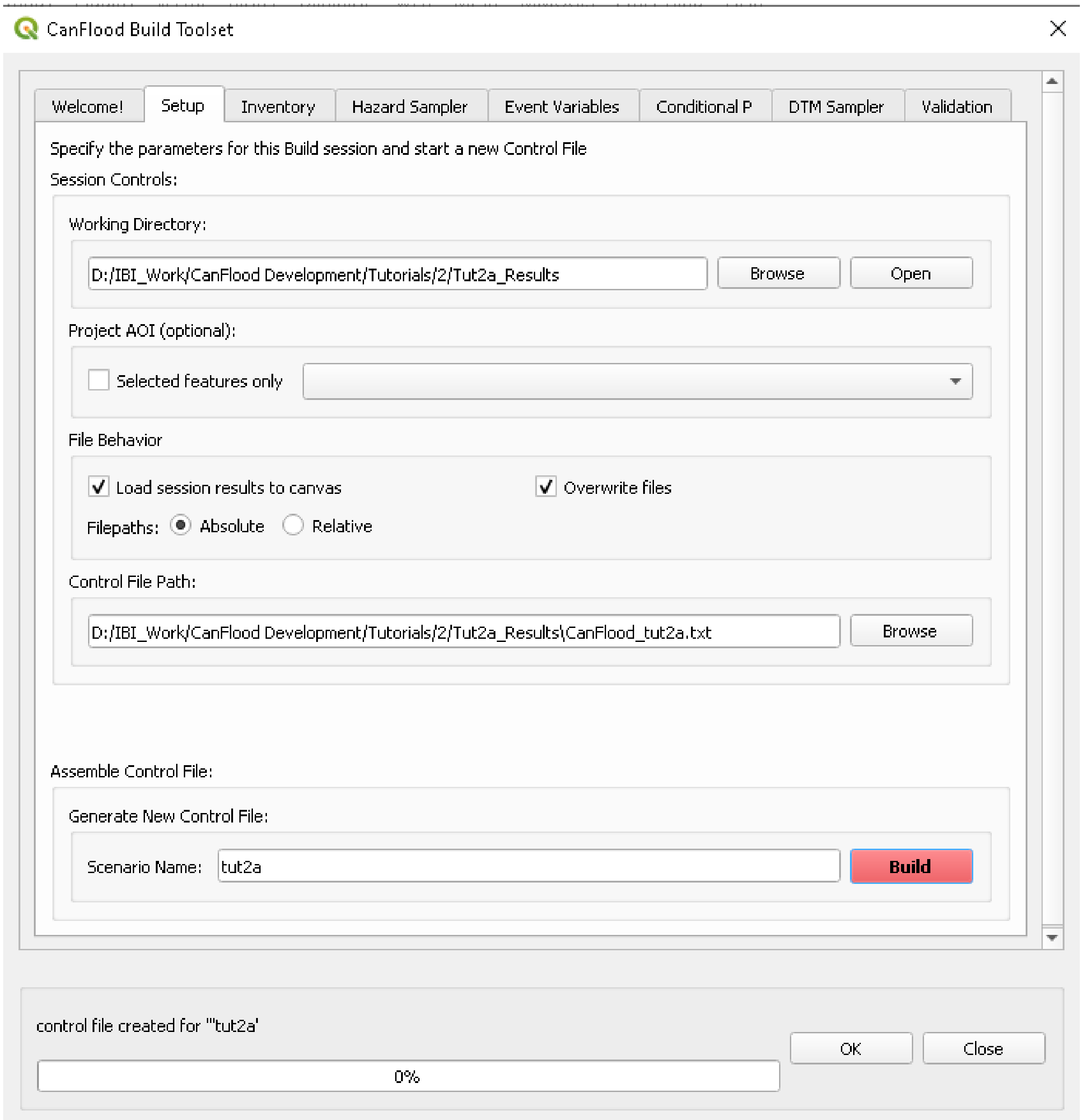


2.3.2. Build the Model

Open the 'Build' toolset.

Scenario Setup

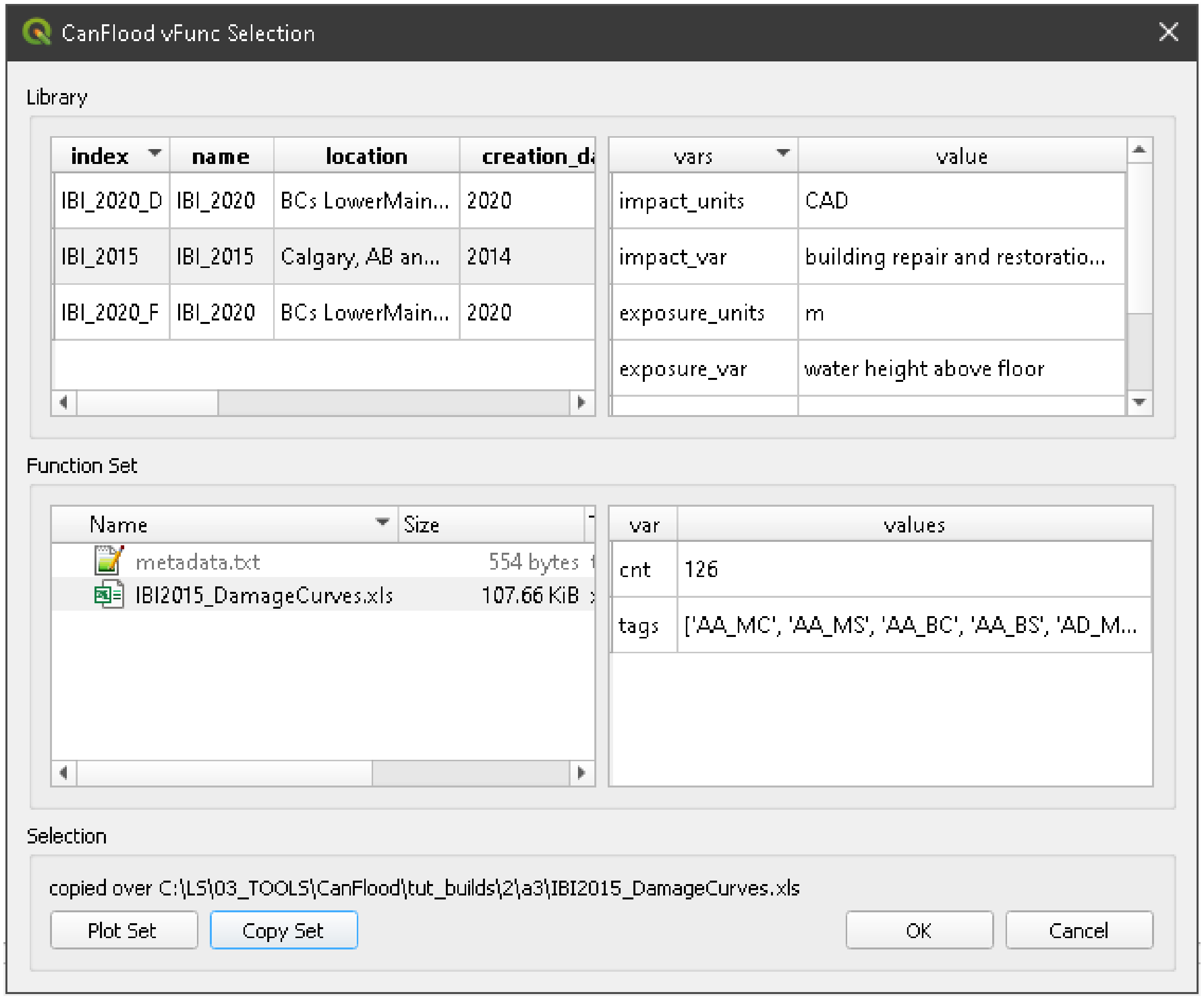
On the 'Setup' tab, configure the session as shown using your own paths, then **click 'Build'**:



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

Select Vulnerability Function Set

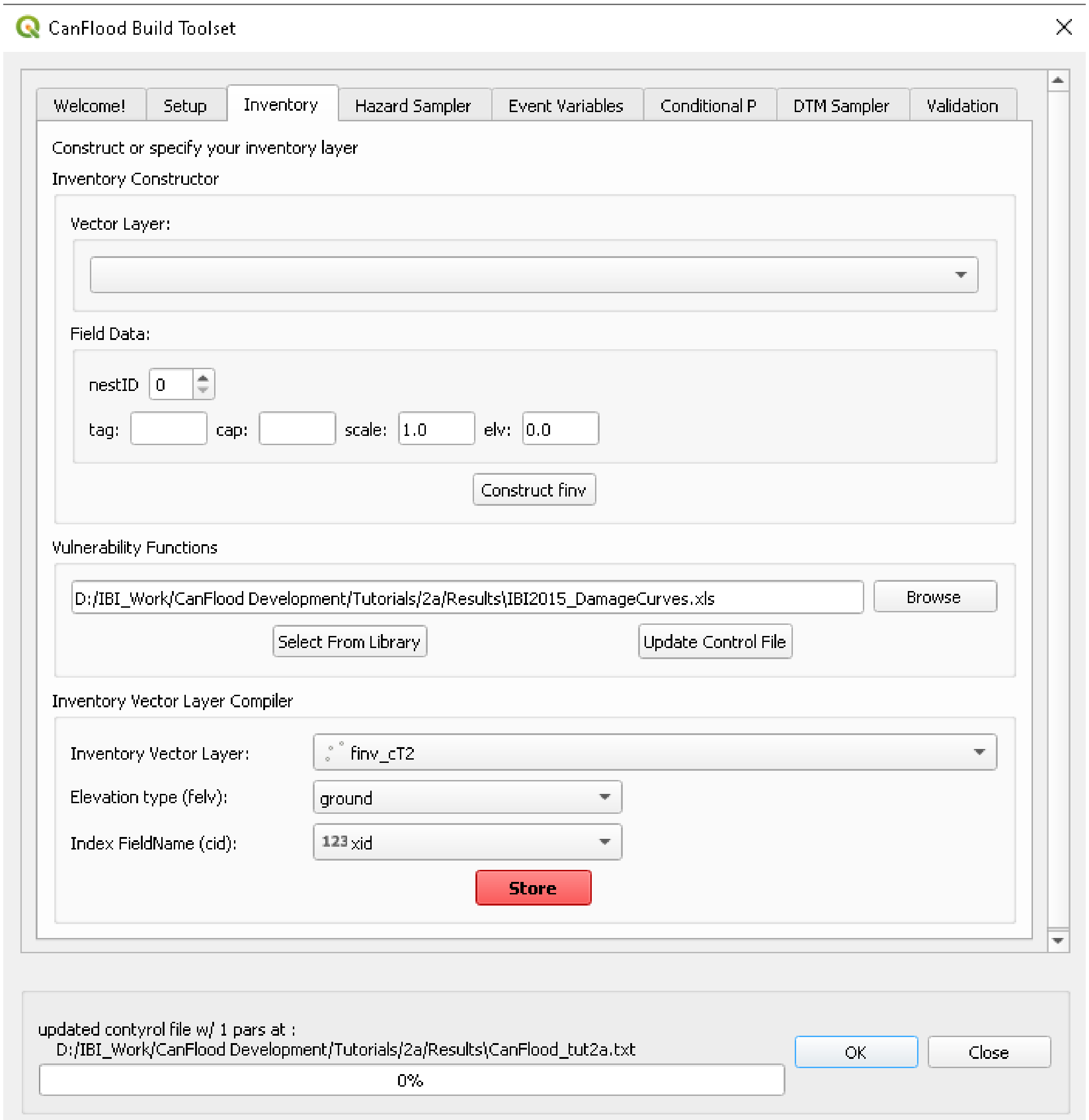
Move to the 'Inventory' tab and **click 'Select From Library'** to launch the library selection GUI shown below. Select the library 'IBI_2015' in the top left window and 'IBI2015_DamageCurves.slx' in the bottom left window, then **click 'Copy Set'** to copy this set of vulnerability functions into your working directory.



Close the 'vFunc Selection' GUI, and you should now see the new .xls file path entered under 'Vulnerability Functions'. Finally, **click 'Update Control File'** to store a reference to this into the control file.

Store Inventory

On the same 'Inventory' tab, select the inventory vector layer, the appropriate Index FieldName, and **set the elevation type to 'ground'** as shown, then **click 'Store'**.



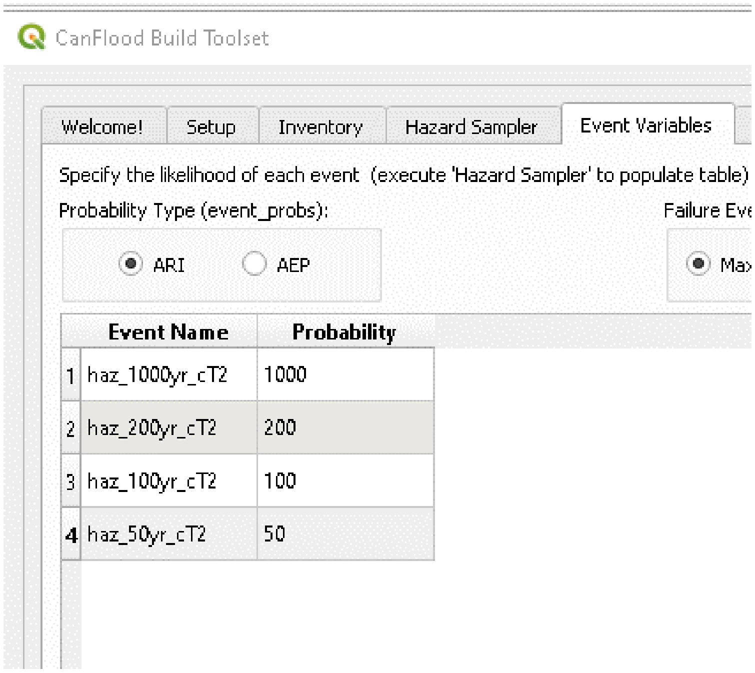
You should see the inventory csv now stored in the working directory.

Hazard Sampler

Move to the ‘Hazard Sampler’ tab, ensure the four hazard rasters are shown in the window and all other fields are default, 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 (ignore the ‘Failure Event Relation’ setting for now), then **click ‘Store’** to generate the ‘evals’ dataset.

