Rainfall-Runoff Response Modelling using wflow

Modelling and Analysis of the Effects of Land-Use Changes on Catchment Response

GROUP 2

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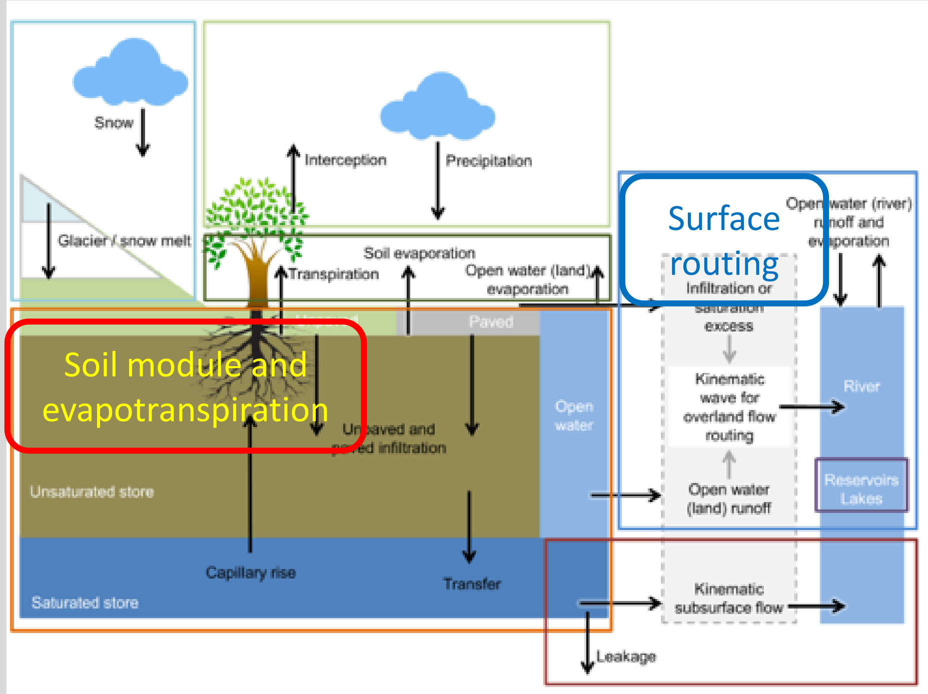
Overview

1. Model Setup
2. Running of the Simulation
3. Analysis of Results
   - Observed Flow vs Old Land Use (2011)
   - Evaluation of Model Performance
   - Old Land Use (2011) vs New Land Use (2023)
   - Analysis of High Intensity Rainfall Events
4. Assumptions & Simplifications
5. Challenges:
   - Difficulties encountered
   - Difficulties we would have encountered if there were no examples provided
6. Conclusion

1. Model Setup: wflow_sbm Model

- Vertical hydrological concept
- The model is run on each grid cell, and the water flows from one grid cell to another through the kinematic wave routine and lateral flow
- Use the kinematic wave approach for channel, overland and lateral subsurface flow, assuming that the topography controls water flow mostly
- Considers the soil as a 'bucket' with a saturated and unsaturated store
- Its simple numerical solution means that results from a daily timestep model may be different from those with an hourly timestep.



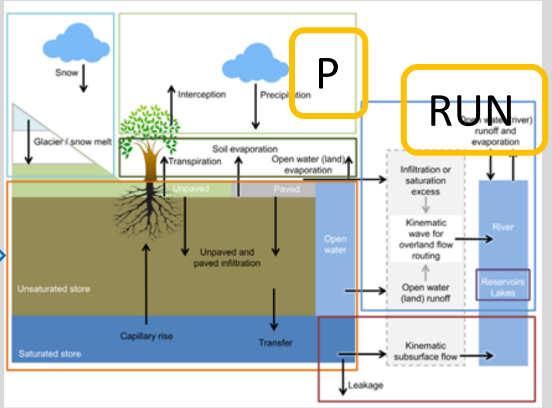
1. Model Setup

➢ Decisions and Required Data

1. The static input maps in *pcraster* format (**DEM ,land-use map, soil map**)
2. Determine the resolution
3. Define multiple **sub-catchments** to report totals/flows for separately
4. Choose forcing data (**P**, Temp, ET)
5. Use gridded forcing data or scalar **time-series;** if time series, edit .ini file,

Only required to provide inputs for this step in this Project

For the modified process, this difference between measured and simulated discharge is added to the unsaturated store for all cells



