CanFlood User's Manual

1. Introduction

CanFlood is a flood risk modelling toolbox built for Canada. CanFlood facilitates flood risk calculations with three basic steps:

1) Building the model
2) Running the model
3) Visualizing/Analyzing the results

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

CanFlood 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.

2. Installation

All installation instructions can be found on GitHub:

https://github.com/IBIGroupCanWest/CanFlood

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

3. Tutorial 1a: Risk (L1)

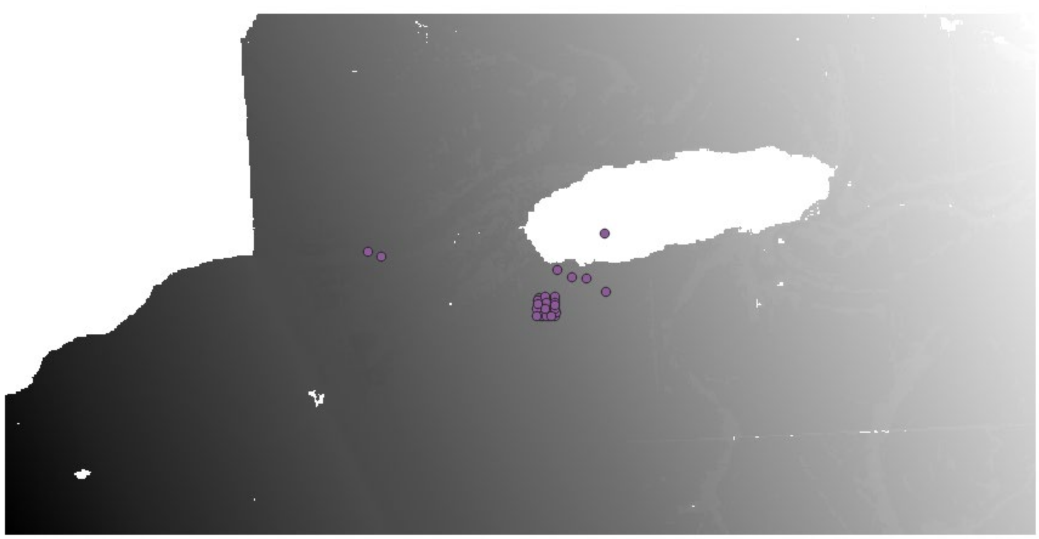
This tutorial guides the user through the simplest application of a risk analysis in CanFlood. This application is for a preliminary risk assessment where only binary impacts are considered for each asset (inundated or not inundated). Options for scaling per-asset and conditional probabilities for the Risk (L1) tool are presented in Section XXX.

3.1. Load data to the project

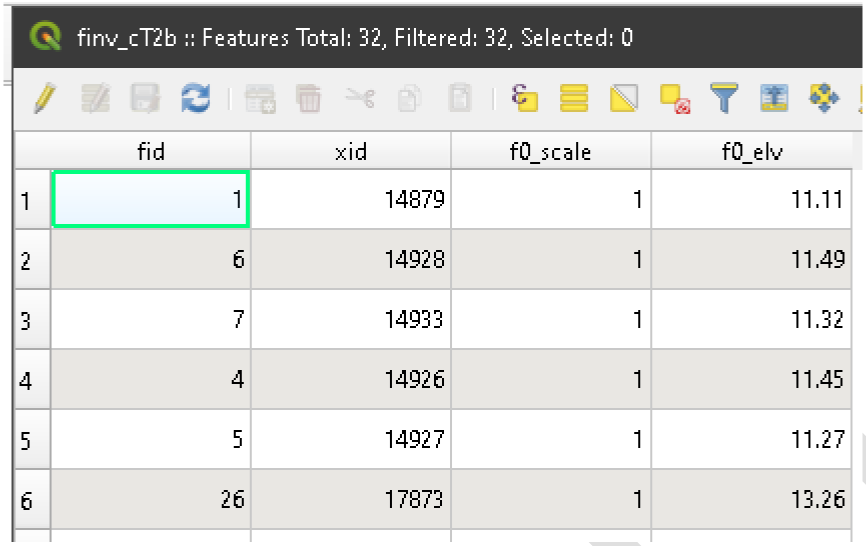
Load all the data for Tutorial 1 into a Qgis project: CanFlood\tutorials\1\data\:

- haz_1000yr_cT2.tif
- haz_1000yr_fail_cT2.tif (not used in Tutorial 1a)
- haz_100yr_cT2.tif
- haz_200yr_cT2.tif
- haz_50yr_cT2.tif
- exlikes_1000yr_cT2.gpkg (not used in Tutorial 1a)
- finv_cT2b.gpkg: inventory spatial layer.

It should look something like this:



Explore the 'finv' inventory attributes. You should see something like this:



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

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

The 4 fields are:

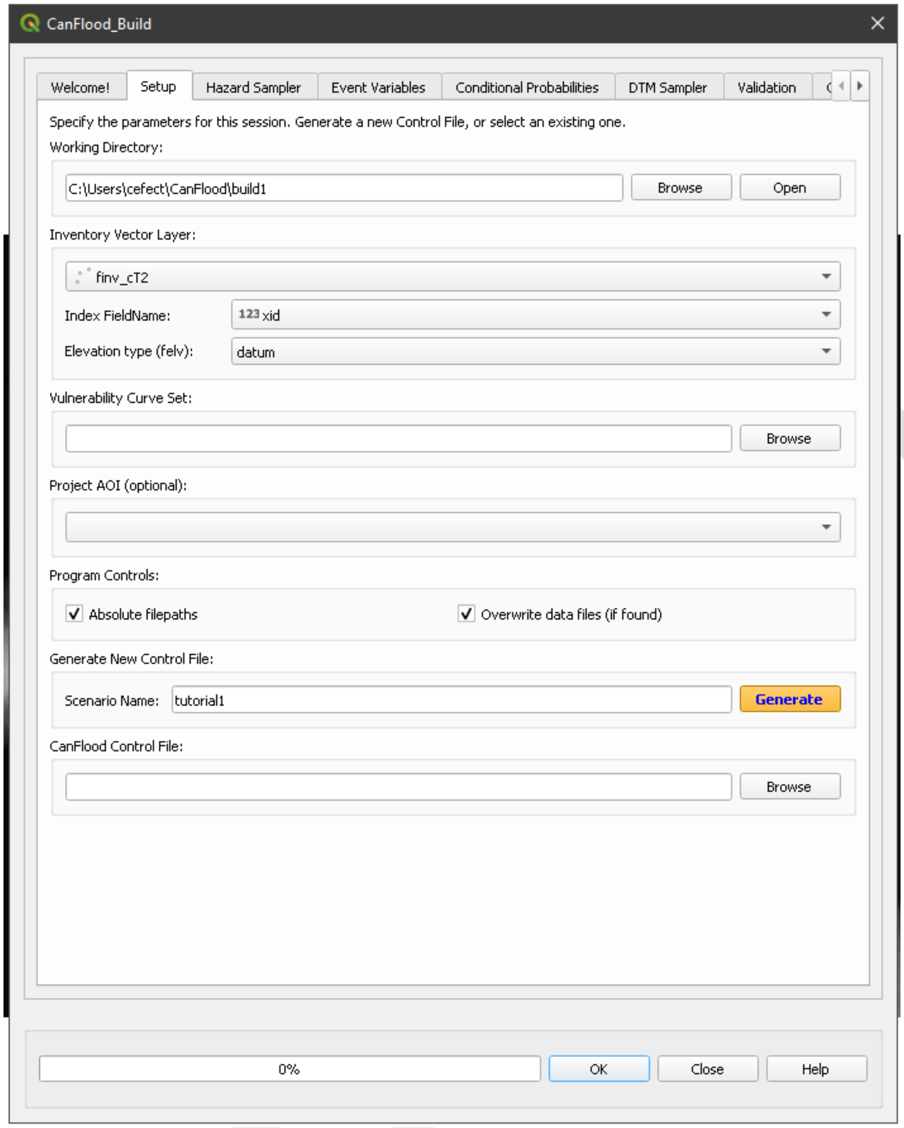
- *fid*: built-in feature identifier (not used);
- *xid*: Index FieldName, unique identifier for the asset;
- *f0_scale*: value to scale the results of the 'f0' calculation for this asset by;
- *f0_elv*: height (above the project datum) at which the asset is vulnerable to flooding;