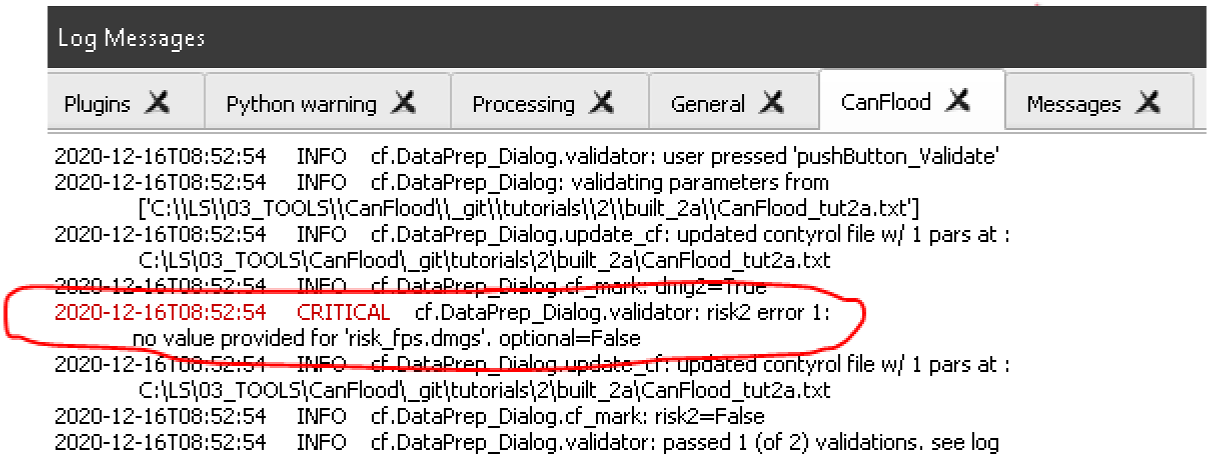


DTM Sampler

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

Validation

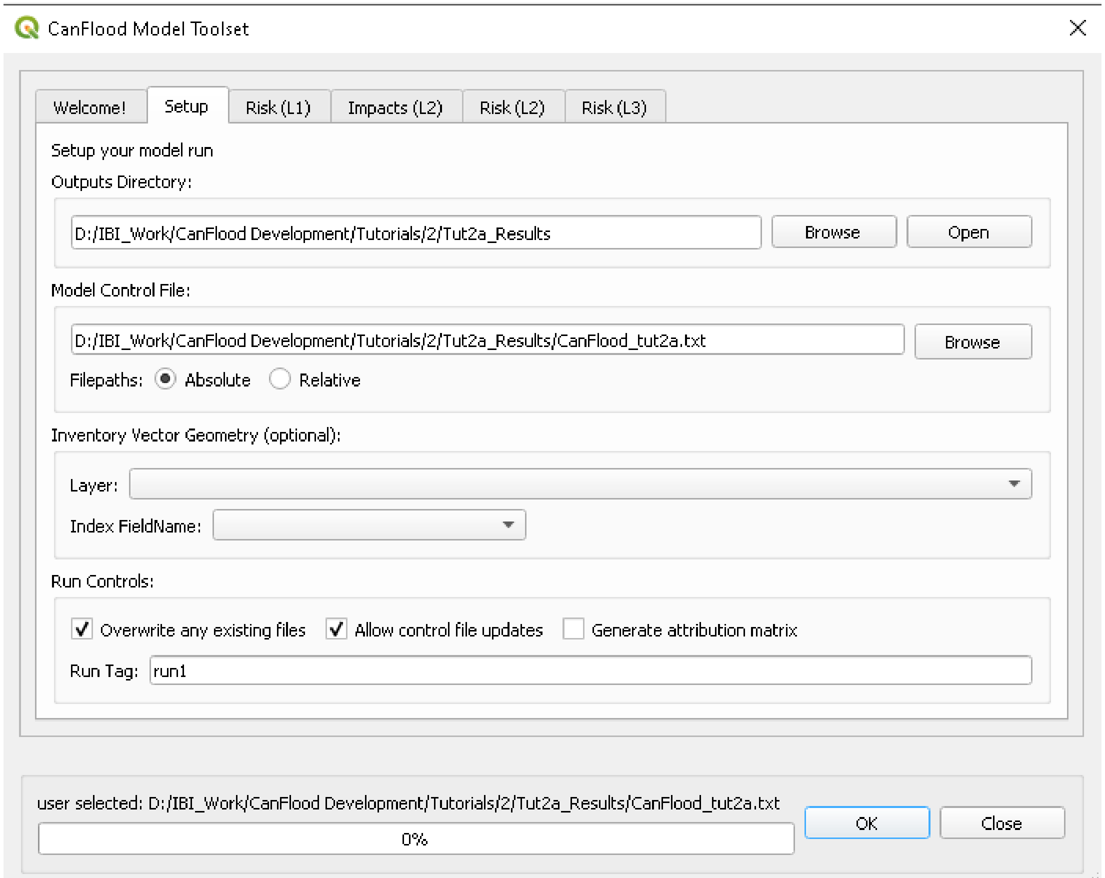
Move to the ‘Validation’ tab, **check the boxes for both L2 models**, then **click ‘Validate’**. You should get a log message ‘passed 1 (of 2) validations. see log’. To investigate the failed validation attempt, open the Log Messages panel, it should look like this:



This shows that the Risk (L2) model is missing the ‘dmgs’ data file and will not run. This is expected behavior as CanFlood separates the exposure calculation (Impacts L2) from the risk calculation. We will calculate this ‘dmgs’ data file in the next section then return to validate the Risk (L2) model. You’re now ready to run the Impacts and Risk (L2) models!

2.3.3. Run the Model

Open the 'Model' dialog. Configure the 'Setup' tab as shown below, ensuring the 'Outputs Directory' is a sub-directory of your previous 'Working Directory'[9]:



Impact (L2)

Move to the 'Impacts (L2)' tab. Ensure the 'Run Risk (L2)' box is **not** checked (we'll execute the risk model manually in the next step) but that 'Output expanded component impacts' **is** checked. **Click 'Run dmg2'**.

[9] Some 'Results' tools work better when the model output data files are in the same file tree as the Control File

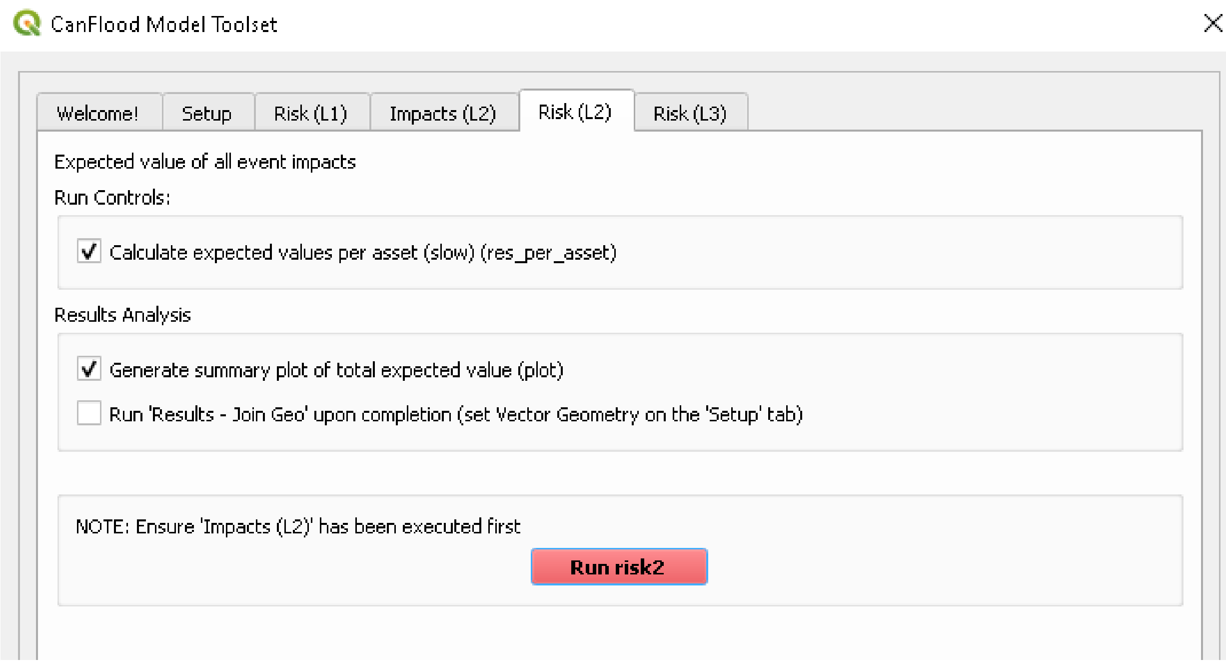
This should create a ‘dmgs’ datafile in your working directory and fill in the corresponding entry on the Control File. Navigate to this csv. It should look something like this:

xid	haz_1000yr_cT3	haz_100yr_cT2	haz_200yr_cT2	haz_50yr_cT3
14879	111300	56809.08916	57469.29217	20000
14880	153703.7015	64998.63284	66620.48356	20000
14925	110752.9984	55068.30843	55131.40927	20000
14926	91890.40424	47295.3492	48750.95904	20000
14927	141110.2813	66576.80321	66783.90949	20000
14928	149352.6144	68650.66705	71820.98313	20000
14933	119539.7125	58472.22211	58836.88032	20000
14934	131787.5569	62503.88204	111358.404	0
14935	115084.1064	54490.71147	89166.28707	0
14936	133000	62037.45463	65760.99719	0
14937	113581.1764	55057.93763	96346.32067	0

These are the raw impacts per event per asset calculated with each vulnerability function, the sampled wsl and the sampled DTM elevation. The second output is the ‘expanded component impacts’, a large optional output background file used by CanFlood that contains the tabulation of each nested function and the applied scaling and cap values. See Section 4.2.2 for more information. Now you’re ready to calculate flood risk!

Risk (L2)

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



Three results files should have been generated (discussed below). For a complete description of the Risk (L2) module, see Section 4.2.3.

2.3.4. View Results

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

- *eventypes_run1_tut2a.csv*: derived parameters for each raster;
- *risk2_run1_tut2a_r2_passet.csv*: expected value per asset expanded Risk (L2) results;
- *risk2_run1_tut2a_ttl.csv*: total expected value of all events and assets Risk (L2) results;
- *dmgs_tut2a_run1.csv*: per asset Impacts (L2) results;
- *dmgs_expnd_tut2a_run1.csv*: expanded component Impacts (L2) results;
- *run1 Impacts-ARI plot for 6 events.svg*: see below.

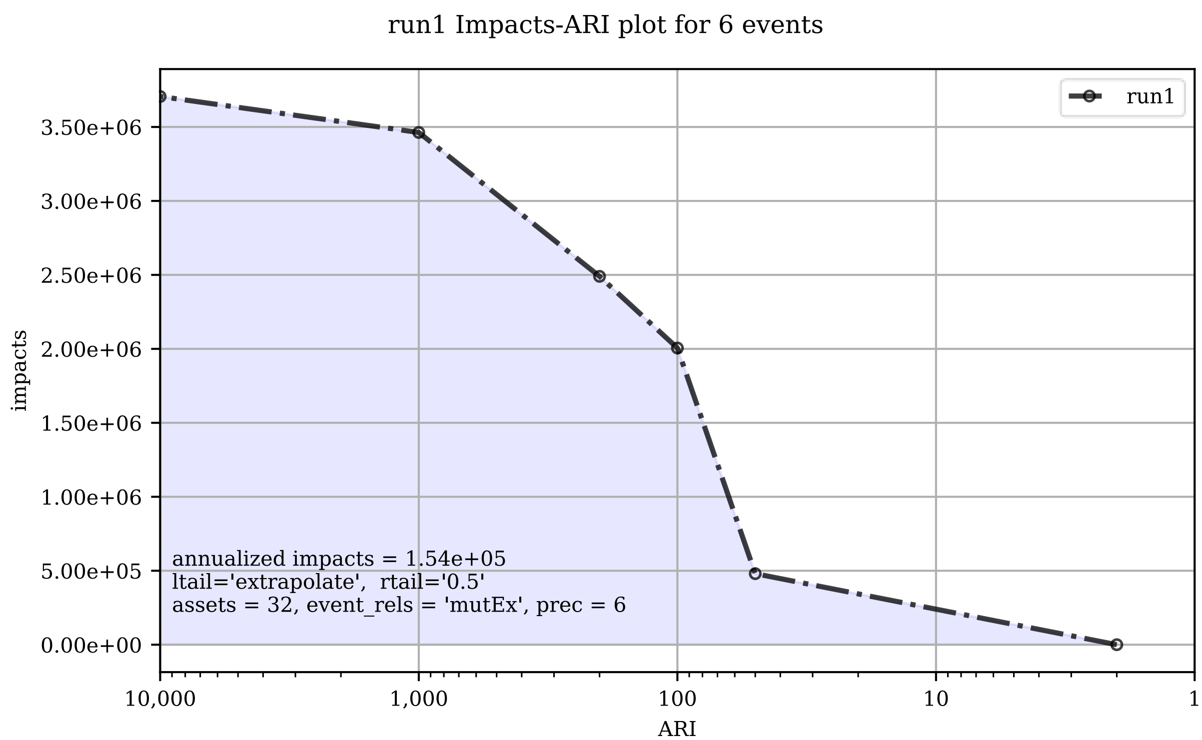
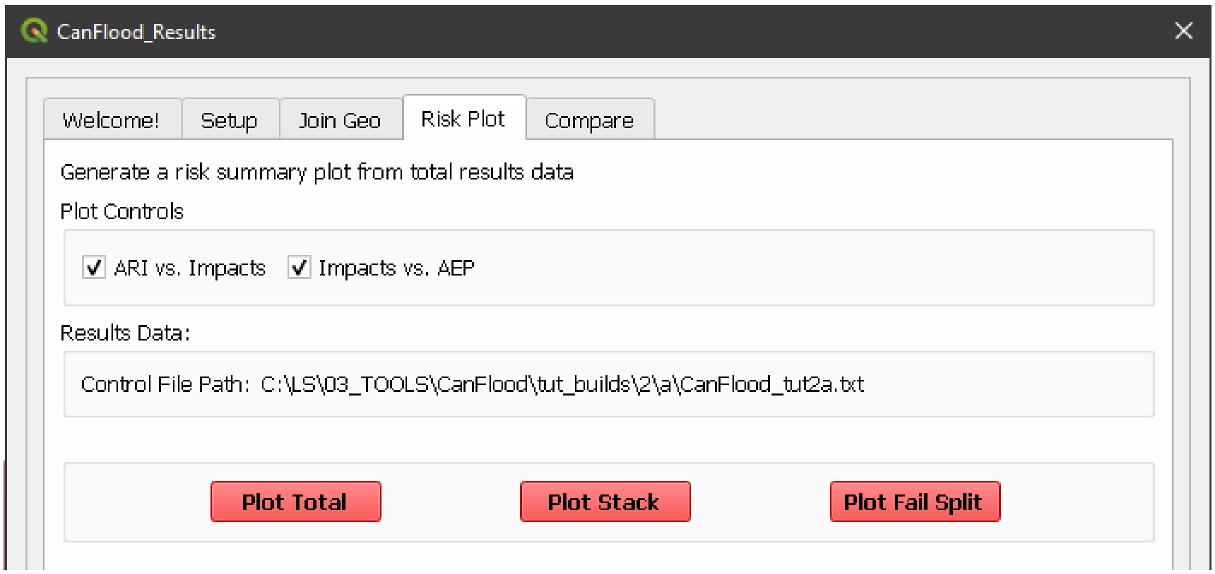


Figure 2-1: Summary risk curve plot of the total Risk (L2) results.

Risk Plots

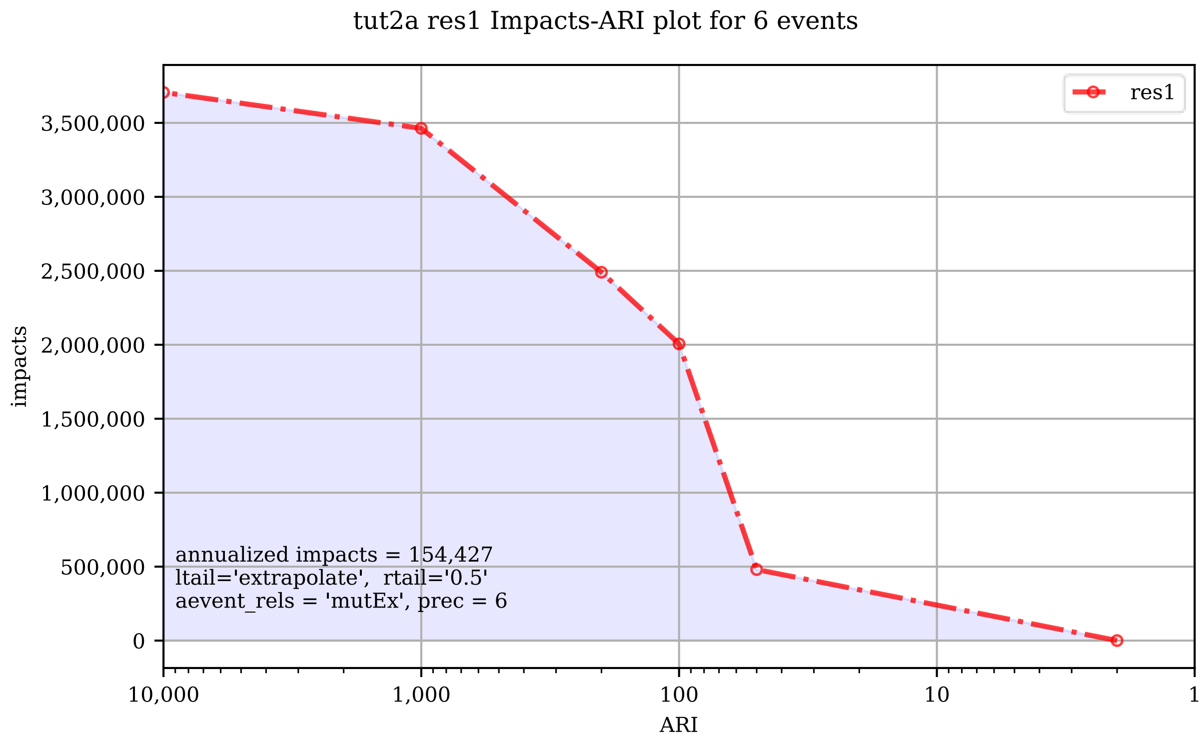
While the Risk models include some automatic risk curves (see above), CanFlood provides some additional plot customization under the ‘Risk Plot’ tool in the ‘Results’ toolset. **Open the ‘Results’**  **toolset**, configure the session by selecting a working directory and the Control File, then navigate to the ‘Risk Plot’ tab, and select both plot types as shown below.

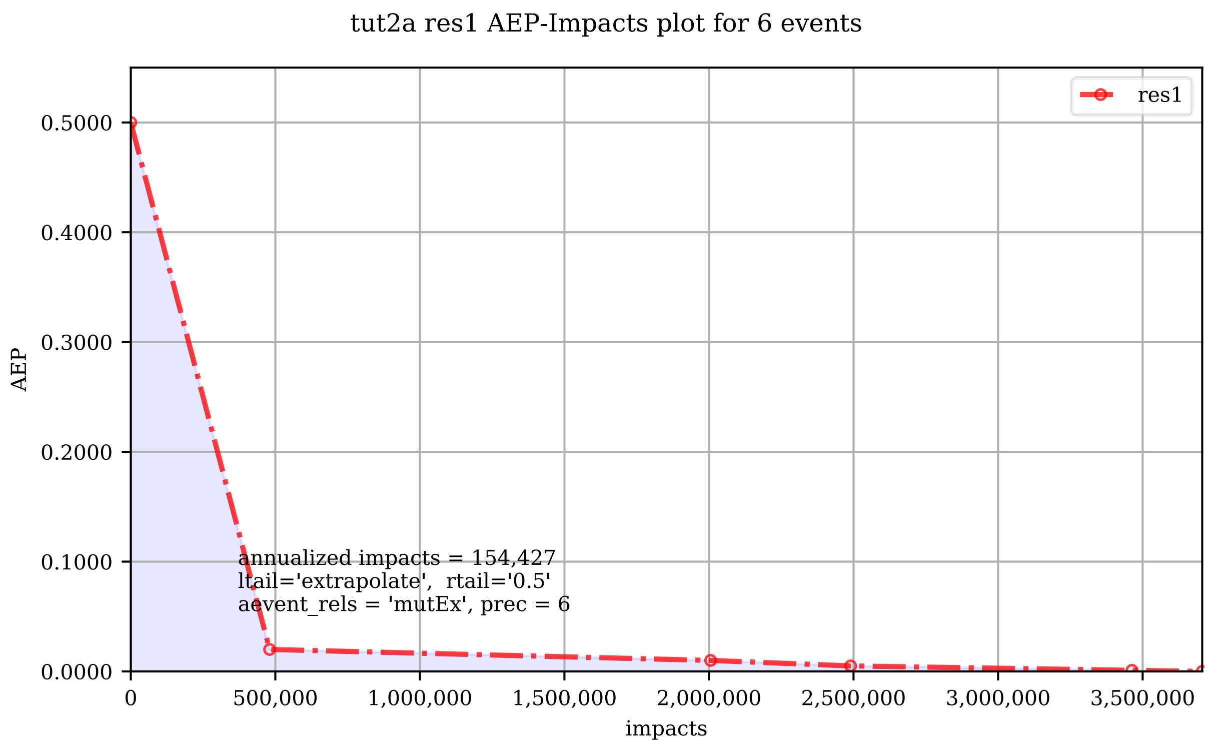


To customize the plot, open the Control File, and under ‘[plotting]’, change the following parameters:

- color = red
- impactfmt_str = ,.0f

These control the color of the plot and the formatting applied to the impact values. Finally, return to the CanFlood window and **hit ‘Plot Total’**. You should see the two plots below generated in your working directory. These plots are the two standard risk curve formats for the same total results data.


tut2a res1 Impacts-ARI plot for 6 events
res1
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
impacts
annualized impacts = 154,427
ltail='extrapolate', rtail='0.5'
aevent_rels = 'mutEx', prec = 6
10,000
1,000
100
10
1
ARI


tut2a res1 AEP-Impacts plot for 6 events
res1
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
AEP
annualized impacts = 154,427
ltail='extrapolate', rtail='0.5'
aevent_rels = 'mutEx', prec = 6
0
500,000
1,000,000
1,500,000
2,000,000
2,500,000
3,000,000
3,500,000
impacts

2.4. Tutorial 2b: Risk (L2) with Dike Failure

We recommend users first complete Tutorials 1 and 2a. Tutorial 2b uses the same input data as 2a but expands the analysis to demonstrate the risk analysis of a simple levee failure through incorporating a single companion failure event into the model. This companion failure event is composed of two layers:

- *haz_1000yr_fail_A_cT3.tif* : 'failure raster' indicating the wsl that would be realized were any of the levee segments to fail during the event; and
- *expoProbPoly_1000yr_A_T2d.gpkg*: conditional exposure probability polygon layer with features indicating the extent and probability of failure of each levee segment during the flood event ('failure polygons'). Notice this layer contains two features that overlap in places, corresponding potential flooding from two breach sites in the levee system. This layer will be used to tell CanFlood when and how to sample the failure raster.

This simplification by using these two layers facilitates the specification of multiple failure probabilities but where any failure (or combination of failures) would realize the same wsl (Section 4.1.5's 'complex conditionals'). Ensure these layers are loaded into the same QGIS project as was used for Tutorial 2a.

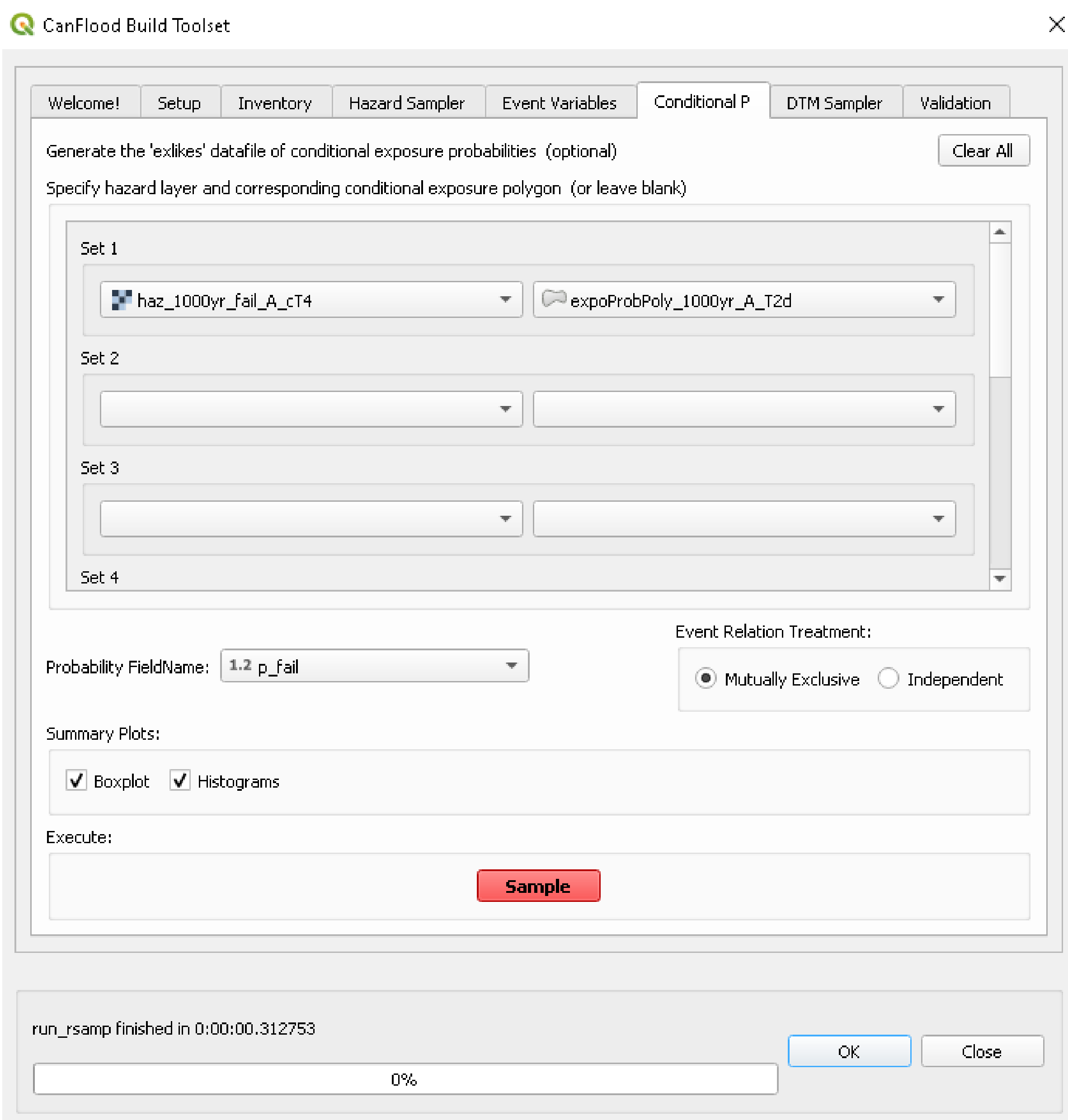
To better understand these new layers, stylize the 'failure polygons' with 30% transparency, a red fill, a single label for 'p_fail', and moving them just beneath the asset inventory ('finv') points layer.

2.4.1. Build the Model

Follow the steps in Tutorials 2a 'Build the Model' but with including the 'failure raster' ('haz_1000yr_fail_A_cT3', probability=1000ARI) in the 'Hazard Sampler' and 'Event Variables' steps. On the 'Event Variables' step, ensure 'Failure Event Relation Treatment' is set to 'Mutually Exclusive'.

Conditional Probabilities

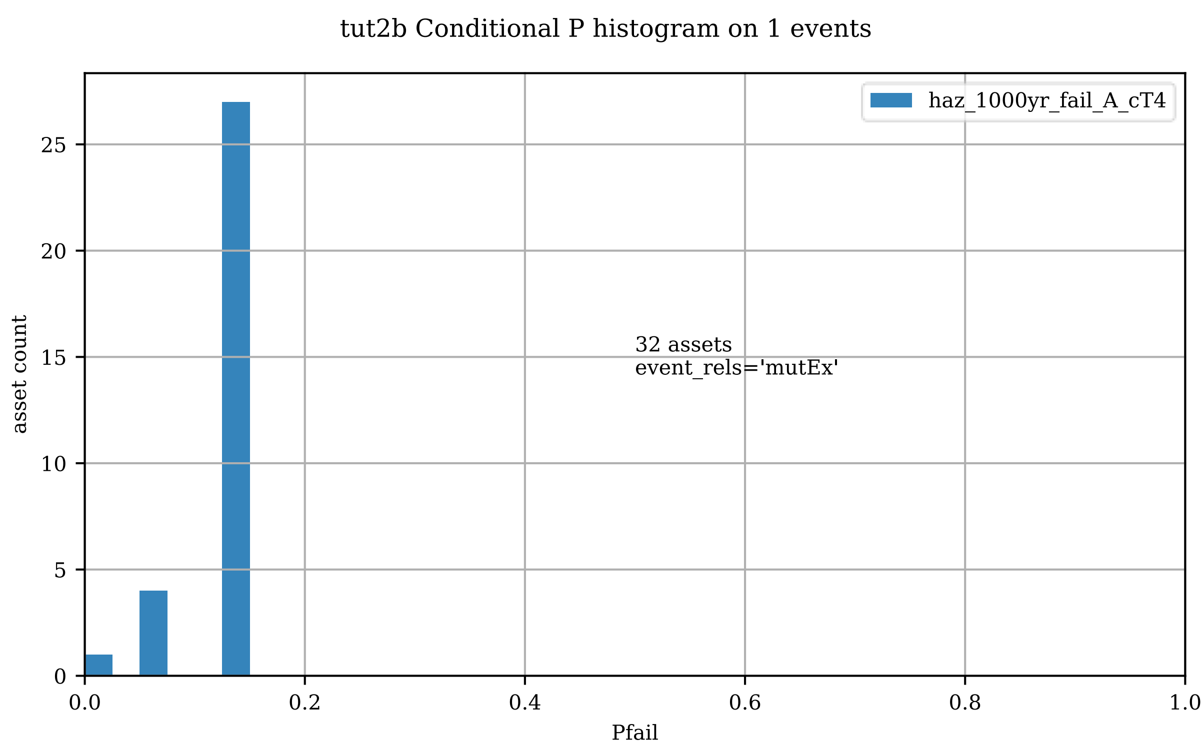
Navigate to the 'Conditional P' tab to resolve the overlapping failure polygons into the resolved exposure probabilities ('exlikes') dataset to tell CanFlood what probability should be assigned to each asset when realizing the companion failure raster. Start by pairing the failure polygons with the failure raster, select the 'Probability FieldName', 'Event Relation Treatment', and 'Summary Plots' as shown, then **click 'Sample'**:



A resolved exposure probabilities ('exlikes') data file should have been created in your working directory with entries like this:

xid	haz_1000yr_fail_A_cT4
14879	0.05
14880	0.15
14925	0.15
14926	0.15
14927	0.15
14928	0.05
14933	0.15
14934	0.15
14935	0.15

Two non-spatial summary plots of this data should also have been generated in your working directory, the most useful for this particular model being the histogram:



These values are the conditional probabilities of each asset realizing the 1000-year companion failure event wsl.[10] See Section 4.2.3 for a complete description of this tool. Complete the model construction by running the 'DTM Sampler' and 'Validation' tools.

2.4.2. Run the Model

Open the 'Model' dialog and setup your session similar to Tutorial 2a but ensure 'Generate attribution matrix' is checked under 'Run Controls' (we'll use this to make plots showing the different components that contribute to the risk totals).

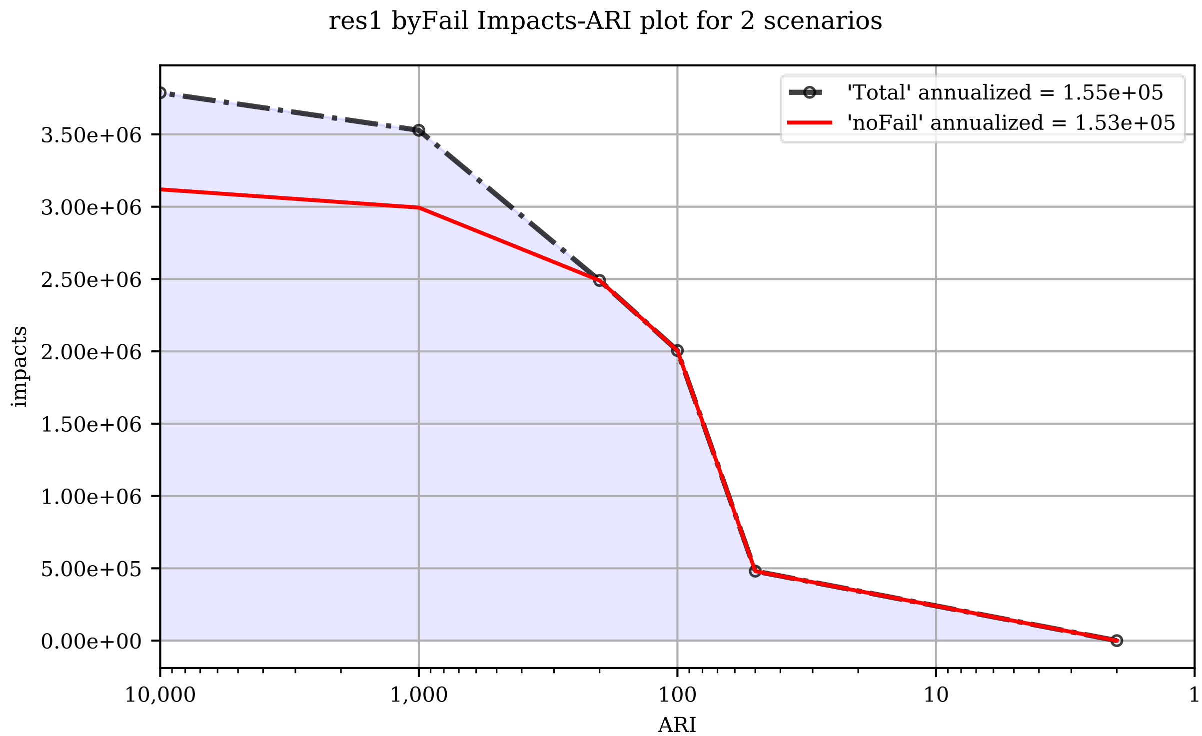
Impacts and Risk

Navigate to the 'Impacts (L2)' tab, check the 'Run Risk (L2) upon completion' box to execute the exposure and risk models in sequence from your Control File. Navigate to the 'Risk (L2)' tab and ensure 'Calculate expected values per asset' is checked. Now move back to the 'Impacts (L2)' tab and **click 'Run dmg2'**. You should see the same types of outputs as Tutorial 2a, but with two additional 'attribution matrix' datasets.

2.4.3. View Results

To better understand the influence of incorporating levee failure, this section will demonstrate how to generate a plot showing the total risk and the portion of that total risk that comes from assuming no failure. Open the 'Results' toolset and configure your session by selecting a working directory and the same Control File used above. Now navigate to the 'Risk Plot' tab, ensure both plot controls are checked, then **click 'Plot Fail Split'**. This should generate two risk plot formulations, including the figure below:

[10] Try running the tool again, but this time selecting 'Max'. If you look closely at the boxplots, you should see a slight difference in the resolved probabilities. This suggests this model is not very sensitive to the relational assumption of these overlapping failure polygons.