3.2. Build the Model

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

3.2.1. Setup

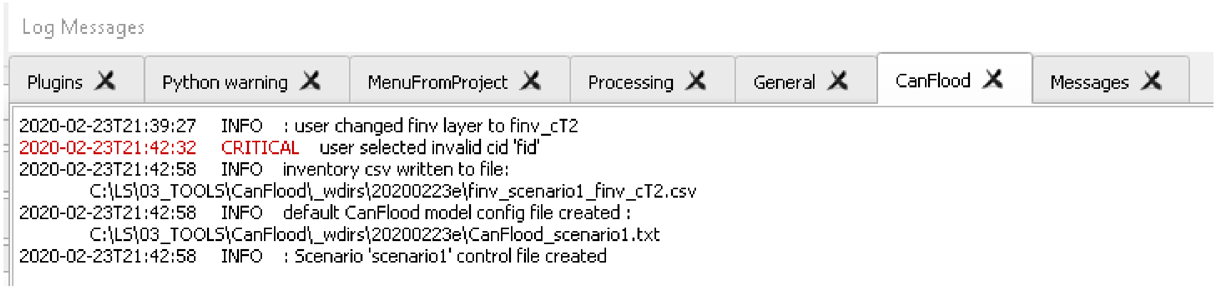
On the 'Setup' tab, fill out the information as shown (selecting your own directories):



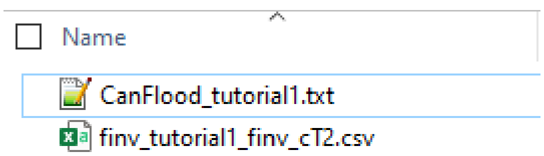
Click 'Generate'.

There should be a message on the Qgis Toolbar indicating the process ran successfully.

If you close the CanFlood dialog and 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:



Then click ‘Open’ to open the specified working directory, you should see the following files have been created in your working directory:

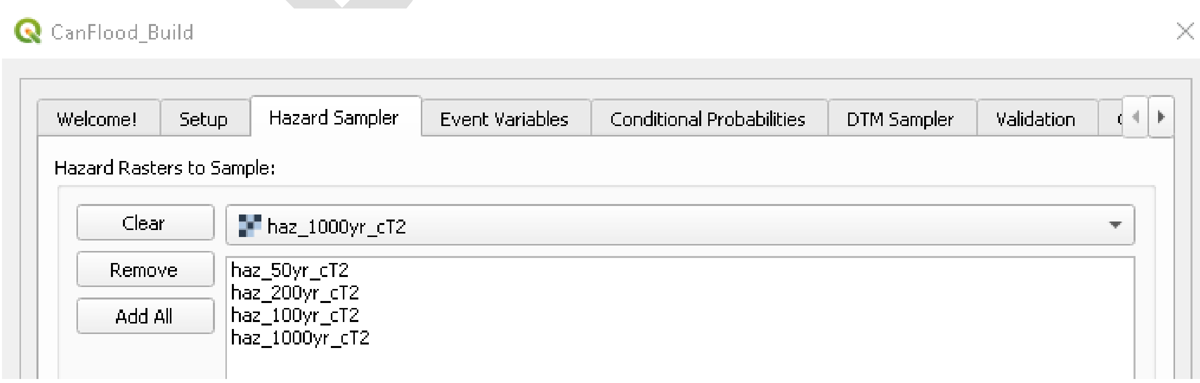


The .txt file is the Control File with default parameters, and the .csv is the inventory in tabular format.

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). Also notice that ‘curves’ has been populated with the directory you provided for ‘Vulnerability Curve Set’, while ‘finv’ has been populated with a csv version of the inventory layer you specified.

3.2.2. Hazard Sampler

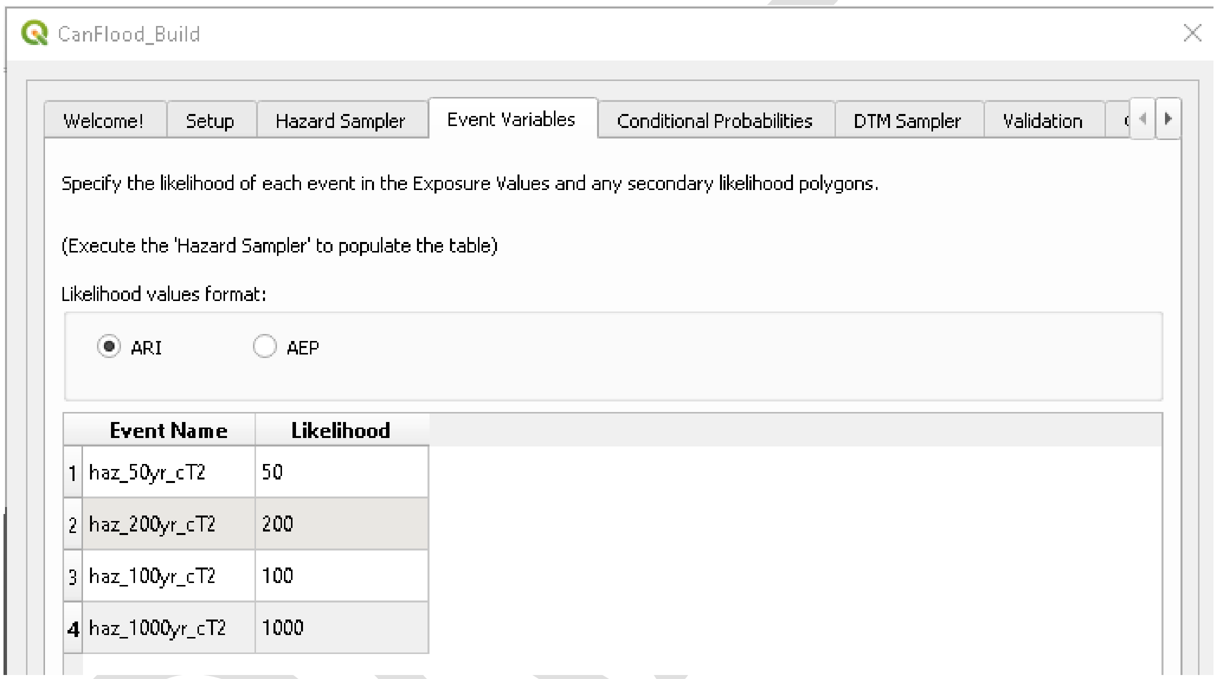
Move to the ‘Hazard Sampler’ tab. Add all the hazard rasters to the display box as shown:



Click ‘Sample’ to generate the exposure dataset. You should see a new file in the working directory called ‘expos_tutorial1_4_32.cs’v, and it’s filepath added to the control file under ‘expos’.

3.2.3. Event Variables

Move to the ‘Event Variables’ tab. Specify the correct values for each event’s likelihood (from the event names) as shown:



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

3.2.4. Validation

Move to the ‘Validation’ tab, check ‘Risk (L1)’, then push ‘Validate’. This will check all of the inputs in the control file and set the ‘risk1’ validation flag to True.

The model control file should now be constructed. Navigate to the control file (shown on ‘Setup’ tab), open and inspect the file. It should look similar to:

CanFlood_tutorial1.txt - Notepad

File Edit Format View Help

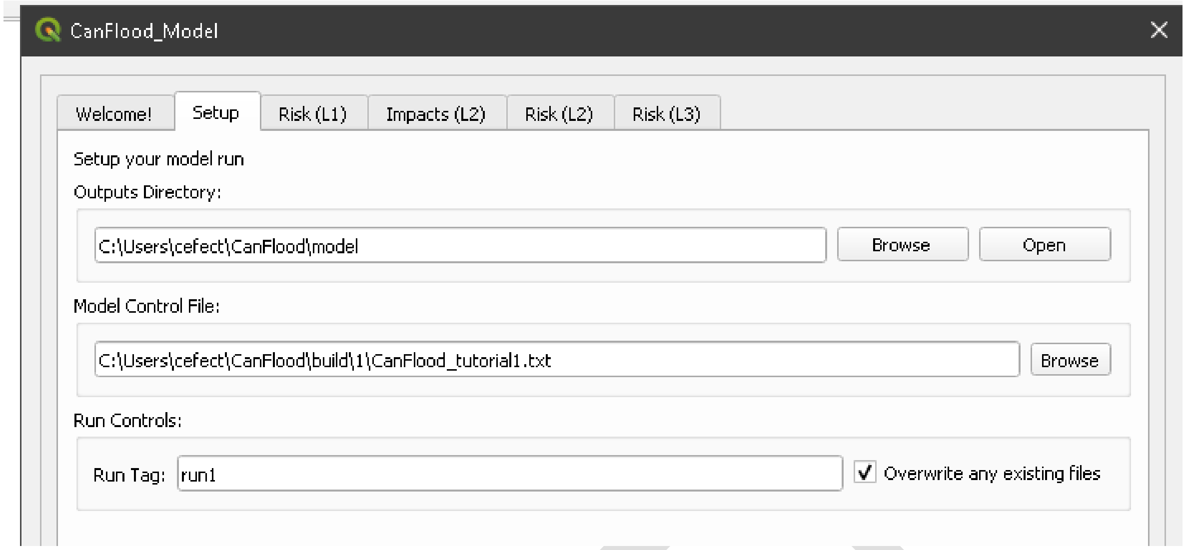
```
[parameters]
name = tutorial1
cid = xid
prec = 2                #float precision for calculations
ground_water = True     #whether to allow wsl < gel
felv = datum
event_probs = ari
ltail = extrapolate     #EAD extrapolation: left tail treatment code (low prob high damage)
rtail = 0.5             #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

[dmg_fps]
curves =
finv = C:\Users\cefect\CanFlood\build\1\finv_tutorial1_finv_cT2b.csv
expos = C:\Users\cefect\CanFlood\build\1\expos_tutorial1_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\1\evals_4_tutorial1.csv
#evals file path set from canflood.build.builddialog.py at 2020-03-20 15.31.41

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

3.3. Run the Model

Select the ‘Model’ button

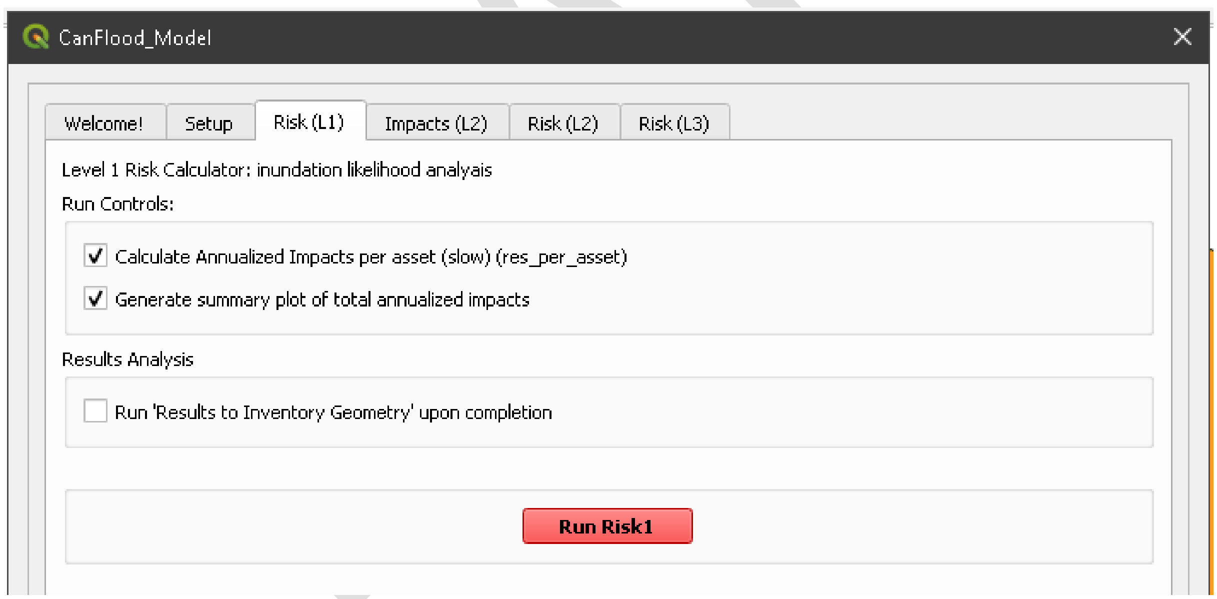
3.3.1. Setup

On the ‘setup’ tab, select a working directory (does not have to match that from the previous step) where all your results will be stored. Also select the control file created in the previous section. It should look similar to this:



3.3.2. Execute

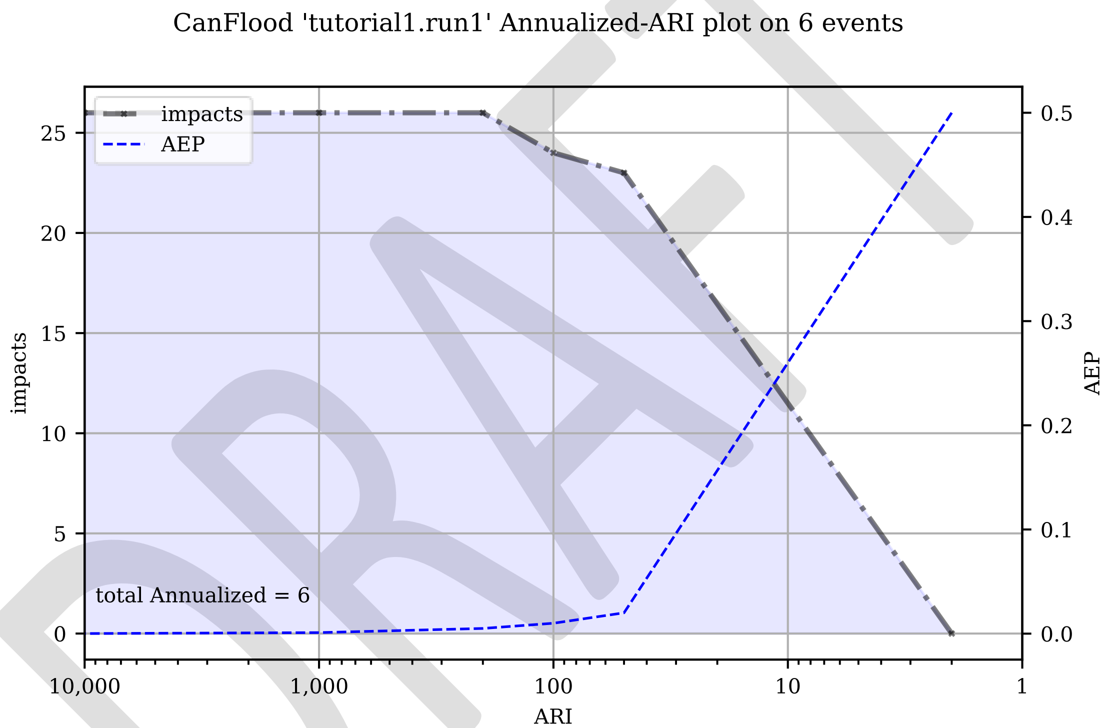
Navigate to the ‘Risk (L1)’ tab. Check the first 2 boxes as shown below and press ‘Run Risk1’.



3.3.3. View Results

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

- *risk1_run1_tutorial1_passet.csv:* Expected value of inundation per asset;
- *risk1_run1_tutorial1_ttl.csv*: Total results, expected value of total inundation per event (and for all events)
- *tutorial1_smry_plot.svg*: a plot of the total results



Congratulations on your first CanFlood model!

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

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

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

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

4.1. Build the Model

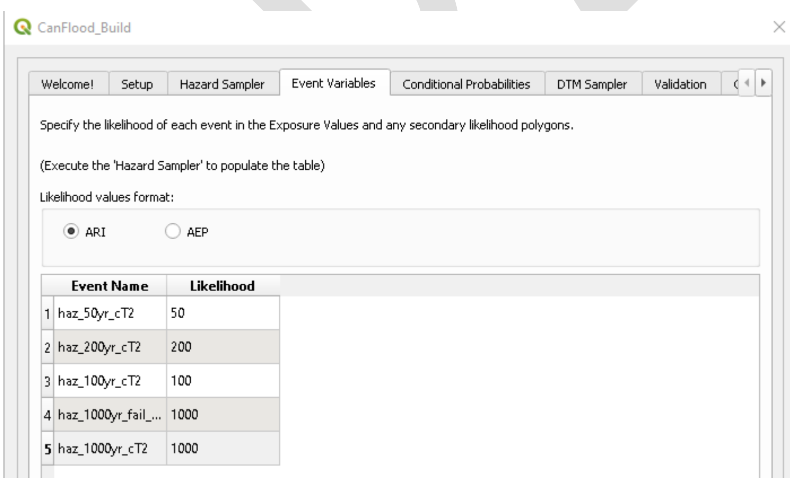
In a new working directory, follow the same 'Setup' steps described in Section 3.2.1.

4.1.1. Hazard Sampler

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

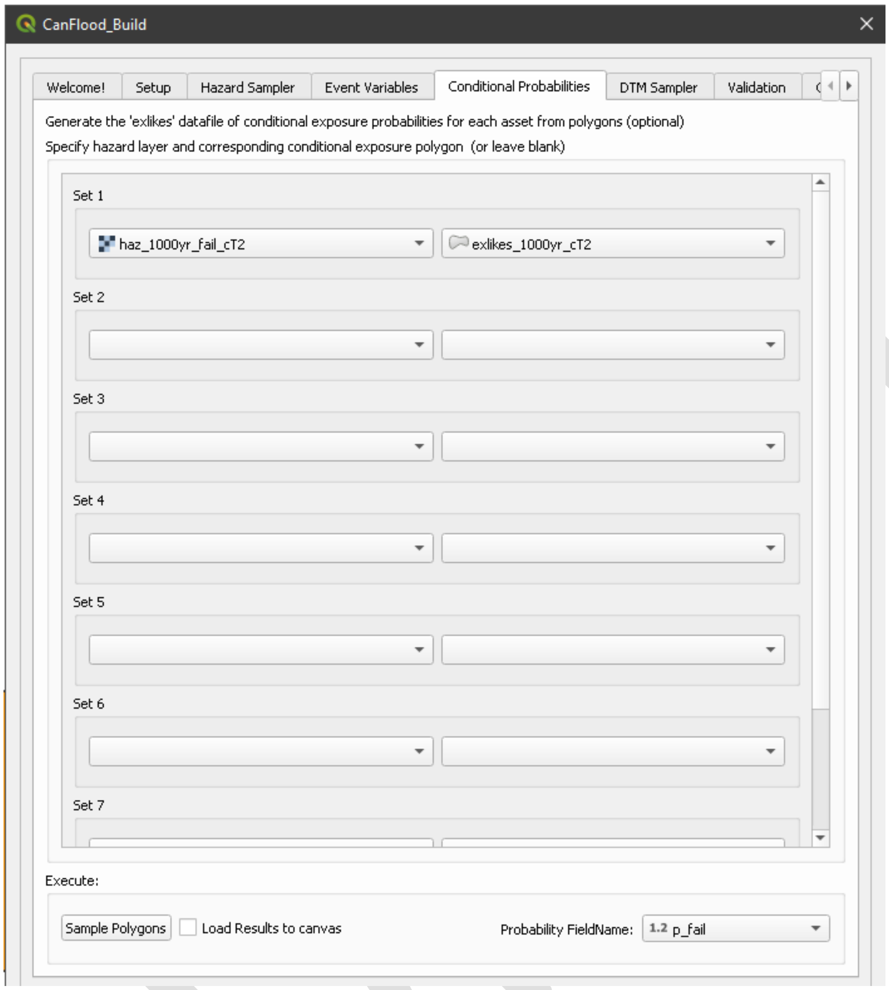
4.1.2. Event Variables

Move to the 'Event Variables' tab. Specify the correct values for each event's likelihood (from the event names) as shown, then press 'Store' to generate the 'evals' dataset.



4.1.3. Conditional Probabilities

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



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

4.1.4. Validation

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