In this plot, the red line represents the contribution to risk without the companion failure events, which should be nearly identical to the results from Tutorial 2a, and a second line showing the total results.[11] The space between these two lines illustrates the contribution to risk from incorporating levee failure into the model.

2.5. Tutorial 2c: Risk (L2) with Complex Failure

We recommend users first complete Tutorial 2b. Tutorial 2c uses the same input data as 2b but expands the analysis to demonstrate the incorporation of more complex levee failure with two companion failure events into the model.

In the same QGIS project as was used for Tutorial 2a, ensure the following are also added to the project:

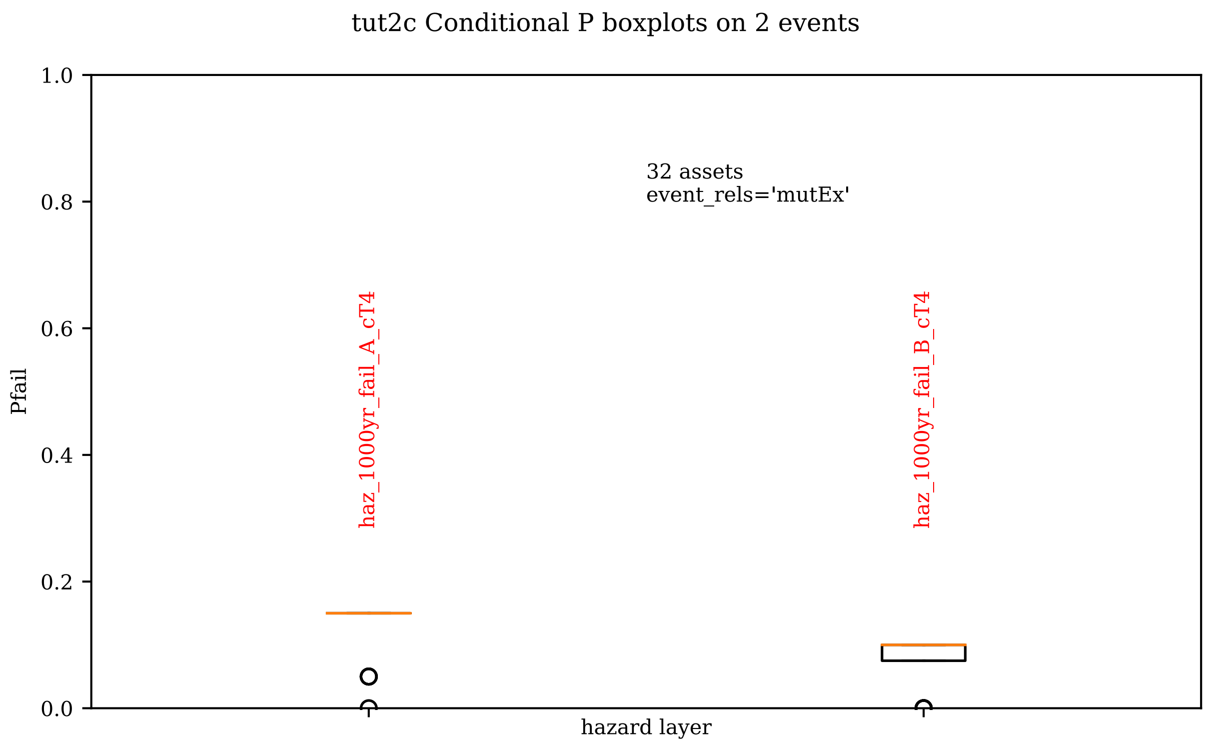
- *expoProbPoly_1000yr_B_T2a.gpkg*: failure polygon 'B';
- *haz_1000yr_fail_B_cT3.tif* : failure raster 'B'.

[11] Alternatively, the 'Compare' tool can be used to generate a comparison plot between the two tutorials.

These layers represent an additional companion failure event ‘B’ for the 1000-year event where the failure wsl and probabilities are different but complimentary from those of Tutorial 2b’s companion failure event ‘A’.

2.5.1. Build the Model

Follow the steps in Tutorials 2b ‘Build the Model’ but with including the additional companion failure event ‘B’ in the ‘Hazard Sampler’, ‘Event Variables’ and ‘Conditional P’ steps. For the latter two, ensure both event relation treatments are set to ‘Mutually Exclusive’. Looking at the ‘Conditional P’ boxplot shows the difference in failure probabilities specified by the two companion failure events:



Complete the model construction by running the ‘DTM Sampler’ and ‘Validation’ tools.

2.5.2. Run the Model

Open the ‘Model’ dialog and follow the steps in Tutorial 2b to setup this model run.

Impacts and Risk

Execute the ‘Impacts (L2)’ and ‘Risk (L2)’ models similar to Tutorial 2b but ensure ‘Generate attribution matrix’ is de-selected.

To explore the influence of the 'event_rels' parameter, open the control file, change the 'event_rels' parameter to 'max', change the 'name' parameter to something unique (e.g., 'tutc_max'), then save the file with a different name. On the 'Setup' tab, point to this modified control file, a new outputs directory, and run both models again as described above[12].

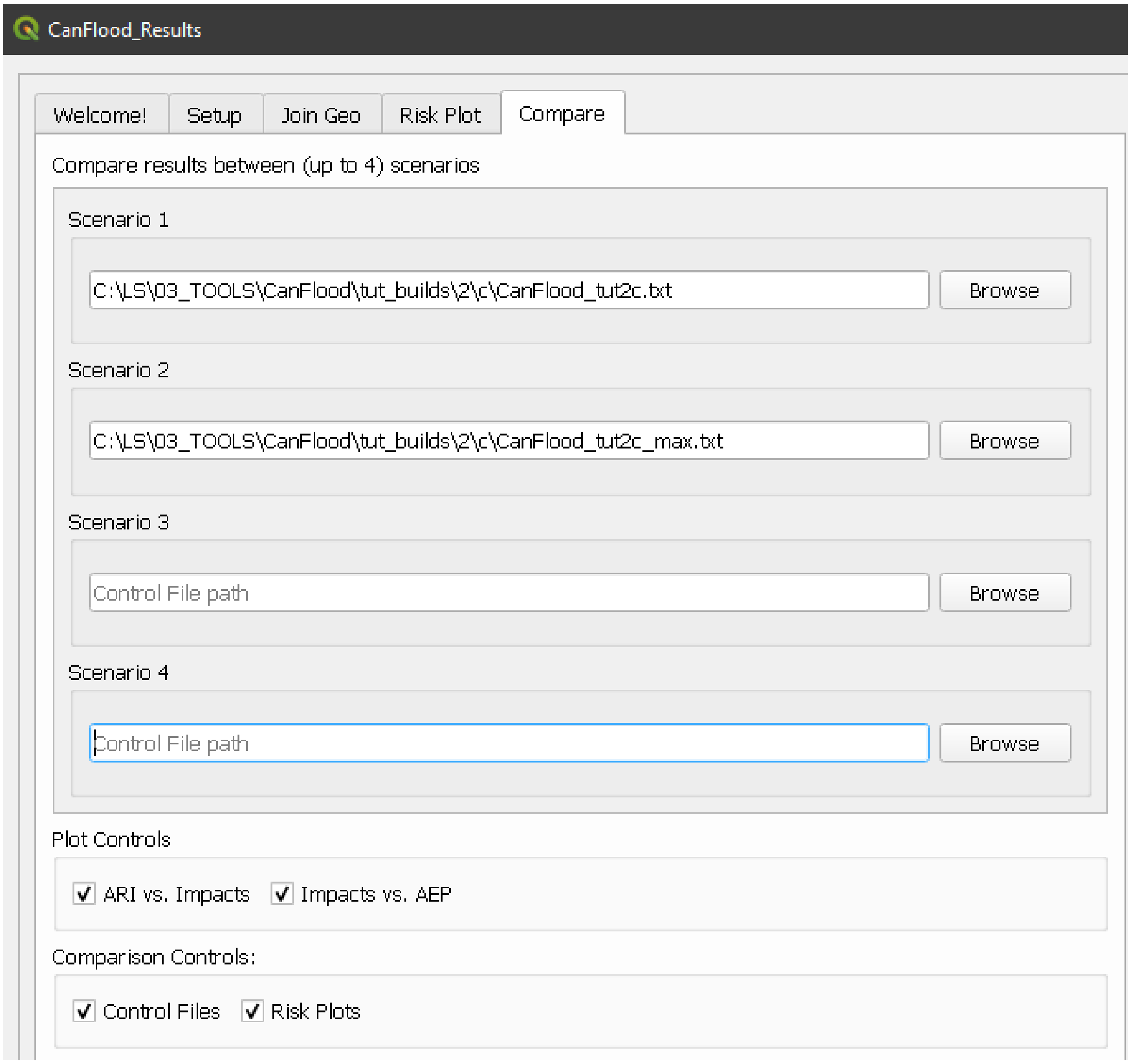
2.5.3. View Results

After executing the 'Risk (L2)' model for the 'event_rels=mutEx' and 'event_rels=max' control files, two similar collections of output files should have been generated in the two separate output directories specified during model setup. To visualize the difference between these two model configurations, **open the 'Results' toolset** and select a working directory and the original 'event_rels=mutEx' control file as the 'main control file' on the 'Setup' tab[13]. Before generating the comparison files, configure the plot style by opening the same main control file, and changing the following '[plotting]' parameters:

- 'color = red'
- 'linestyle = solid'
- 'impactfmt_str = ,.0f'

[12] Advanced users could avoid re-running the 'Impacts (L2)' model by manipulating the Control File to point to the 'dmgs' results from the previous run as these will not change between the two formulations.
[13] The control file specified on the 'Setup' tab will be used for common plot styles (e.g.,

To generate a comparison plot of these two scenarios, navigate to the 'Compare' tab, select the 'Control File' for both model configurations generated in the previous step, ensure 'Control Files' and 'Risk Plots' are checked under 'Comparison Controls', as shown below:



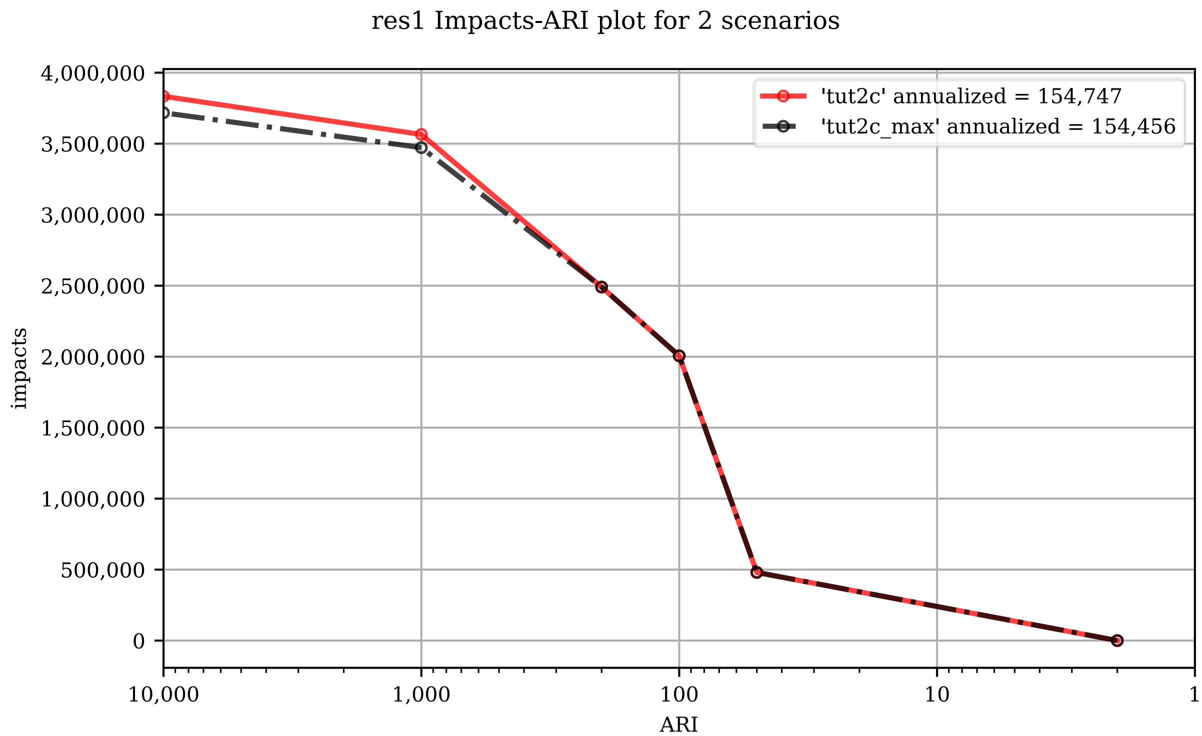
Click 'Compare' to perform the comparison. You should see two files generated in your working directory:

- Comparison plot showing both risk curves on the same axis; and
- Control file comparison spreadsheet.

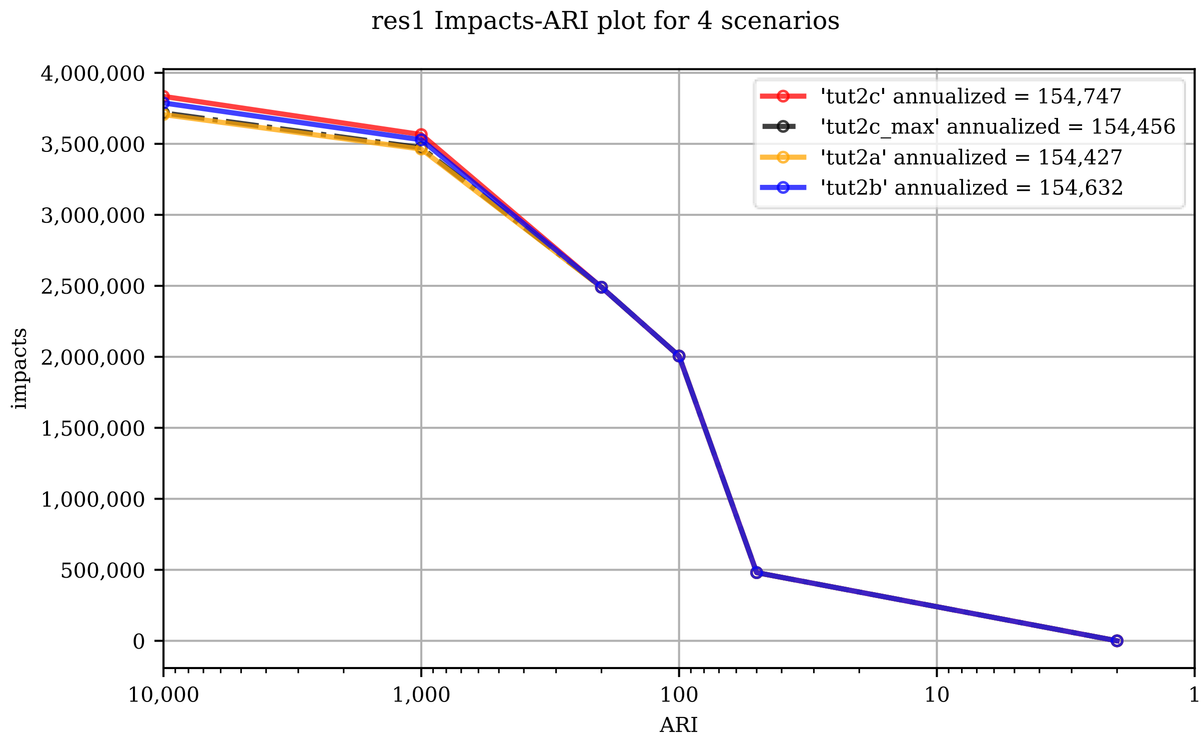
The control file comparison spreadsheet is shown below and is an easy way to quickly identify distinctions between model scenarios.

	tut2c	tut2c_max	compare
parameters.name	tut2c	tut2c_max	FALSE
parameters.cid	xid	xid	TRUE
parameters.prec	6	6	TRUE
parameters.ground_water	TRUE	TRUE	TRUE
parameters.felv	ground	ground	TRUE
parameters.event_probs	ari	ari	TRUE
parameters.ltail	extrapolate	extrapolate	TRUE
parameters.rtail	0.5	0.5	TRUE
parameters.drop_tails	FALSE	FALSE	TRUE
parameters.integrate	trapz	trapz	TRUE
parameters.as_inun	FALSE	FALSE	TRUE
parameters.event_rels	mutEx	max	FALSE
dmg_fps.curves	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	TRUE
dmg_fps.finv	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	TRUE
dmg_fps.expos	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	TRUE
dmg_fps.gels	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	TRUE
risk_fps.dmgs	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	FALSE
risk_fps.exlikes	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	TRUE
risk_fps.evals	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	TRUE
validation.risk1	FALSE	FALSE	TRUE
validation.dmg2	TRUE	TRUE	TRUE
validation.risk2	TRUE	TRUE	TRUE
validation.risk3	FALSE	FALSE	TRUE
results_fps.attrimat02	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	FALSE
results_fps.attrimat03	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	FALSE
results_fps.r2_passet	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	FALSE
results_fps.r2_ttl	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	FALSE
results_fps.eventypes	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	FALSE
plotting.color	red	black	FALSE
plotting.linestyle	solid	dashdot	FALSE
plotting.linewidth	2	2	TRUE
plotting.alpha	0.75	0.75	TRUE
plotting.marker	o	o	TRUE
plotting.markersize	4	4	TRUE
plotting.fillstyle	none	none	TRUE
plotting.impactfmt_str	,.0f	.2e	FALSE
cf_fp	C:\LS\03_TOOLS\C	C:\LS\03_TOOLS\CanFlc	FALSE

On the comparison plot (shown below), notice the difference in the risk curves and annualized values is negligible, indicating the treatment of event relations is not very significant for this model.



Re-running the comparison tool on all four Tutorial 2 Control Files yields the following:



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.

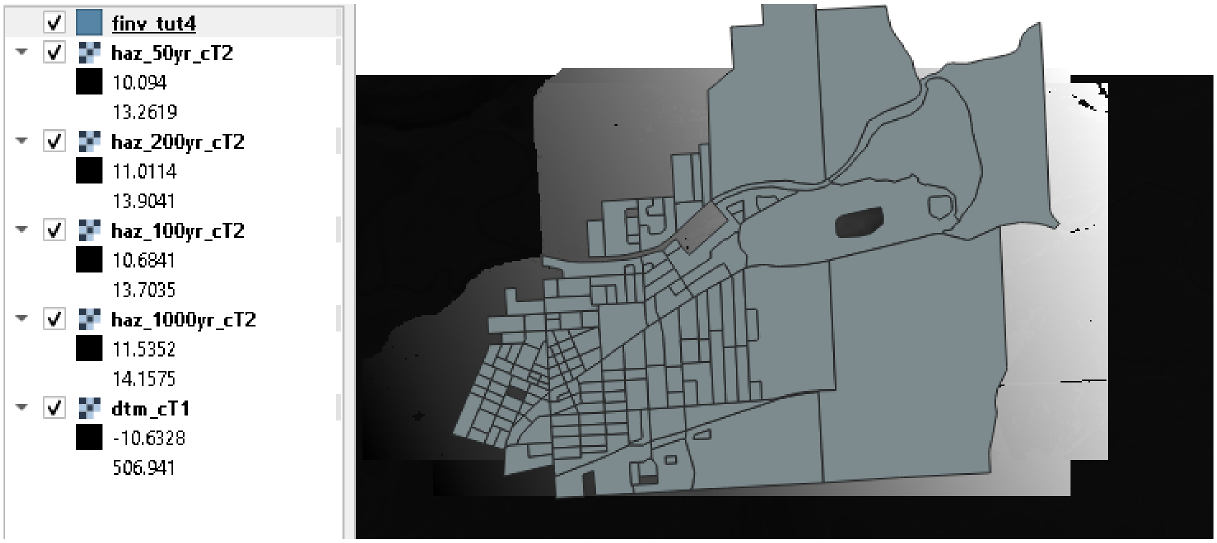
2.7. Tutorial 4a: Risk (L1) with Percent Inundation (Polygons)

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

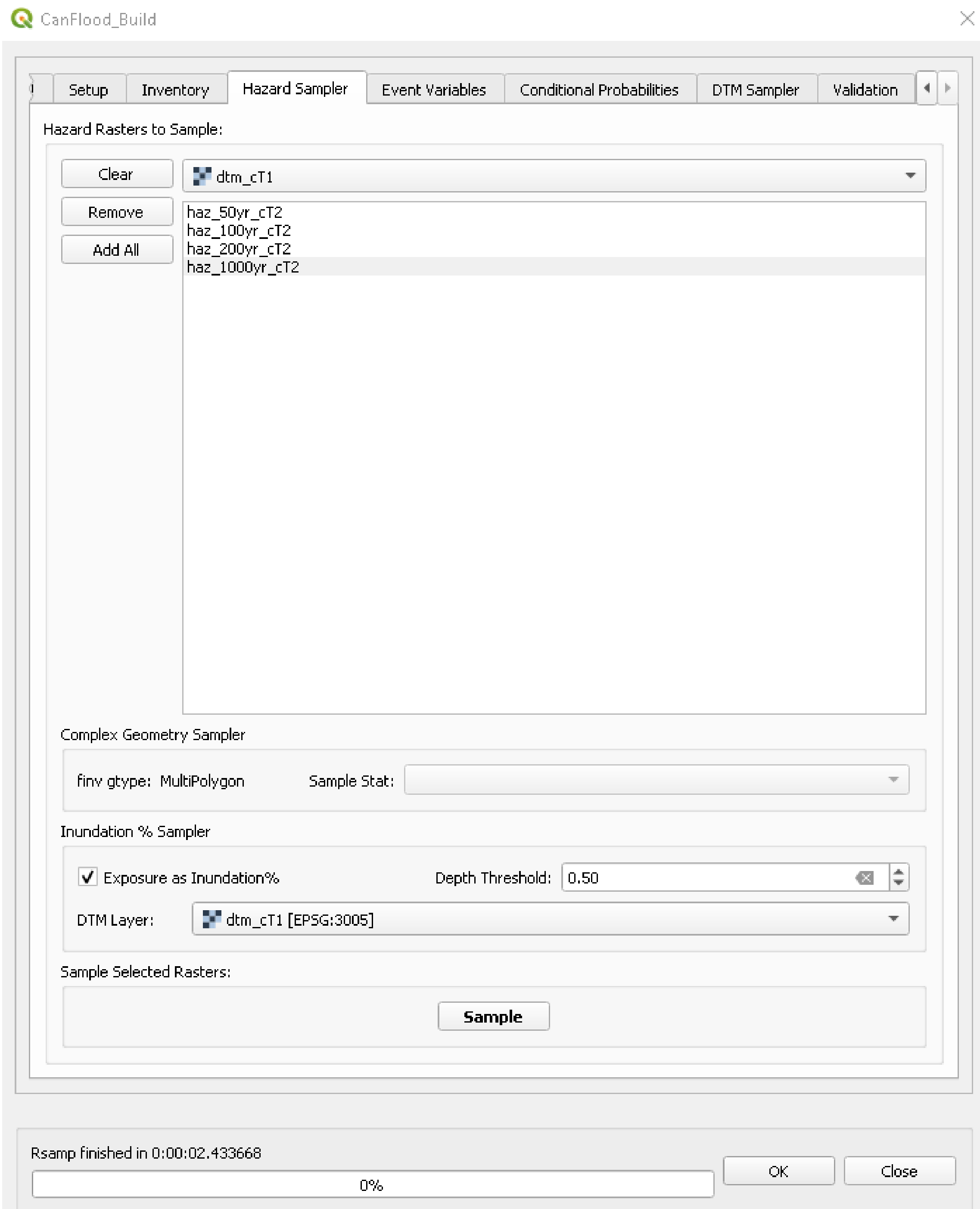
Setup

Setup your scenario for both the 'Setup' tab and 'Inventory' tab as instructed in Tutorial 1a. Ensure 'Elevation type' is set to 'datum'[14] before selecting 'Build Scenario'.

[14] 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).

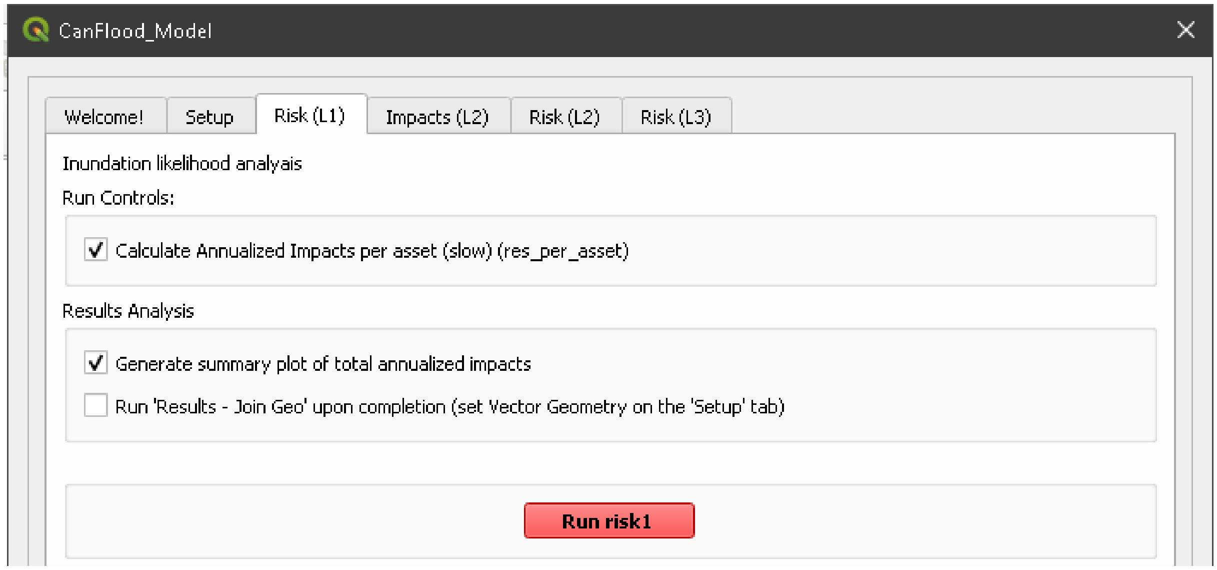
Event Variables and Validation

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 asset inventory (‘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 and GAR15 data

This tutorial demonstrates how to construct a CanFlood 'Risk (L1)' model from two web-sources:

- The National Pollutant Release Inventory (NPRI); and
- The GAR15 Atlas global flood hazard assessment[15]

For more information on these data sets, see Appendix A.

Because this tutorial deals with data having disparate CRSs, users should be familiar with QGIS's native handling of project and layer CRS discussed here.

2.9.1. Load Data to Project

Begin by setting your Qgis project's CRS to 'EPSG:3978' (Project > Properties > CRS > select 'EPSG:3978')[16]. Now you are ready to download, then add, the data layer for Tutorial 5 from CanFlood's tutorial page (CanFlood\tutorials\5\data\):

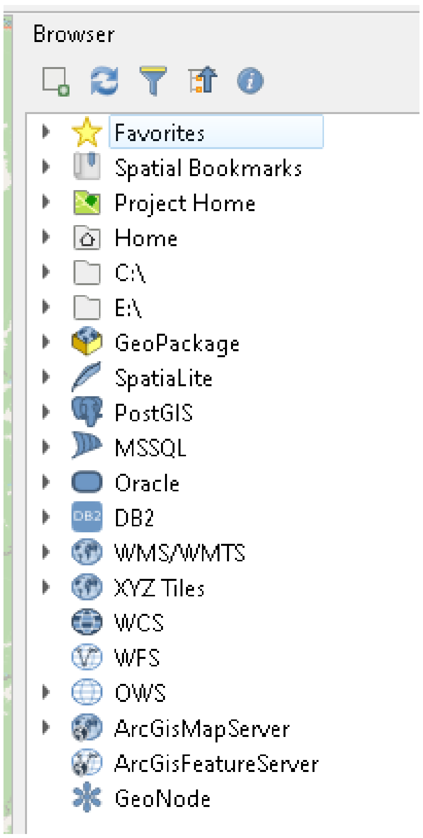
- *tut5_aoi_3978.gpkg*: AOI polygon for tutorial.

Be sure to the set the AOI layer style to something that allows you to see through the polygon. Before inventory construction can begin, we must add the NPRI and GAR15 raw data to the QGIS project. While many options are possible for accessing and importing such data, this tutorial will demonstrate how to use CanFlood's built-in 'Add Connections' feature (Section 4.4.1) to first add a connection to the profile, then download the desired layers.

[15] See Rudari and Silvestro (2015) for details on the GAR15 flood hazard model
[16] Depending on your profile settings, the project's CRS may be automatically set by the first loaded layer.

Connect to Web-Data

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



This shows all the connections in 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. Your Log Messages should look like this:

```
2020-12-15T17:48:59    INFO    pushed webConnect
2020-12-15T17:48:59    INFO    cf.WebConnect: found config file: C:/Users/cefect/AppData/Roaming/QGIS/QGIS3\profiles\dev/QGIS\QGIS3.ini
2020-12-15T17:48:59    INFO    cf.WebConnect.retrieve_fromFile: reading connection info fron
         C:\LS\03_TOOLS\CanFlood\_git\canflood\_pars\WebConnections.ini
2020-12-15T17:48:59    INFO    cf.WebConnect.retrieve_fromFile: retrieved 2 connection parameters from file
         ['GAR15', 'NPRI']
2020-12-15T17:48:59    INFO    cf.WebConnect.addAll: added 2 connections:
         ['GAR15', 'NPRI']
2020-12-15T17:48:59    INFO    cf.WebConnect: added 2 connections
```

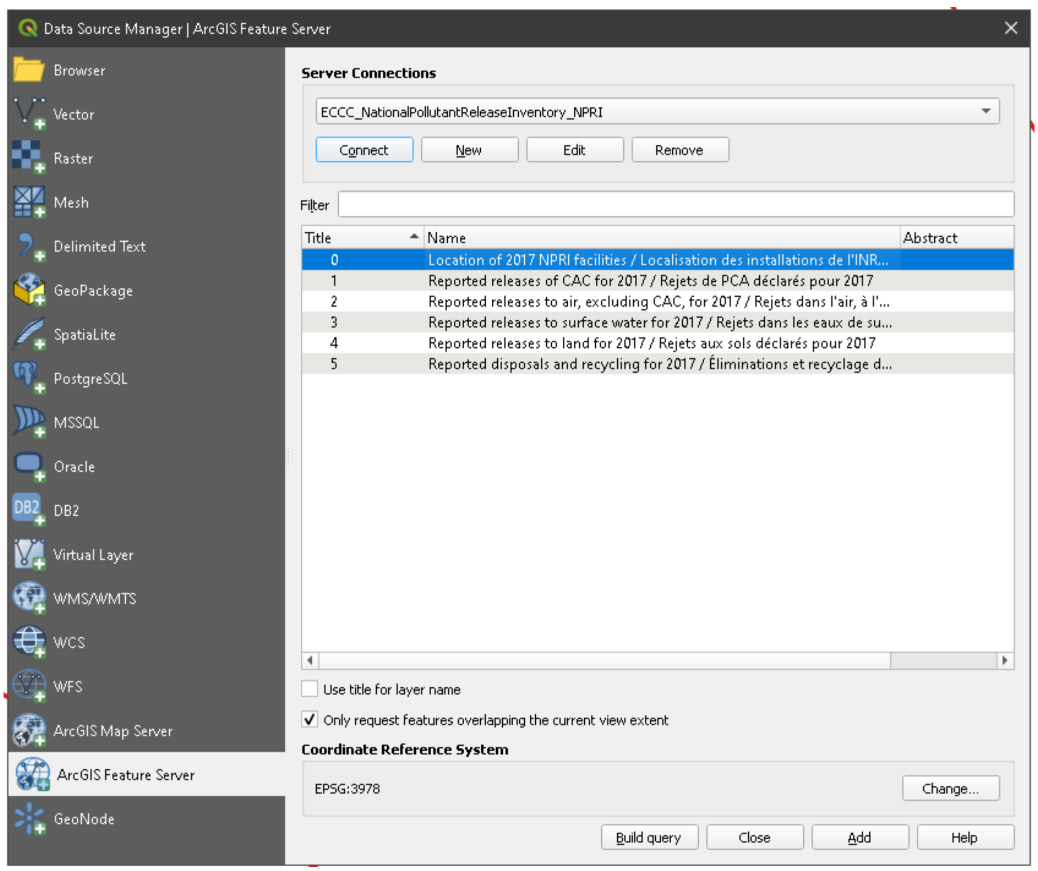
This describes each of the connections that CanFlood added to your profile. To verify this, navigate back to the 'Browser Panel'. You should see the following connections (under each connection type):

- UNISDR_GAR15_GlobalRiskAssessment (WCS)
- ECCC_NationalPollutantReleaseInventory_NPRI (ArcGisFeatureServer)

Note that these connections will remain in the user's profile for future QGIS sessions, meaning the 'Add Connections' tool should only be required once per install[17].