```
[parameters]
name = tutorial2
cid = xid
prec = 2                #float precision for calculations
ground_water = True     #whether to allow wsl < gel
felv = datum
event_probs = ari       #format of event probabilities (in 'aeps' data file): 'ari' or 'aep'
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

[dmg_fps]
curves =
finv = C:\Users\cefect\CanFlood\build\2\finv_tutorial2_finv_cT2b.csv
expos = C:\Users\cefect\CanFlood\build\2\expos_tutorial2_5_32.csv
gels = #ground elevation data filepath

[risk_fps]
dmgs = #damage data results filepath
exlikes = C:\Users\cefect\CanFlood\build\2\exlikes_tutorial2.csv
evals = #event probability data filepath

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

And your working directory should look like this:

Name	Date modified	Type	Size
CanFlood_tutorial2.txt	2020-03-20 4:48 PM	TXT File	2 KB
exlikes_tutorial2.csv	2020-03-20 4:48 PM	Microsoft Excel C...	1 KB
expos_tutorial2_5_32.csv	2020-03-20 4:45 PM	Microsoft Excel C...	4 KB
finv_tutorial2_finv_cT2b.csv	2020-03-20 4:45 PM	Microsoft Excel C...	1 KB

4.2. Run the Model

Select the 'Model' button .

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

4.2.1. View Results

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

	A	B	C	D	E	F
1	xid	0.001	0.005	0.01	0.02	ead
2	14879	0.7712	0	0	0	0
3	14880	0.7712	0	0	0	0
4	14925	0.7712	0	0	0	0
5	14926	0	0	0	0	0
6	14927	1	1	1	1	0.26
7	14928	1	1	1	1	0.26

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

5. Tutorial 2: Risk (L2) – Simple Events

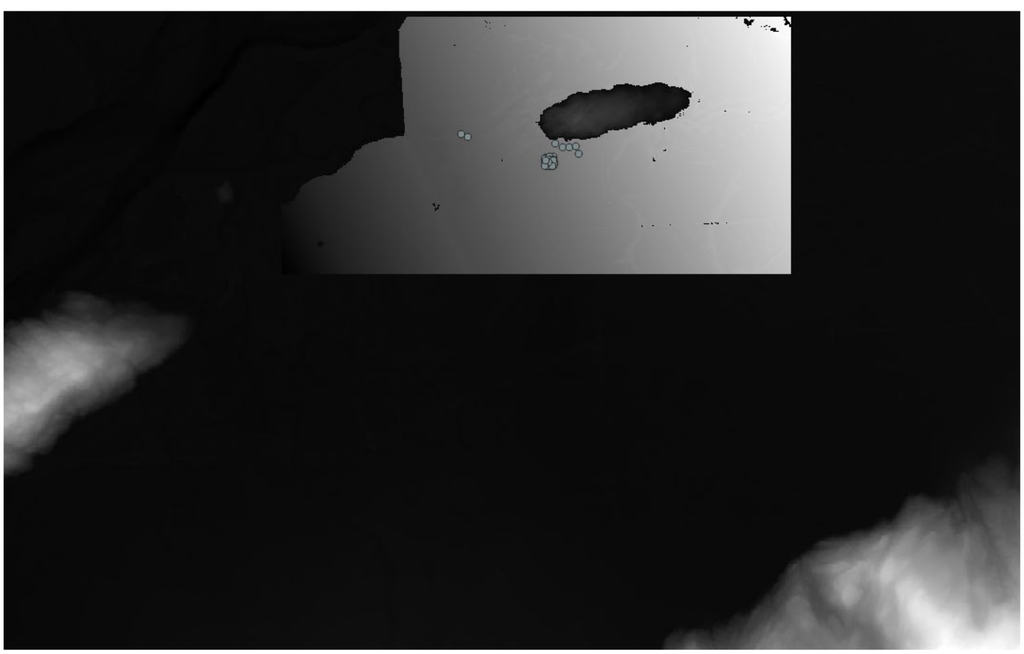
Tutorial 2 demonstrates the use of the Risk (L2) tool in CanFlood. This emulates a more detailed risk assessment where the vulnerability of each assets is described as a function of flood depth (rather than flood presence as in tutorial 1). This tutorial also demonstrates an inventory with 'relative'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

5.1. Load data to project

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

- *finv_cT2.gpkg:* This is an example asset inventory in CanFlood format.
- *CanFlood_curves_rfda_20200218.xls:* This is an example vulnerability curve set. Each tab corresponds to one depth-damage curve and a 'tag' value in the finv.
- *dtm_cT1.tif*: This is an example DTM raster
- 4 water surface level (WSL) hazard rasters corresponding to 4 different flood events (haz_1000yr_cT2.tif, haz_100yr_cT2.tif, haz_200yr_cT2.tif, haz_50yr_cT2.tif)