Download NPRI Data

Now that the connections have been added to your profile, you are ready to download the layer. To limit the data request, ensure your map canvas roughly matches the extents of the AOI. Now navigate to Qgis' 'Data Source Manager' (Ctrl + L) and select 'ArcGIS Feature Server'. Select 'ECCC_NationalPollutantReleaseInventory_NPRI' from the dropdown 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 as shown in the following:



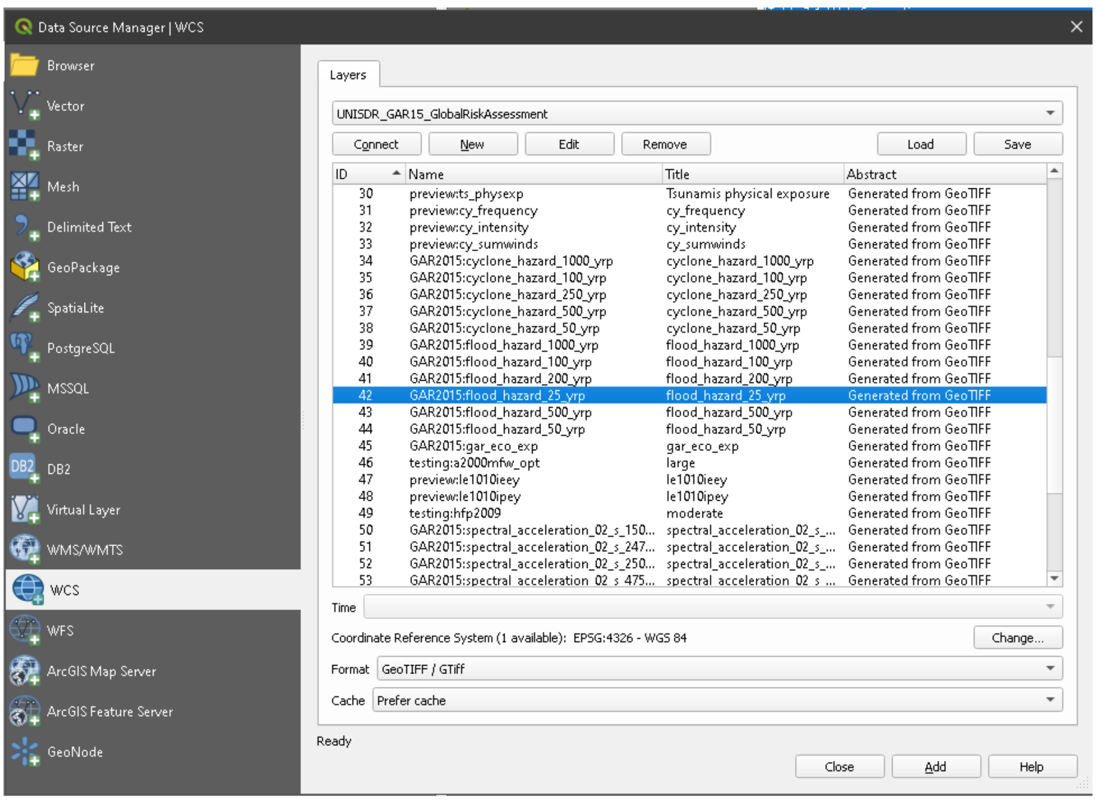
[17] New installations of Qgis should automatically path to the same profile directory (Settings > User Profiles > Open Active Profile Folder), therefore carrying forward your previous connection info.

You should now see a vector points layer added to your project with information on each facility reported to the NPRI (within your canvas view). Take note this layer's CRS is EPSG:3978 (right click the layer in the 'Layers' panel > Properties > Information > CRS), this should match your QGIS project and the AOI.

Download GAR15 Data

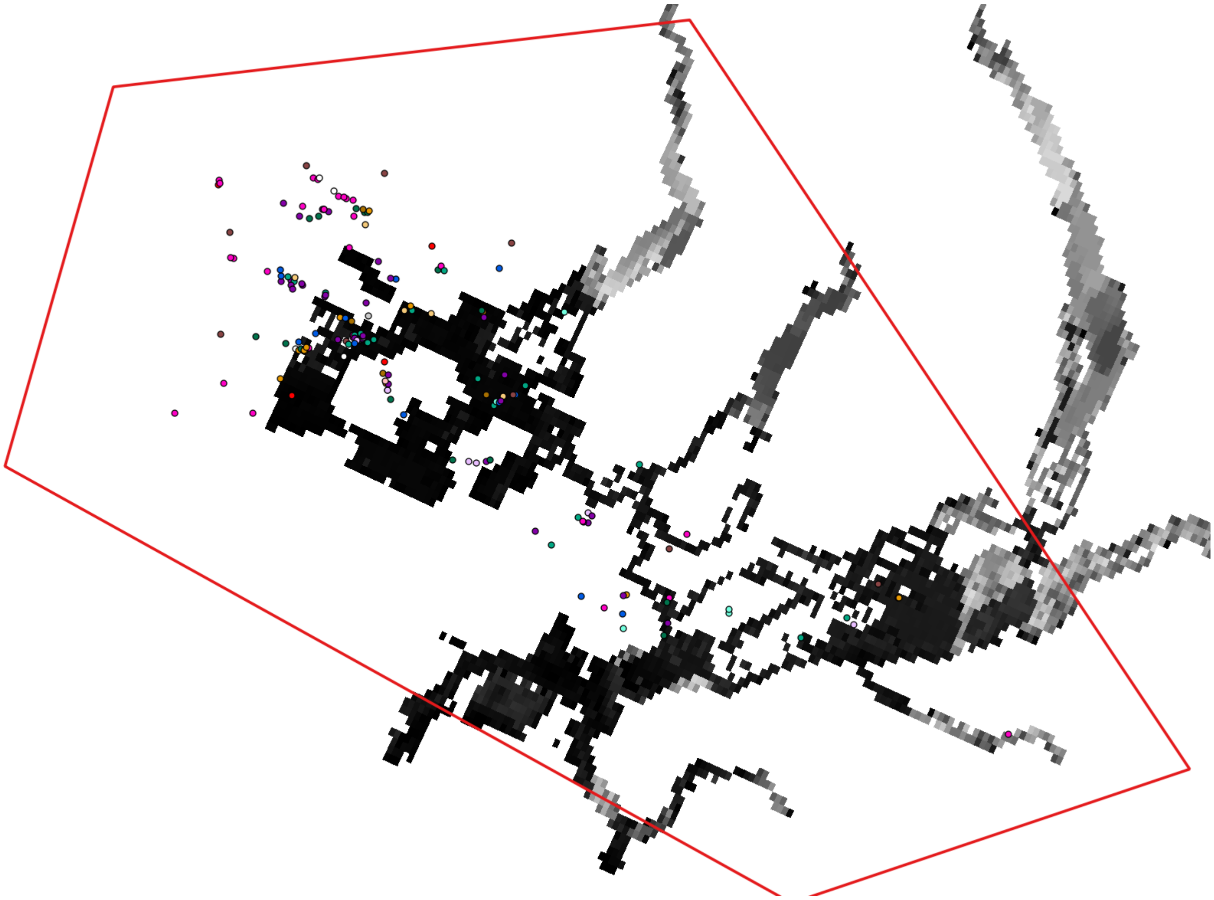
Follow a similar process to download[18] the following layers from 'UNISDR_GAR15_GlobalRiskAssessment' under the 'WCS' tab as shown below:

- GAR2015:flood_hazard_200_yrp
- GAR2015:flood_hazard_100_yrp
- GAR2015:flood_hazard_25_yrp
- GAR2015:flood_hazard_500_yrp
- GAR2015:flood_hazard_1000_yrp



[18] Depending on your internet connection, this process can be slow. It's recommended to set 'Cache'='Prefer cache' to limit additional data transfers, and to turn the layers off or disable rendering once loaded into the project.

You'll have to load one layer at a time, and you may be prompted to 'Select Transformation'[19]. Your canvas should now look like this:



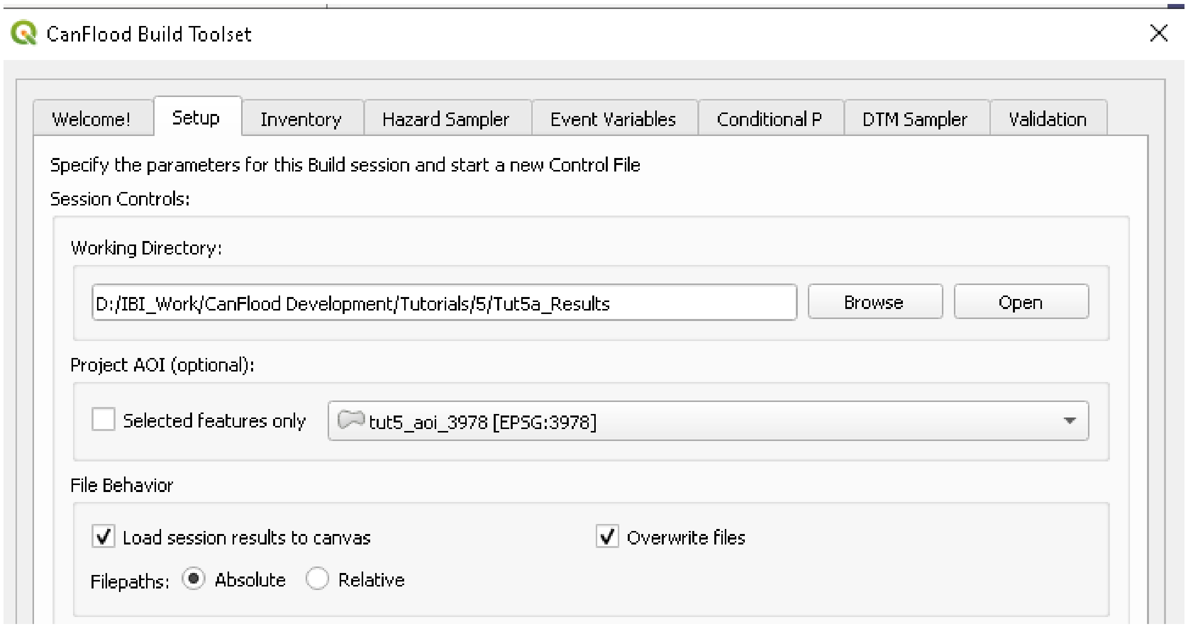
2.9.2. Build the Model

This section describes how to complete the construction of a Risk (L1) model from the downloaded NPRI and GAR15 data. For instructions on the remainder of the Risk (L1) modelling process, see Section 2.2.

Setup

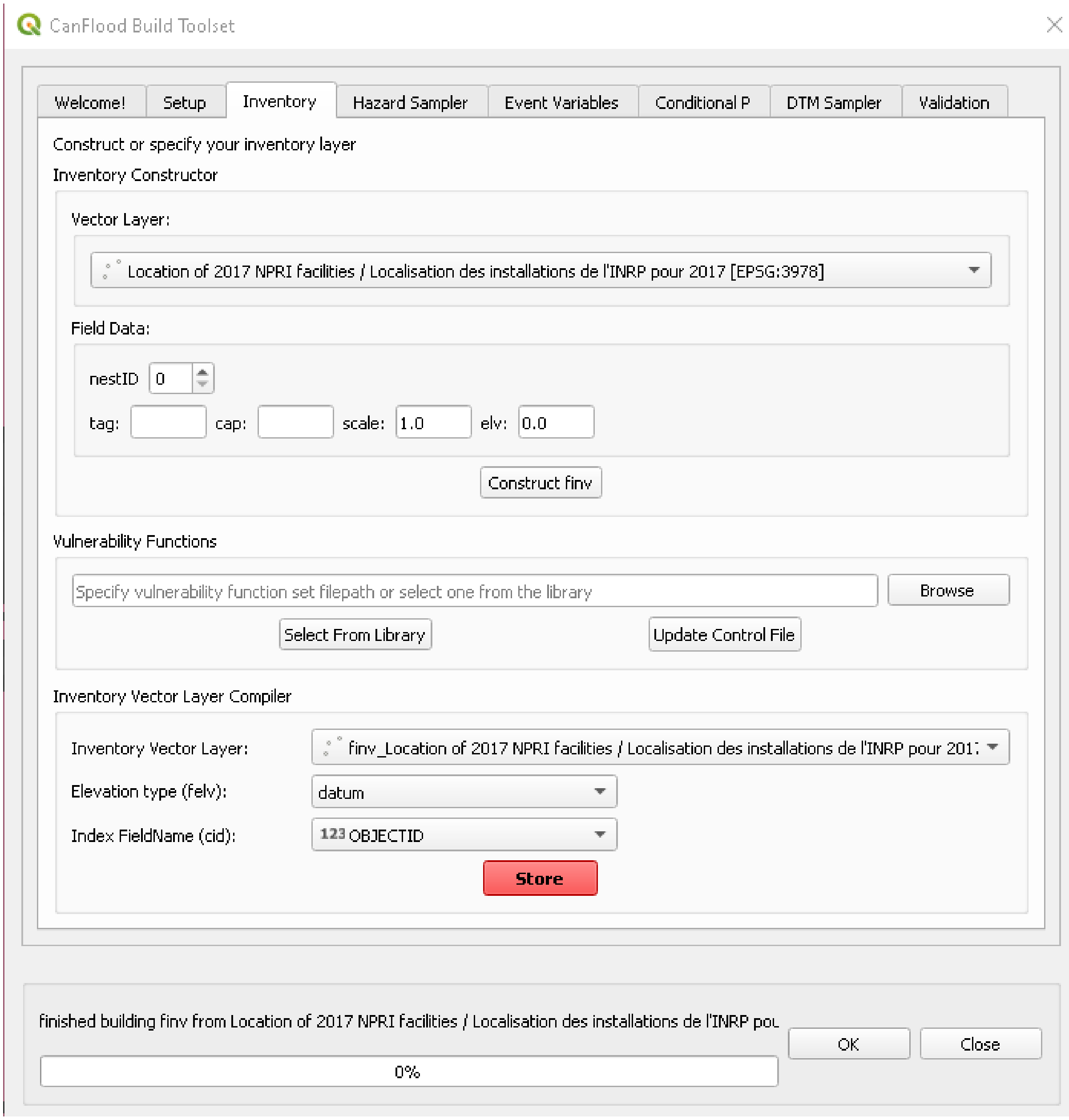
Follow the instructions in Section 2.2.2 *Setup*; however, ensure 'tut5_aoi_3978' is selected under 'Project AOI' and 'Load session results…' is selected.

[19] You can safely select any transformation or close the dialog. These transformations are only for display, we'll deal with transforming the data onto our CRS below.