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

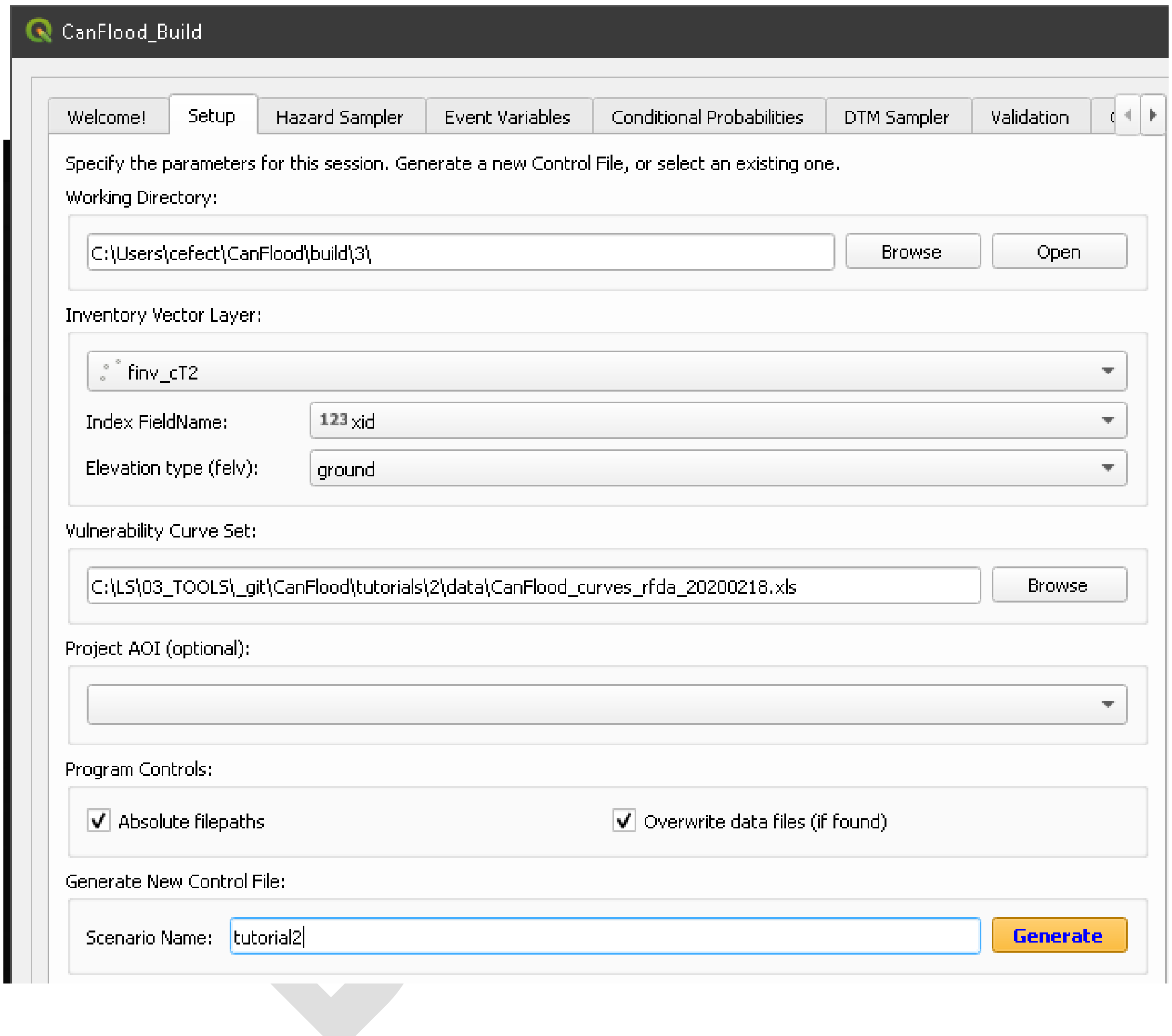


5.2. Build the Model

Open the 'Build' toolset.

5.2.1. Setup your scenario

On the 'setup' tab, configure the session as shown, then click 'Generate':

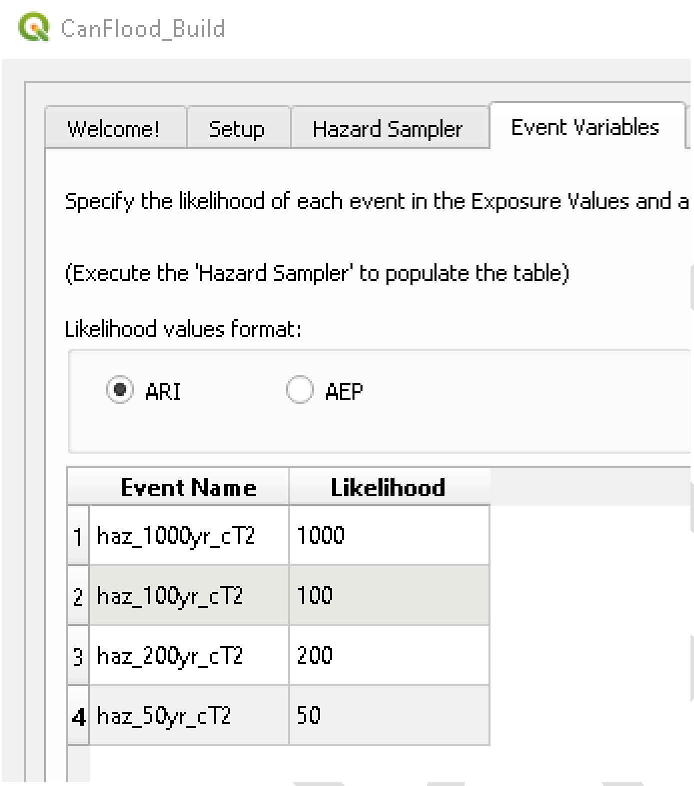


5.2.2. Hazard Sampler

Move to the 'Hazard Sampler' tab, add the 4 hazard rasters to the window, and click 'Sample'.

5.2.3. Event Likelihoods

Move to the ‘Event Likelihoods’ tab, you should now see the 4 hazard events populating the table. Fill in the ‘Likelihood’ values as shown, then hit ‘store’ to generate the ‘evals’ dataset.



5.2.4. DTM Sampler

Move to the ‘DTM Sampler’ tab. Select the dtm raster then click ‘Sample DTM’ to generate the ‘gels’ dataset.

5.2.5. Validation

Move to the 'Validation' tab, check the boxes for both L2 models, then click 'Validate'. Your Control File look similar to the below:

```
CanFlood_tutorial2 - Notepad
File  Edit  Format  View  Help
cid = xid
prec = 2                #float precision for calculations
ground_water = True     #whether to allow wsl < gel
felv = ground
event_probs = ari
ltail = extrapolate     #EAD extrapolation: left tail treatment code (low prob high damage)
rtail = 0.5             #EAD extrapolation: right trail treatment (high prob low damage)
drop_tails = True       #whether to remove the extrapolated values from the results
integrate = trapz       #integration method to apply: trapz, simps

[dmg_fps]
curves =
C:/Users/jill.stone/Desktop/LMFRA/CanFLood/CanFlood_006_20200317/CanFlood_010_20200320/canflood/data/da
ta2/CanFlood_curves_rfda_20200218.xls
finv =
C:/Users/jill.stone/Desktop/LMFRA/CanFLood/CanFlood_006_20200317/CanFlood_010_20200320/canflood/build/t
utorial2\finv_tutorial2_finv_cT2.csv
expos =
C:/Users/jill.stone/Desktop/LMFRA/CanFLood/CanFlood_006_20200317/CanFlood_010_20200320/canflood/build/t
utorial2\expos_tutorial2_4_32.csv
gels =
C:/Users/jill.stone/Desktop/LMFRA/CanFLood/CanFlood_006_20200317/CanFlood_010_20200320/canflood/build/t
utorial2\gels_tutorial2_1_32.csv

[risk_fps]
dmgs = #damage data results filepath
exlikes = #secondary exposure likelihood data filepath
evals =
C:/Users/jill.stone/Desktop/LMFRA/CanFLood/CanFlood_006_20200317/CanFlood_010_20200320/canflood/build/t
utorial2\evals_4_tutorial2.csv

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

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

5.3. Run the Model

Open the 'Model' dialog. Configure the 'setup' tab similarly to Tutorial 1a.

5.3.1. Impact (L2)

Move to the Impacts (L2) tab. Uncheck the 'Run Risk Model' box (we'll do that in the next step). Click 'Run Impacts2'. The CanFlood log tab should look something like this:

```
2020-02-23T22:14:06    INFO    .Model.setup_binv: for "f0' got (32, 5)
2020-02-23T22:14:06    INFO    .Model.setup_binv: for "f1' got (32, 5)
2020-02-23T22:14:06    INFO    .Model.setup_binv: for "f2' got (0, 5)
2020-02-23T22:14:06    INFO    .Model.setup_binv: expanded inventory from 3 nest sets to finv (64, 5)
2020-02-23T22:14:06    WARNING    .Model.setup_binv: got 12 (of 64) wsl below ground
2020-02-23T22:14:06    INFO    .Model.bdmg: running on 64 assets and 4 events
2020-02-23T22:14:06    INFO    .Model.bdmg: calculating for 4 (of 4) ftags w/ positive depths: ['BA_S', 'CA_S', 'BA_C', 'CA_C']
2020-02-23T22:14:06    INFO    .Model.run: got damages for 32 events and 4 assets
2020-02-23T22:14:06    INFO    .Model.run: finished
2020-02-23T22:14:06    INFO    .output_df: wrote to (32, 4) to file:
        C:\LS\03_TOOLS\CanFlood\_wdirs\20200223e\res\dmgs_scenario1_run1.csv
2020-02-23T22:14:06    INFO    .update_cf: updated contyrol file w/ 1 pars at :
        C:\LS\03_TOOLS\CanFlood\_wdirs\20200223e\CanFlood_scenario1.txt
2020-02-23T22:14:06    INFO    : Impacts2 complete
```

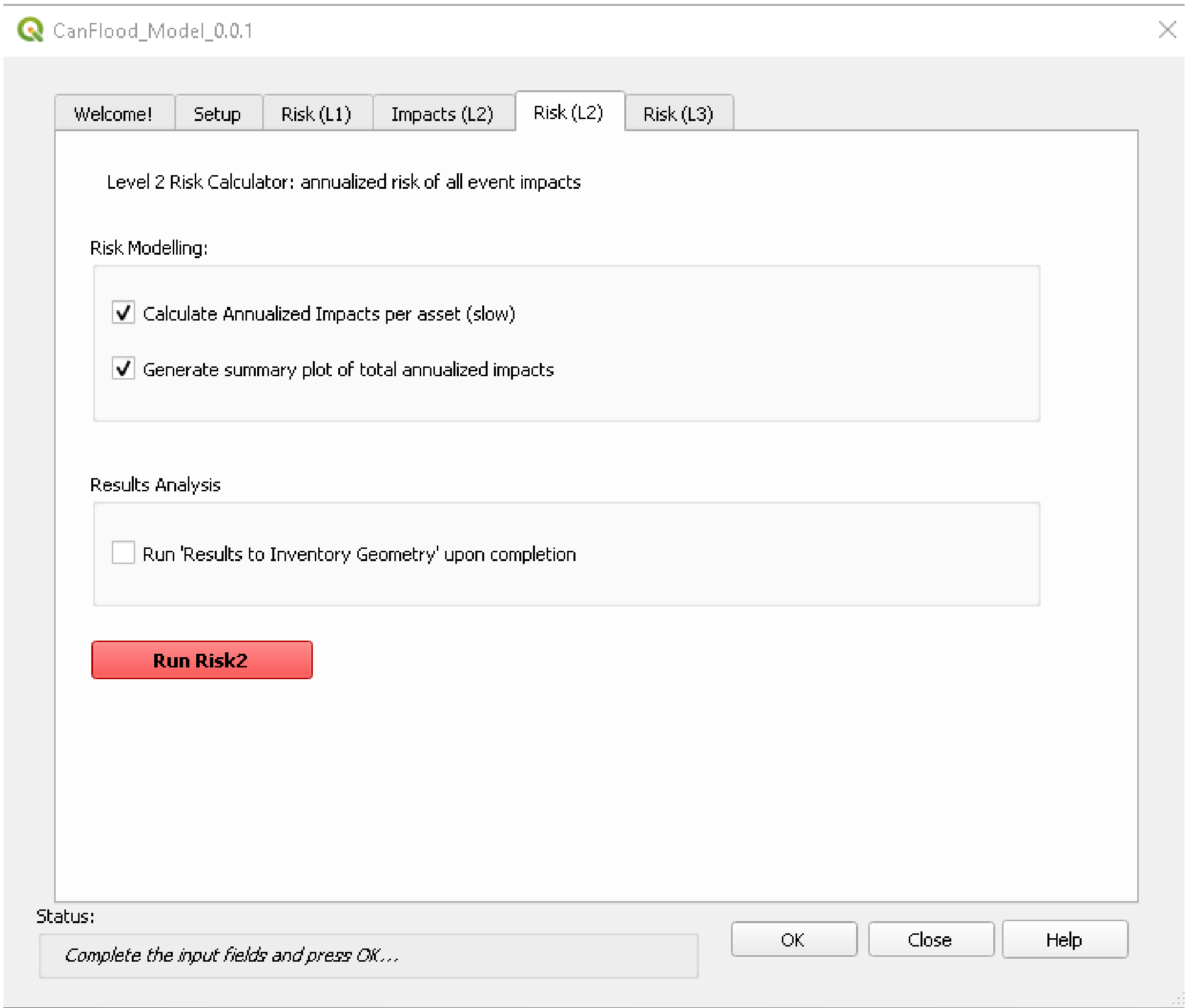
On the Control File, a filepath for 'dmgs' should now be shown. Navigate to this csv. It should look something like this:

xid	haz_1000yr_cT2_dmg	haz_100yr_cT2_dmg	haz_200yr_cT2_dmg	haz_50yr_cT2_dmg
14879	111300	111300	111300	111300
14880	153700.672	153700.672	153700.672	153700.672
14925	126924.392	126924.392	126924.392	126924.392
14926	107662.592	107662.592	107662.592	107662.592
14927	162014.16	162014.16	162014.16	162014.16
14928	153000	153000	153000	153000
14933	138414.888	138414.888	138414.888	138414.888
14934	131785.024	131785.024	131785.024	131785.024
14935	115081.952	115081.952	115081.952	115081.952
14936	133000	133000	133000	133000

These are the damages per event per asset. Now you're ready to calculate flood risk!

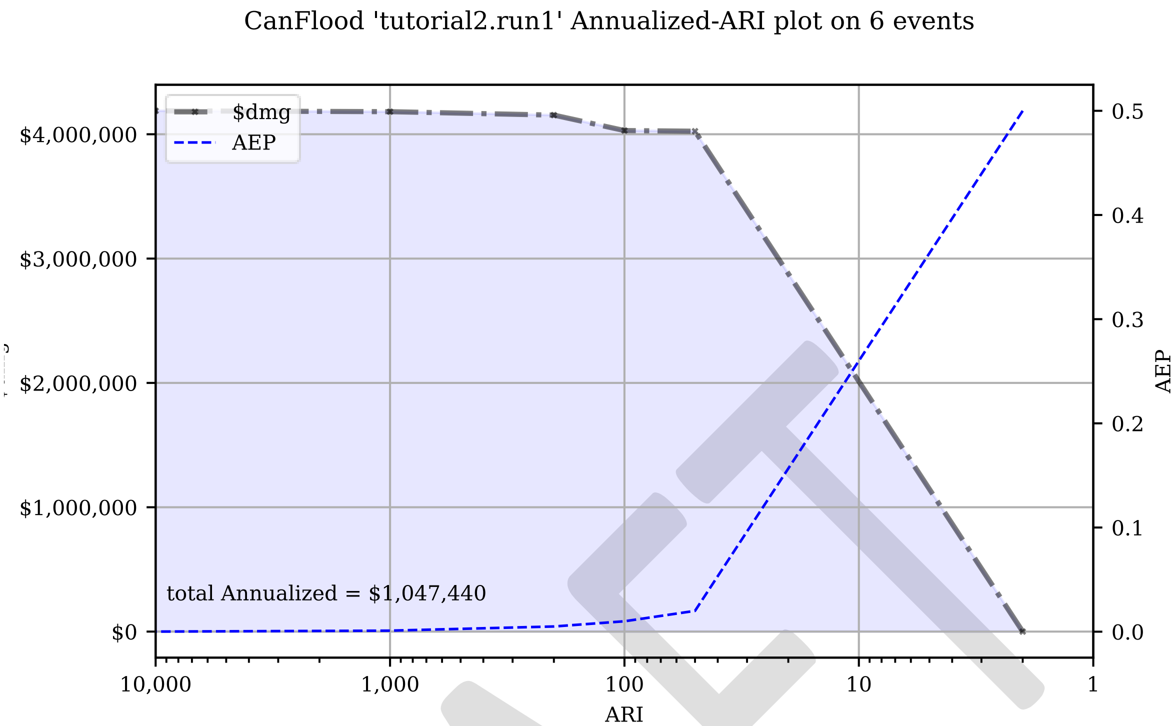
5.3.2. Risk (L2)

Move to the 'Risk (L2)' tab. Check the first two boxes, and click 'Run Risk2':



Your working directory should now contain these files:

- dmgs_tutorial2_run1.csv: impact results per asset (from Impact (L2) run)
- risk2_run1_tutorial2_passet.csv: expected value per asset
- risk2_run1_tutorial2_ttl.csv: total expected value for all events.
- tutorial2_smry_plot.svg: summary of total, see below.



For a complete description of the Risk (L2) module, see Section 8.1.

6. Data Requirements

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

6.1. Asset Inventory (finv)

The asset inventory is a comprehensive list of the objects or assets who's impacts will be evaluated by the CanFlood model. The asset inventory is a spatial data set with these attributes:

- fX_tag: value telling the model which vulnerability function to assign to this asset
- fX_scale: value to scale the vulnerability function by (e.g. floor area)
- fX_cap: value to cap vulnerability prediction by (e.g. improvement value)
- fX_elv: elevation to anchor the vulnerability function (e.g. first floor height + DTM)
- geometry: geospatial data telling the model where to sample the hazard rasters..
- inventory indexer: unique integer used by the model to link together datasets.

To facilitate complex assets (e.g. a house vulnerable to structural and contents damages), CanFlood asset inventories support nesting of the 4 key attributes (tag, scale, cap, elv) (using the X in fX). In this way, a single asset can sample up to 10 different vulnerability functions. 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 damages, and BA_C estimates contents damages. Additional fX columns could be added to nest vulnerability functions for basements, garages, and so on.