Construct and Store Inventory

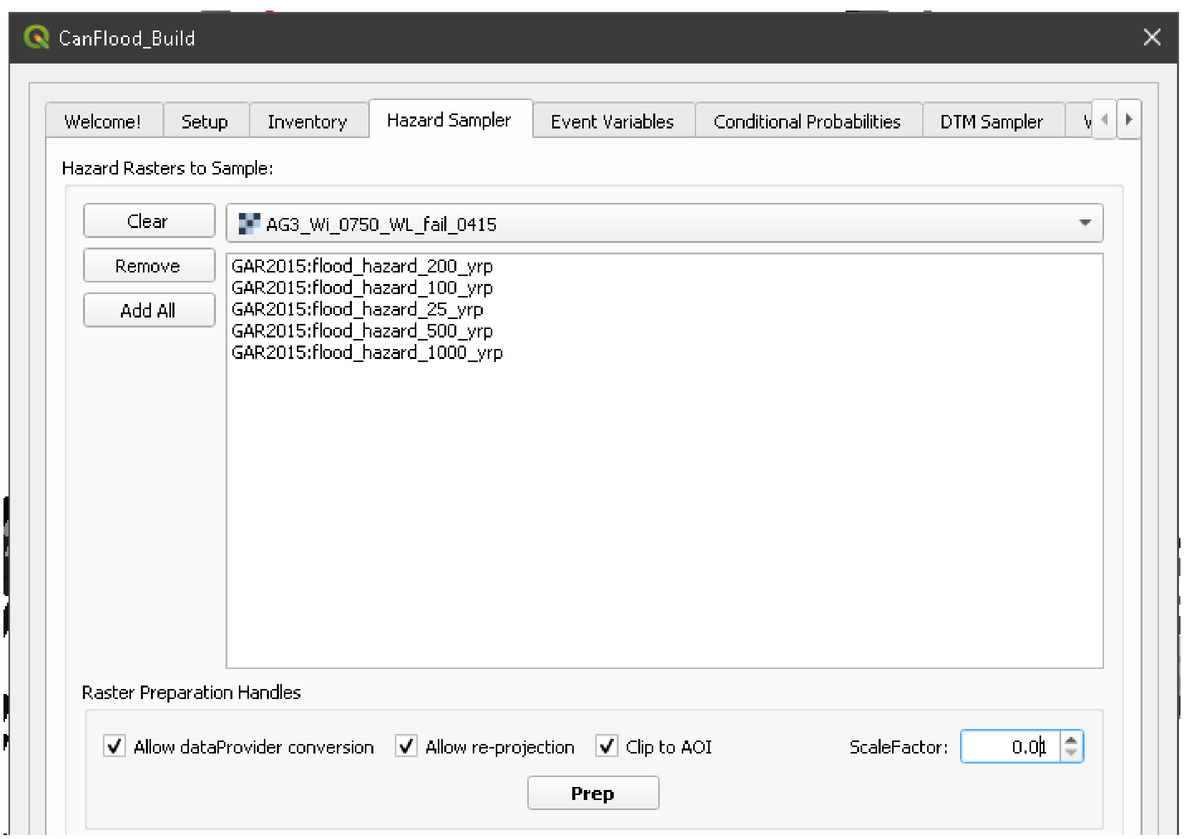
Navigate to the 'Inventory' tab. To convert the downloaded NPRI data into an L1 inventory layer that CanFlood will recognize, we need to add 'elv' and 'scale' fields and values. For this simple analysis, we assume each asset has a vulnerability height of zero (i.e., any positive flood depth leads to exposure). This assumption is accomplished in CanFlood by setting 'felv'= 'datum' and setting each 'f0_elv'=0. Using the Vector Layer drop down, select the NPRI layer and ensure the 'nestID', 'scale', and 'elv' fields match what is shown below. Finally, **click 'Construct finv'** to build the new inventory layer. To generate the asset inventory ('finv') csv, ensure this new layer is selected in the 'Inventory Vector Layer' drop down. Now configure the 'felv' and 'cid' parameters as shown below, then **click 'Store'**:


CanFlood Build Toolset
Welcome!
Setup
Inventory
Hazard Sampler
Event Variables
Conditional P
DTM Sampler
Validation
Construct or specify your inventory layer
Inventory Constructor
Vector Layer:
Location of 2017 NPRI facilities / Localisation des installations de l'INRP pour 2017 [EPSG:3978]
Field Data:
nestID 0
tag:
cap:
scale: 1.0
elv: 0.0
Construct finv
Vulnerability Functions
Specify vulnerability function set filepath or select one from the library
Browse
Select From Library
Update Control File
Inventory Vector Layer Compiler
Inventory Vector Layer:
finv_Location of 2017 NPRI facilities / Localisation des installations de l'INRP pour 201
Elevation type (felv):
datum
Index FieldName (cid):
123 OBJECTID
Store
finished building finv from Location of 2017 NPRI facilities / Localisation des installations de l'INRP pou
OK
Close
0%

Hazard Sampler

Now you're ready to sample the GAR15 hazard layers with your new NPRI inventory. Unlike the hazard layers used in previous tutorials, the GAR15 hazard layers provide *depth* (rather than wsl) data in *centimeters* (rather than meters) in a coordinate system other than that of our project. Further, these hazard layers' extents are much larger than what is needed by our project; and because they are web-layers, many of Qgis' processing tools will not work. Therefore, we'll need to apply the four Raster Preparation tools described in Table 4-1 before proceeding with the 'Hazard Sampler'.

Navigate to the 'Hazard Sampler' tab, ensure the five GAR2015 layers are listed in the window, and click 'Sample'. You should get an error telling you the layer CRS does not match that of the project. Instead, configure the Raster Preparation handles as shown and click 'Prep':



You should see five new rasters loaded to your canvas (with a ‘prepd’ suffix). These layers should have rotated pixels, be clipped to the AOI, have reasonable flood depth values (in meters), and have the same CRS as the project[20]. Further, each of these rasters should be saved to your working directory. This new set of hazard layers should conform to the expectations of the Hazard Sampler, allowing you to proceed with construction of an L1 model as described in Section 2.2.

[20] In some cases, QGIS may fail to recognize the CRS assigned to these new rasters, indicated by a “?” shown to the right of the layer in the layers panel. In these cases, you will need to define the projection by going to the layer’s ‘Properties’ and under ‘Source’ set the coordinate system to match that of the project (EPSG: 3978).

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

The asset inventory ('finv') is a comprehensive list of the objects or assets whose exposure will be evaluated by the CanFlood model routines. The asset inventory is a spatial dataset that requires the following fields when employed in Risk (L1) models:

- *fX_scale*: value to scale the vulnerability function by (e.g. floor area);
- *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.

For Impacts (L2) and Risk (L2) models, the following additional fields are required:

- *fX_tag*: value telling the model which vulnerability function to assign to this asset;
- *fX_cap*: value to cap vulnerability prediction by (e.g. improvement value).

Additional fields are allowed but ignored by CanFlood. The 'X' placeholder shown above is called the 'nestID' and is used to group the four key attributes that parametrize a 'nested function' required by the Impacts (L2) model (Section 4.2.2). The 'Build' toolset provides a 'Inventory Constructor' tool that can populate an inventory template as a convivence; however, completing this template for a study area generally requires extensive data analysis outside the CanFlood plugin.

3.2. Hazard Events

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

- **Event probability**: probability 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.

- **Event raster**: location and wsl of the flood event. CanFlood’s Build toolset expects this as a raster data file, but CanFlood’s Model routines only require tabular data. Values must be relative to the project datum (wsl) and are typically developed using hydraulic modelling software.
- **Companion failure events** (optional): contains information about the probability and resulting exposure of a flood protection system failure during the hazard event. Each hazard event can be assigned multiple failure events (see Section 1.5) by specifying the same event probability for each in the ‘evals’ dataset (see Section 4.1.4).
    - **Failure raster**: location and wsl of the companion failure event.
    - **Failure polygon:** Conditional exposure probability polygon layer with features indicating the extent and probability of element failures during the event (see Section 4.1.5).

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).

4. Toolsets

This section describes the use and function of CanFlood's toolsets.

4.1. Build

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.

4.1.1. 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.

4.1.2. 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.

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

Inventory Constructor

The 'Inventory Constructor' tool helps construct a Flood Asset Inventory template from some vector geometry within CanFlood's 'nested function' framework (Section 3.1). Additional data analysis outside the CanFlood platform is generally required to populate these fields.

Vulnerability Function Library

To support the construction of preliminary risk models, the CanFlood plugin provides a collection of vulnerability function libraries commonly used in Canada. Users should carefully study legacy vulnerability functions and their construction methods before incorporating them into any risk analysis. At a minimum, functions should be scaled to account for spatial and temporal transfers.

4.1.3. Hazard Sampler

The Hazard Sampler tool generates the exposure dataset ('expos') from a set of hazard event rasters. Generally, these hazard event rasters represent the wsl results of some hazard model (e.g. HEC-RAS) at specific probabilities. The hazard sampler has two basic modes:

- **Wsl**: Sample raster values at each asset (default). For line and polygon assets, this requires the user specify a sampling statistic.
- **Inundation**: Calculate percent-inundation of each asset (for line and polygon geometry only). This requires a DTM Layer be specified and a 'Depth Threshold'.

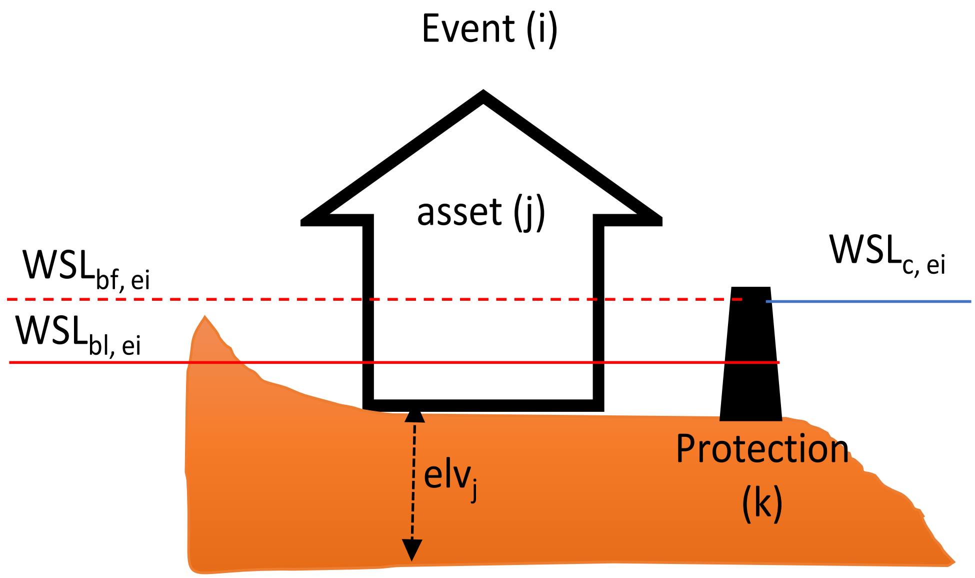


Figure 4-1: Risk calculation definition diagram where the dashed line is the wsl value of event 'e_i'

Using the definitions in Figure 4-1, the wsl exposure from an event *i* to a single asset *j* with height elv_j is calculated as:

$$expo_{i,j} = WSL_{bl,ei} - elv_j$$

The hazard sampler performs the following general steps to the set of user-supplied hazard layers and inventory layer:

1) Slice the inventory layer by the AOI (if 'Project AOI' is specified)
2) For each layer, sample the raster value or calculate the percent inundation of each asset;
3) Save the results in the 'expos' csv file to the working directory and write this path to the Control File;
4) Load the results layer to canvas (optional)

Raster Preparation

The raster sampler expects all the hazard layers to have the following properties:

- Layer CRS matches project CRS;

- Layer pixel values match those of the vulnerability functions (e.g., values are typically meters);
- Layer dataProvider is 'gdal' (i.e., the tool does not support processing web-layers).

To help rasters conform to these expectations, CanFlood includes a 'Raster Preparation' feature on the 'Hazard Sampler' tab with the tools summarized in Table 4-1.

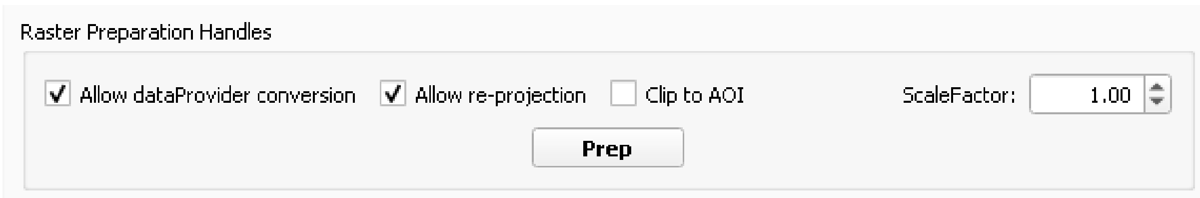


Table 4-1: Raster Preparation tools

Tool Name	Handle	Description
Downloader	Allow dataProvider conversion	If the layer's dataProvider is not 'gdal' (i.e., web-layers), a local copy of the layer is made to the user's 'TEMP' directory.
Re-projector	Allow re-projection	If the layer's CRS does not match that of the project, the 'gdalwarp' utility is used to re-project the layer.
AOI clipper	Clip to AOI	This uses the 'gdalwarp' utility to clip the raster by the AOI mask layer.
Value Scaler	ScaleFactor	For ScaleFactors not equal to 1.0, this uses the Raster Calculator to scale the raster values by the passed ScaleFactor (useful for simple unit conversions).

After executing these tools, a new set of rasters are loaded to the project (if 'Load session results to canvas' is checked).

Sampling Geometry

To support a wide range of vulnerability analysis, the Hazard Sampler tool is capable of developing wsl and inundation exposure variables from the three basic geometry types as shown in Table 4-2. 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 4-2: 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.

4.1.4. 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.

4.1.5. Conditional P

To incorporate defense failure (Section 1.5), CanFlood 'Risk (L1)' and 'Risk (L2)' models expect an resolved exposure probabilities ('exlikes') data set that specifies the conditional exposure probability of each asset to each hazard failure raster. The 'Conditional P' tool provides a conversion from a collection of failure influence area polygons and rasters (i.e., the outputs of a flood protection reliability analysis) to the resolved exposure probabilities ('exlikes') dataset. For each conditional failure event, the 'Conditional P' tool expects the user to provide a pair composed of the following layers:

- Raster of wsl that would be realized in the failure event
- Vector layer with polygon features indicating the extent and probability of element failures during the hazard event ('failure polygons'). These features can be non-overlapping (simple conditionals) or overlapping (complex conditionals) as discussed below.

The user can specify up to eight event-raster/conditional-exposure-probability-polygon pairings with the GUI.

CanFlood distinguishes 'complex' and 'simple' conditional exposure probability polygons based on the geometry overlap of their features as summarized in Table 4-3 and shown in Figure 4-2.

Table 4-3: Conditional exposure probability polygon treatment summary.

Type	Features	Treatment	Example (Figure 4-5)
trivial	none	Failure not considered, no resolved exposure probabilities ('exlikes') required	n/a
simple	not overlapping	'Conditional P' tool joins the specified attribute value from the polygon feature onto each asset to generate resolved exposure probabilities ('exlikes').	f2, f3
complex	overlapping	see below	f1

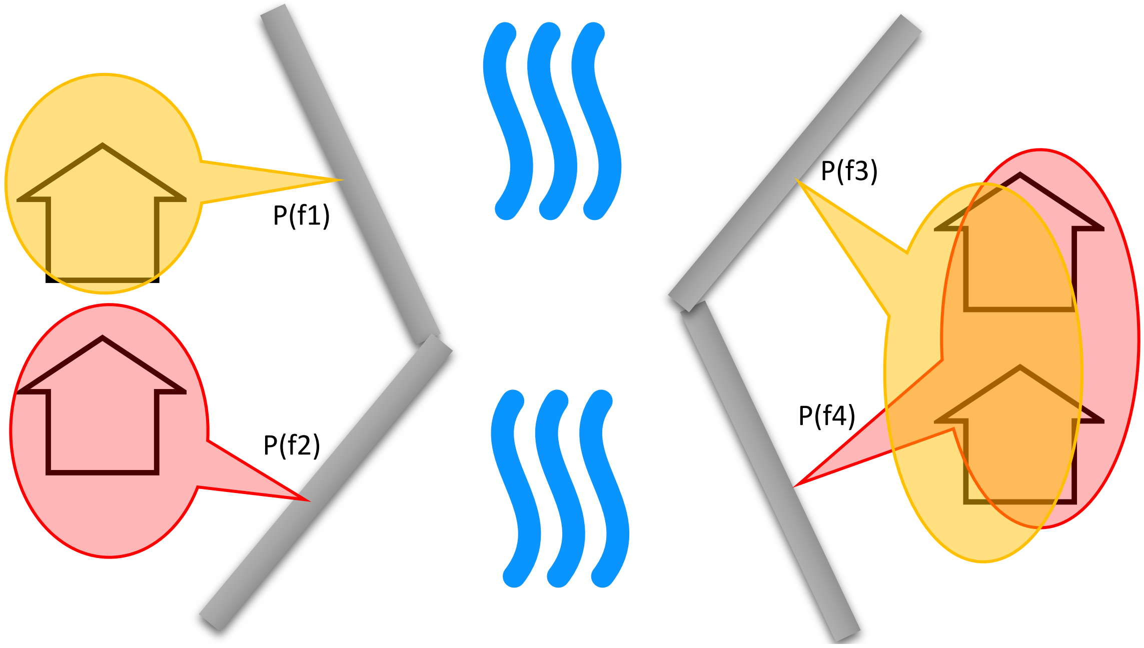


Figure 4-2:Simple [left] vs. Complex [right] conditional exposure probability polygon conceptual diagram showing a single layer with four features.

For complex conditionals, ‘Conditional P’ provides two algorithms to resolve overlapping failure polygons down to a single failure probability (for a given asset on a given failure raster) based on two alternate assumptions for the mechanistic relation between the failure mechanisms summarized in Table 4-4.

Table 4-4: Conditional exposure probability polygon resolution algorithms for complex conditional

Relation	**Algorithm Summary**
Mutually Exclusive	$$P(X) = \sum_{i=1}^{n} P(i)$$
Independent[1]	$$P(X) = \sum_{i=1}^{n} \left(1^{i-1} \sum P(A_I)\right)$$
Where P(X) is the resolved failure probability for a single asset on a given event and P(i) is the failure probably value sampled from a failure polygons feature. 1) Bedford and Cooke (2001)	

4.2. Model

The ‘Model’ toolset provides a GUI to facilitate access to CanFlood’s 3 flood risk models. CanFlood’s L2 models are split between exposure 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, exposure 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.