7. Build Toolset

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

- *Scenario Setup*: This is a mandatory tab for starting the control file (and converting the inventory to csv format)
- *Hazard Sampler*: This tab facilitates sampling the different flood event WSL rasters with the inventory geometry. This results in an exposure table of WSL per event per asset.
- *Event Likelihoods*: This tab is used to assign event probabilities to the different events sampled by the Hazard Sampler.
- *Likelihood Sampler:* This tab is used to assign secondary event polygons to the events (not implemented in 0.0.1)
- *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. Validated 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.

7.1. 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.

7.2. Hazard Sampler

Generate the exposure dataset ('expos') from a set of hazard event rasters.

7.3. Event Variables

store user specified event variables into the 'evals' dataset

7.4. Conditional Probabilities

Generate conditional probability data set ('exlikes') for each asset. The user can specify up to eight event raster/secondary exposure polygon pairings with the GUI. Where conditional probability polygons overlap, the union_probabilities() method is used to calculate the union probability of multiple events using the exclusion principle (https://en.wikipedia.org/wiki/Inclusion%E2%80%93exclusion_principle#In_probability).

7.5. Converting from Other Platforms

On the 'other' tab some tools are provided to aide in conversion from common data formats to that of CanFlood.

7.5.1. RFDA conversion

RFDA was developed by the Province of Alberta in 2014 as a Qgis 2 plugin. RFDA did not include any spatial analysis or annualization functions. 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.

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

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

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

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

Inventory Conversion

The RFDA Inventory Conversion requires a point vectorlayer as an input (this can easily be built from .xls by exporting to csv then creating a csv layer in Qgis from the lat/long values). Based on the concatenated ‘class’ and ‘struct_type’ values in the inventory, each asset is assigned a f0_tag with a ‘_M’ suffix to denote this as a main floor curve (e.g. BD_M). Based on 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. Once converted, the user can start the CanFlood model building process.

DamageCurves Converter

This tool converts the tabular location based RFDA 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 how using CanFlood's nested curve capabilities. By default, the Inventory Conversion tool assins the 'Floor combined' curves using the 'bmst_f'.

8. Model Toolset

8.1. Risk (L2)

CanFlood's Level 2 Risk tool is designed to perform a 'classic' object-based deterministic flood risk assessment using depth-damage curves, asset heights, and WSL values to estimate annualized damages. 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 XXX, where:

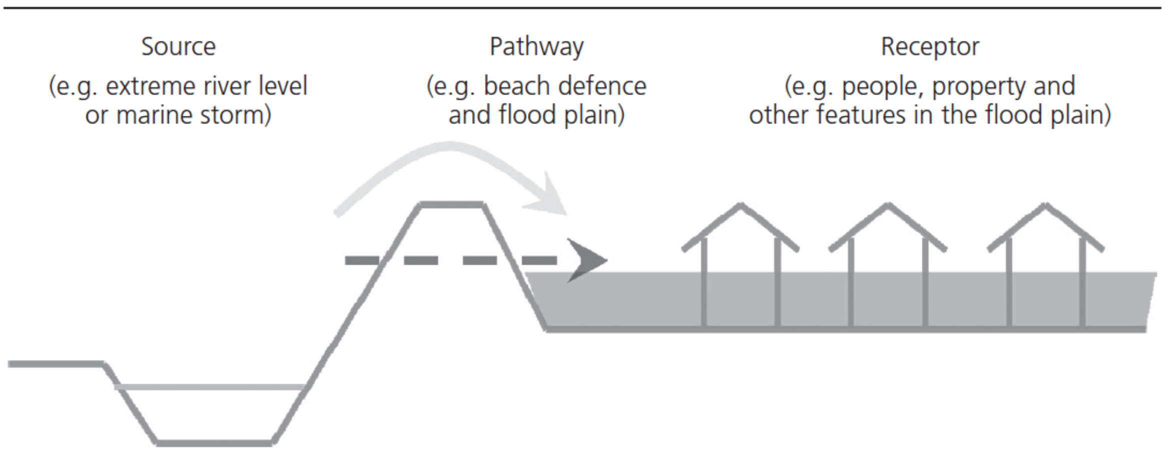


Figure 1: Sayers (2012)'s Source-Path-Receptor framework.

- *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.

8.1.1. Parameter Summary

The following table summarizes the relevant parameters for CanFlood's Risk (L2) tool that can be specified in the Control File:

```
"""
dmgs -- damage data results file path (default N/A)

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

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

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 recurrence 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 -- zero 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')

risk2 -- Risk2 validation flag (default False)

"""
```

8.1.2. Simple Event

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

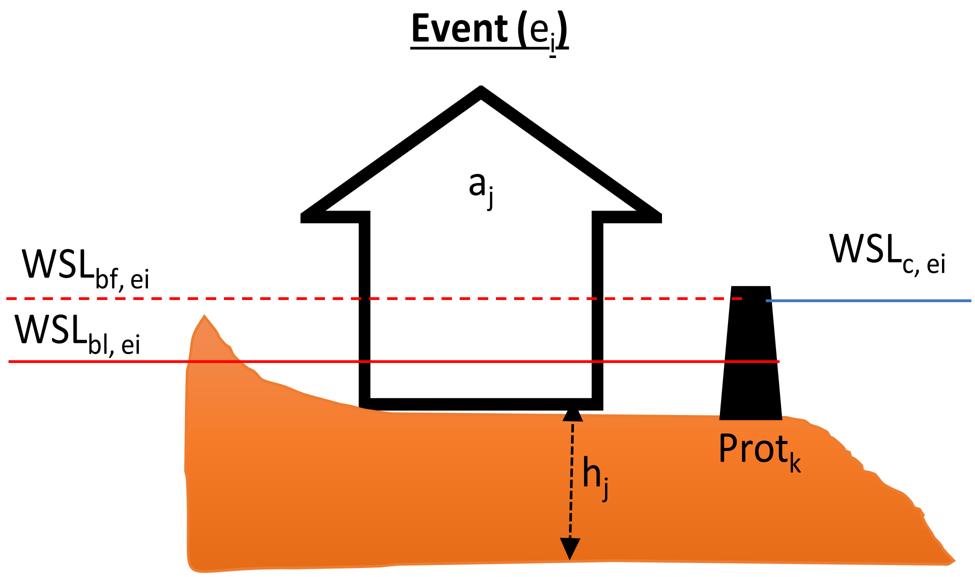


Figure 2: Risk calculation definition diagram where the dashed line is the WSL value of event ej

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

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

Where tag is the variable linking the asset to the corresponding vulnerability curve in the vulnerability curve set ('curves'), and $WSL_{bl,ej}$ is the WSL sampled at the asset location and contained in the exposure dataset ('expos')[1]. The total impact of an event x_i is the sum of impacts from all assets. The expected value of flood impacts *E[X]* (also called *Expected Annual Damages* (EAD), or *Average Annual Damages* (AAD), or *Annualized Loss*) is defined for discrete events as:

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

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

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

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

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

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

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 XXX.

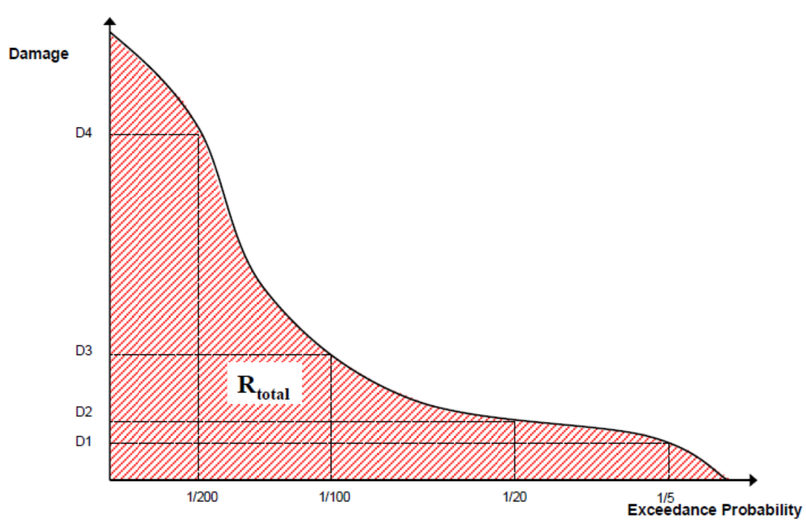


Figure 3: Damage-probability Curve from Messner(2007).

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

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

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

8.1.3. With Flood Protection Infrastructure

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

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

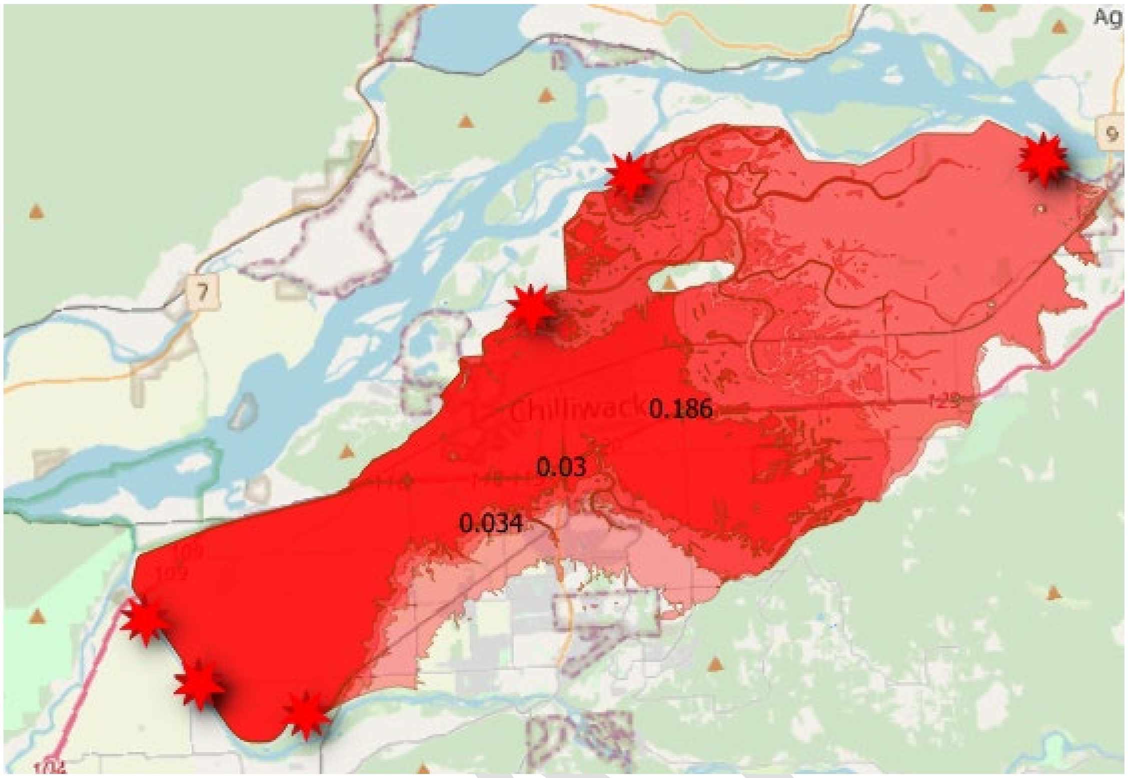


Figure 4: Example conditional exposure polygons showing breach locations and associated failure probabilities..

Conditional Probability Polygons

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

Companion Rasters

In conjunction with facilitating the spatial specification of the conditional probability of realizing hazard variables, CanFlood also allows the user to specify companion hazard rasters for a single 'event'. A common application for this is a 'failure' and 'non-failure' hazard raster for a single hydraulic event (e.g. 100yr with levee failure and 100yr without levee failure)[2]. To specify companion rasters for the failure scenario, simply include the raster in the exposure data set[3] and ensure the event likelihood is specified[4] with the same value as the non-failure event. CanFlood selects the maximum expected value of impacts per asset from the duplicated events as shown in the following formula (see XXX for variable reference):

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

Where $WSL_{bf,ej}$ is the WSL sampled at the asset location from the companion raster ('failure' raster), $P_{bf,ei}$ is the conditional likelihood of realizing the companion raster (specified in the 'exlikes' datafile)[5], and the remaining variables are as specified in XXX. Once a single impact value is obtained for each asset, the expected value algorithm proceeds as described in XXX. XXX summarizes CanFlood's full expected value algorithm.

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

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

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

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

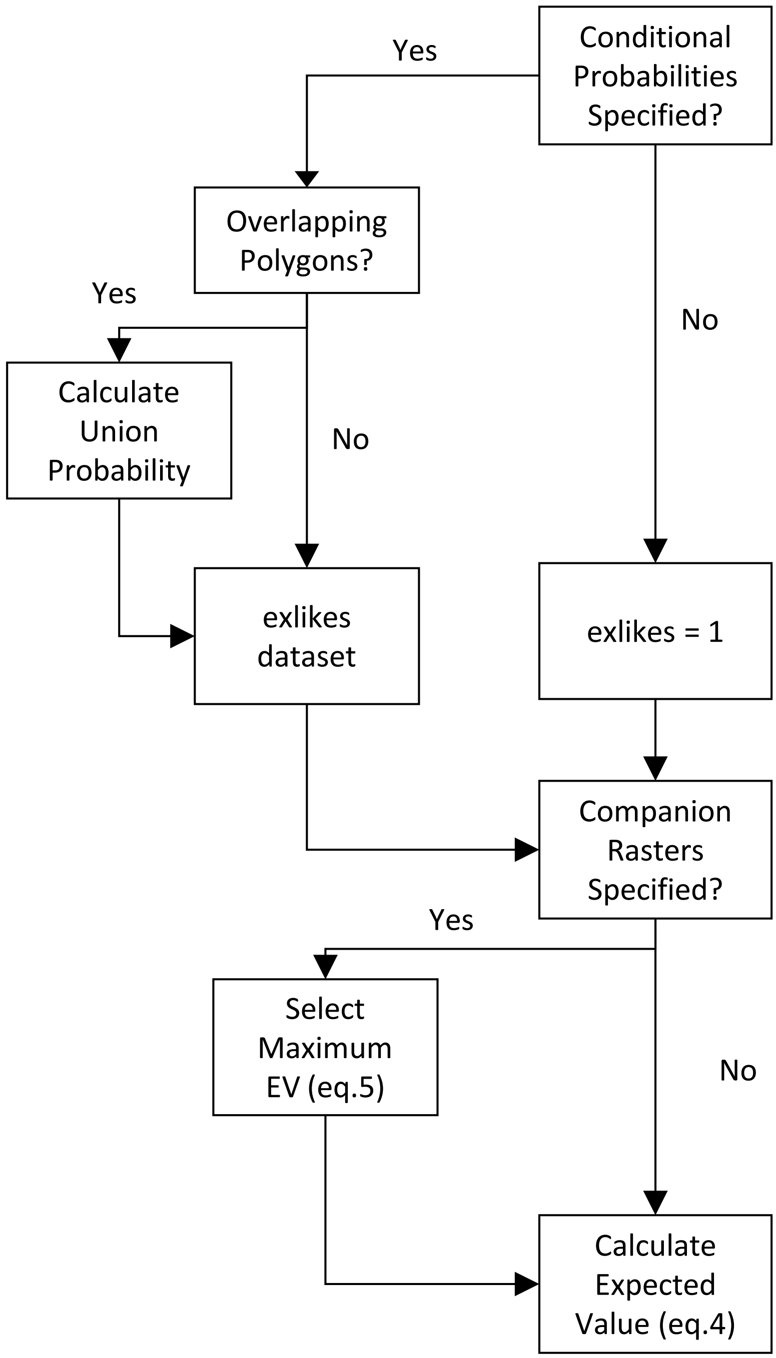


Figure 5: CanFlood's Risk (L1 and L2) tool expected value calculation algorithm

References

Messner, Frank. 2007. “FLOODSite: Evaluating Flood Damages: Guidance and Recommendations on Principles and Methods.” T09-06–01. Helmholz Unweltforschungszentrum (UFZ). http://repository.tudelft.nl/view/hydro/uuid:5602db10-274c-40da-953f-34475ded1755/.

Sayers, Paul B., ed. 2012. *Flood Risk: Planning, Design and Management of Flood Defence Infrastructure*. London: ICE Publishing.

USACE. 1996. “RISK-BASED ANALYSIS FOR FLOOD DAMAGE REDUCTION STUDIES.” EM 1110-2-1619.