4.2.1. 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 4-5: 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 exposure	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

4.2.2. Impacts (L2)

CanFlood's 'Impacts (L2)' tool is designed to perform a 'classic' object-based deterministic flood damage assessment using vulnerability curves, asset heights, and wsl values to estimate flood impacts from multiple events. This tool calculates the impacts on each asset from each hazard event (if the provided raster wsl was realized). 'Impacts (L2)' does not consider or account for event probabilities (conditional or otherwise) as these are handled in the Risk (L2) routine (see Section 4.2.3).

To facilitate complex assets (e.g. a house vulnerable to structural and contents damages), Impacts (L2) supports composite vulnerability functions parameterized with the 4 key attributes ('tag', 'scale', 'cap', 'elv') with the 'f' suffix and 'nestID' numerator (e.g. f0, f1, f2, etc.). In this way, CanFlood can simulate a complex vulnerability function by combining the set of simple component 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 f*X* columns could be added as component vulnerability functions for basements, garages, and so on. Each of group of four key attributes is referred to as a 'nested function', where the collection of nested functions comprises the complete vulnerability function of an asset.

Impacts (L2) calculates the impact of an event e_i to a single asset j from it's collection of nested vulnerability functions k as:

$$c_{i,j} = \sum_{k=0}^{n} F\left(expo_{i,j,k},\ tag_{j,k},\ cap_{j,k},\ scale_{j,k}, elv_{j,k}\right) \quad (1)$$

Where each nested vulnerability function is parameterized by the following provided in the control file (Section 3.1):

- *tag*: variable linking the asset to the corresponding vulnerability curve in the vulnerability curve set ('curves');
- *cap*: maximum value cap placed on the vulnerability curve result;
- *scale*: scale value applied to the vulnerability curve result;
- *elv*: vertical distance from the exposure value.

And the following provided in the exposure dataset ('expos'):

- *expo*: magnitude of flood exposure sampled at the asset.

The 'Impacts (L2)' routine first calculates the impacts of each nested function, then scales the values, then caps the values, before combining all the nested values to obtain the total impact for a given asset.

Generally, the exposure dataset ('expos') is constructed with the 'Hazard Sampler' (Section 4.1.3) tool and contains a set of sampled wsl for each asset and each event. However, the only requirements on the 'expos' file are that it matches the expectations of the vulnerability functions provided by the user.

Ground Water

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.

Expanded Component Impacts

For advanced analysis, users can select the 'dmgs_expnd' option to output the complete impacts calculated on each nested function of each asset. This large, intermediate, data file provides the raw, scaled, capped, and resolved[21] impact values for each asset and each nested function. This can be useful for additional data analysis and troubleshooting but does not need to be output for any model routines (i.e., it is provided for information only).

4.2.3. Risk (L2)

CanFlood's 'Risk (L2)' tool is designed to perform a 'classic' object-based deterministic flood risk assessment using impact estimates and probabilities to calculate an annualized risk metric. 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 4-3, 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.

[21] The 'capped' values with null and rounding treatment

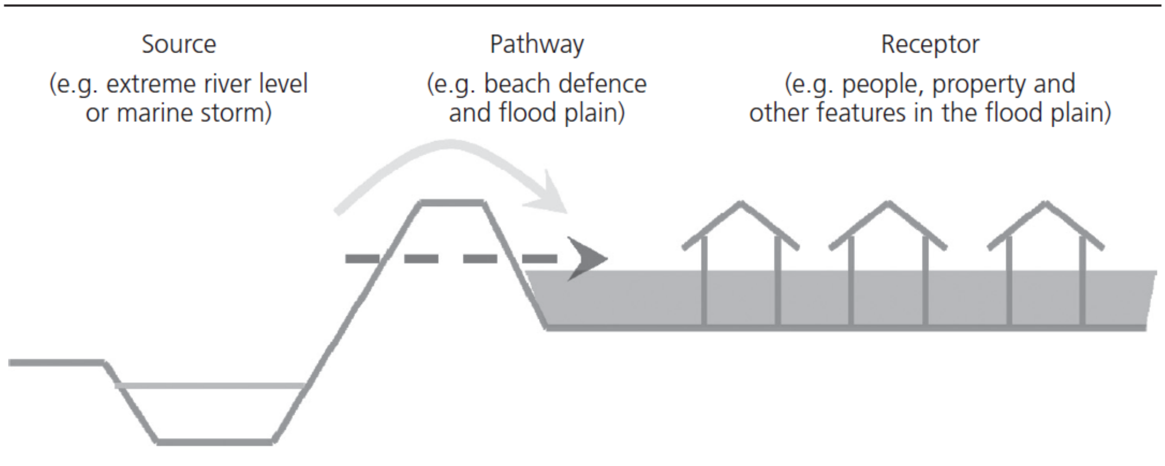


Figure 4-3: Sayers (2012)'s Source-Path-Receptor framework.

Outputs provided by this tool are summarized in Table 4-5.

Events without Failure

A simple application of the 'Risk (L2)' model is a study area with no significant flood protection infrastructure (e.g. a floodplain with no levees), like in Tutorial 2a (Section 0). In this case, each hazard event has a single probability and a single raster and the results from the 'Impacts (L2)' tool simply need to be integrated to yield the annualized risk metric. The primary risk metric calculated by CanFlood is the expected value of flood impacts *E[X]* (also called *Expected Annual Damages* (EAD), or *Average Annual Damages* (AAD), or *Annualized Loss*) and is defined for discrete events as:

$$\mathrm{E}[X] = \sum_{i=1}^{\infty} x_i \, p_i \,. \tag{2}$$

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:

$$\mathrm{E}[X] = \int_{\mathbb{R}} x f(x) \, dx. \tag{3}$$

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:

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

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 4-4.

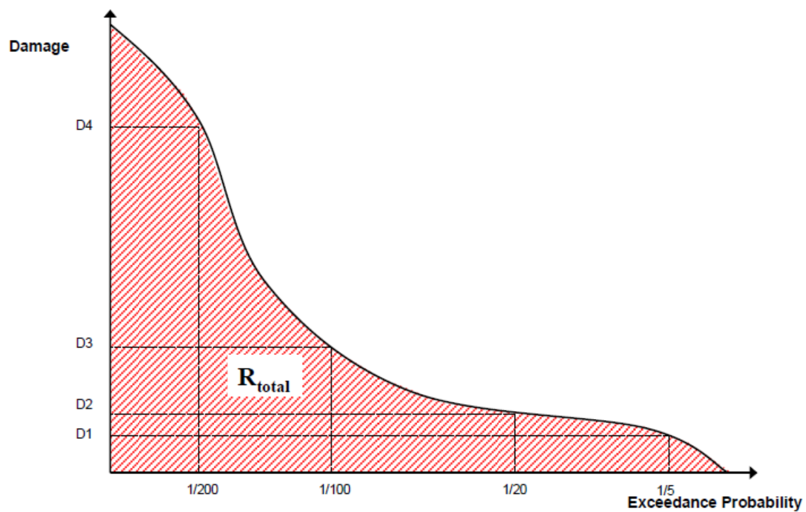


Figure 4-4: Damage-probability Curve from Messner (2007).

The following algorithm is implemented in CanFlood's 'Risk (L1)' and 'Risk (L2)' models to calculate expected value:

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).

Events with Failure

When resolving a hazard event with some failure, CanFlood combines the expected value (E(X)) of each companion failure event with that of a base 'no-fail' event to obtain the event's total expected value required by the risk metric equation (formula 4). To provide flexibility in the data requirements from a defense reliability analysis, CanFlood distinguishes two failure event analysis dimensions based on the geometry of the provided conditional exposure probability polygons ('failure polygons') and the number of failure events as summarized in Figure 4-5. 'Failure polygons' complexity is discussed in Section 4.1.5 and is resolved into the resolved exposure probabilities ('exlikes') dataset by calculating a single exposure probability for each companion failure event (Figure 4-5 'b1' and 'b2' into 'f1'). Once simplified into this resolved exposure probabilities ('exlikes') dataset, a failure event's failure polygons set relation, count, and complexity is ignored.

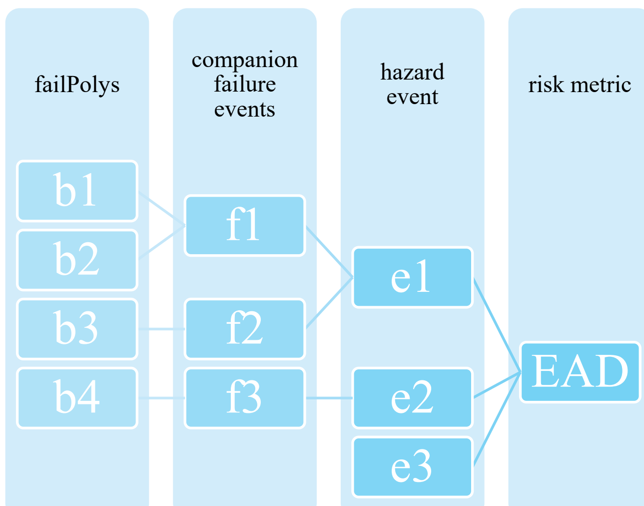


Figure 4-5: Example diagram showing three hazard events, one without failure (e3), one with simple (e2) and one with complex failure events (e1), and two companion failure events with simple (f2, f3) and the other (f1) with complex conditional exposure probability polygons (failure polygonss).

Table 4-6 summarizes the treatment of hazard events based on the count of failure events assigned to each.

Table 4-6: Hazard event treatment by failure event count.

Type	Count	Treatment[1]	Example (Figure 4-5)
trivial	0	$E(X)_{fail}=0$ $E(X)_{nofail}$ from equation 2	e3
simple	1	'max' or 'mutEx'	e2
complex	>1	'max', 'mutEx' or 'indep'	e1
1) See Table 4-7			

Events with Complex Failure

Table 4-7 summarize the algorithms implemented in CanFlood to calculate expected value for those hazard events with more than one companion failure event i.e., 'complex' failure events.

Table 4-7: Expected value algorithms for failure events.

name	code	summary
Modified Maximum	max	$E(X) = \sum_{i=1}^{n} \max(1 * \mathrm{Co}, \quad \mathrm{P(f)} * \mathrm{Cf}, \ldots)$
Mutually Exclusive	mutEx	$E(X) = \sum_{i=1}^{n} \sum (P(o) * \mathrm{Co}, \quad \mathrm{P(f)} * \mathrm{Cf}, \ldots)$
Independent	indep	a) Construct a matrix of all possible failure event combinations (positives=1 and negatives=0) b) Substitute matrix values with P and (1-P) c) Multiply the set to obtain the probability of the combination (P_{comb}) d) Multiply P_{comb} by the maximum impact of events within the set to obtain the combination's impact (C_{comb}) e) $E(X) = \sum_{i=1}^{n} Pcomb_i * Ccomb_i + \sum_{i=1}^{n} P(o)_i * Co_i$
P(o) = 1-sum(Ci)		

4.2.4. 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.

4.3. Results

The ‘Results’ toolset is a collection of tools to assist the user in performing secondary data analysis and visualization on CanFlood models. The remainder of this section describes the function of the tools within this toolset.

4.3.1. Join Geo

This tab provides a tool to join the non-spatial risk results back onto the inventory geometry for spatial post-processing. A basic version of this tool can be run automatically by the ‘Risk (L1)’ and ‘Risk (L2)’ tools. On the ‘Join Geo’ tab, the user can perform additional customization of these layers, including applying pre-packaged layer styles.

4.3.2. Risk Plot

This tab contains multiple tools for generating non-spatial plots on a single model scenario. The plots generated on this tab all pull style information from the Control File’s ‘[plotting]’ group, and results data from the ‘[results_fp]’ group. Plots are available in the two standard risk curve formats:

- ARI vs. Impacts
- Impacts vs. AEP

See Section 2.4.3 for examples.

Plot Total

This tool generates a simple plot of the total results. A basic version of this tool can be run automatically from the ‘Risk (L1)’ and ‘Risk (L2)’ tools for convenience.

Plot Stack

This tool generates risk curves showing the total contributions from each composite vulnerability functions discussed in Section 3.1 on a single plot.

Plot Fail Split

This tool generates composite risk curve showing the total results with a second curve showing the contribution from the ‘non-failure’ portion of each event (i.e., subtracting any contributions from companion failure events) on a single plot.

4.3.3. Compare

4.4. Miscellaneous

The following section describes some additional tools provided in the CanFlood platform that support flood risk modelling in Canada. These can be accessed from the CanFlood menu (Plugins > CanFlood).

4.4.1. Add Connections

CanFlood's 'Add Connections' tool adds a pre-compiled set of web-resources to a user's Qgis profile for easy access and configuration (i.e., adding credentials). The set of web-resources added by this tool are configured in the 'canflood_pars\WebConnections.ini' file (in the user's plugin directory). Appendix A summarizes the web-connections added by this tool.

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 > 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 > click 'Add' to load the layer in the project.

Many plugins and tools used by Qgis (and CanFlood) do not support such web-layers (esp. rasters), so conversion and download may be required.

4.4.2. 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 vector layer as an input[22]. 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.

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[23]. Once converted, the user can start the CanFlood model building process.

[22] Can be built from an .xls file by exporting to csv then creating a csv layer in QGIS from the lat/long values
[23] A corresponding simple $/m2 curve is created by the DamageCurves Converter

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 'composite vulnerability function' feature).

5. 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.

References

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Appendix A: Web Connections

Acronym	Description	Service	Reference
UNISDR_GAR15_GlobalRiskAssessment			
GAR15	UNISDR's data layers from the global risk assessment conducted for the Global Assessment Report on Disaster Risk Reduction 2015 (GAR15) by the CIMA Research Foundation. This data is hosted by the Global Risk Data Platform and contains six global flood depth rasters (in cm; return periods = 25, 50, 100, 200, 500, 1000 years) having 1km resolution.	WCS	see below
ECCC_NationalPollutantReleaseInventory_NPRI			
NPRI	Government of Canada's service to collect information on the release, disposal and transfer of more than 320 substances. The web-service provides release reports from the most recent year. The layer 'NPRI-Reporting Facilities' shows the location of facilitates reporting any type of release.	ArcGisFeatureServer	homepage
NRCan_NationalHumanSettlementLayer_NHSL			
NHSL	Collection of thematic datasets that describe the physical, social and economic characteristics of urban centres and rural/remote communities across Canada, and their vulnerability to natural hazards of concern	ArcGisFeatureServer	MapServer
NRCan_AutomaticallyExtractedBuildings			
	Topographical feature class that delineates polygonal building footprints automatically extracted from airborne Lidar data, high-resolution optical imagery or other sources.	WMS	Open Canada

GAR15

Server

Global Risk Data Platform
(https://preview.grid.unep.ch/index.php?preview=home&lang=eng)

Data and Model

From *preventionweb* (https://risk.preventionweb.net/capraviewer/):

> *The GAR Atlas global flood hazard assessment uses a probabilistic approach for modelling riverine flood major river basins around the globe. This has been possible after compiling a global database of stream-flow data, merging different sources and gathering more than 8000 stations over the globe in order to calculate the range of possible discharges from very low to the maximum possible scales at different locations along the rivers. The calculated discharges were introduced in the river sections to model water levels downstream. This procedure allowed for the determination of stochastic event-sets of riverine floods from which hazard maps for several return periods (25, 50, 100, 200, 500, 1000 years) were obtained. The hazard maps are developed at 1kmx1km resolution and have been validated against satellite flood footprints from different sources (DFO archive, UNOSAT flood portal) performing well especially for big events For smaller events (lower return periods), the GAR Atlas flood hazard maps tend to overestimate with respect to similar maps produced locally (hazard maps where available for some countries and were used as benchmark). The main issue being that, due to the resolution, the GAR Atlas flood hazard maps do not take into account flood defenses that are normally present to preserve the value exposed to floods.*

Additional summary is provided in:

UNISDR. 2015. "Global Assessment Report on Disaster Risk Reduction 2015 - Annex 1 - Global Risk Assessment." Geneva: United Nations. https://www.preventionweb.net/english/hyogo/gar/2015/en/gar-pdf/Annex1-GAR_Global_Risk_Assessment_Data_methodology_and_usage.pdf.

Additional detail is provided in:

Rudari, Roberto, and Francesco Silvestro. 2015. "IMPROVEMENT OF THE GLOBAL FLOOD MODEL FOR THE GAR 2015." UNISDR. https://www.preventionweb.net/english/hyogo/gar/2015/en/bgdocs/risk-section/CIMA%20Foundation,%20Improvement%20of%20the%20Global%20Flood%20Model%20for%20the%20GAR15.pdf.