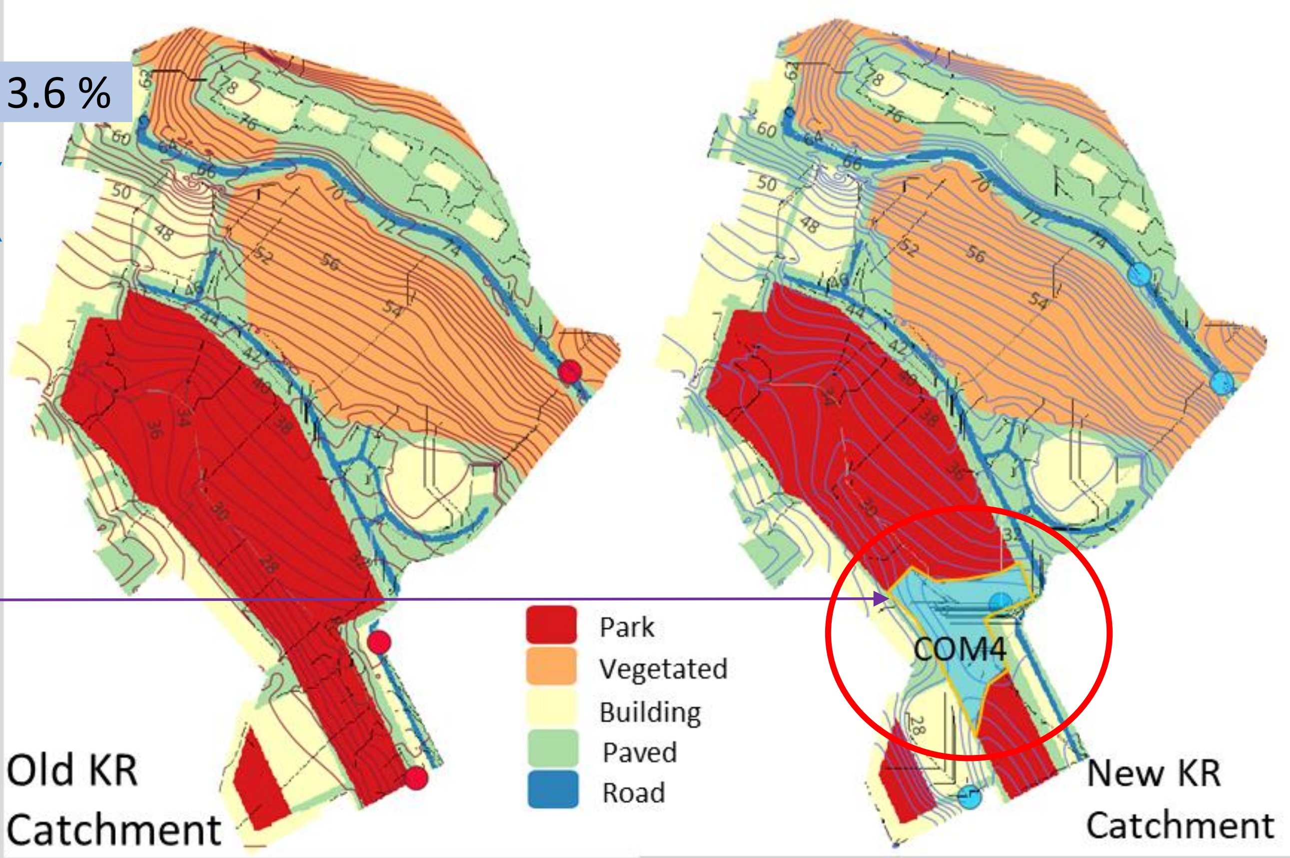
1. Model Setup

- **Changes in landuse.map**

	Old Catchment		New Catchment	
Type	Area(m^2)	(%)	Area(m^2)	(%)
Park	22594	25.10%	19351	21.50%
Vegetated	23731	26.36%	23731	26.36%
Building	17088	18.98%	20332	22.59%
Paved	23275	25.85%	23275	25.85%
Road	3335	3.70%	3335	3.70%
Total Area(m^2)			90023	

3.6 %

- The pervious Park area is altered to the impervious building COM4;
- **Higher runoff** coefficient coverd COM4 area indicates more rainfall will be converted to direct runoff.

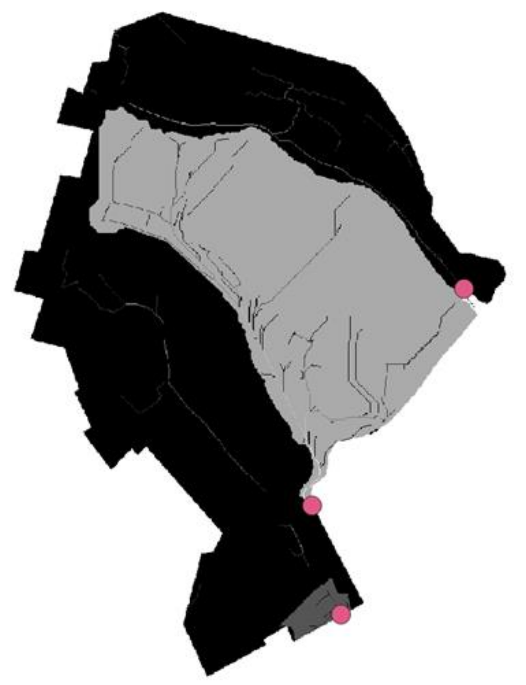


1. Model Setup

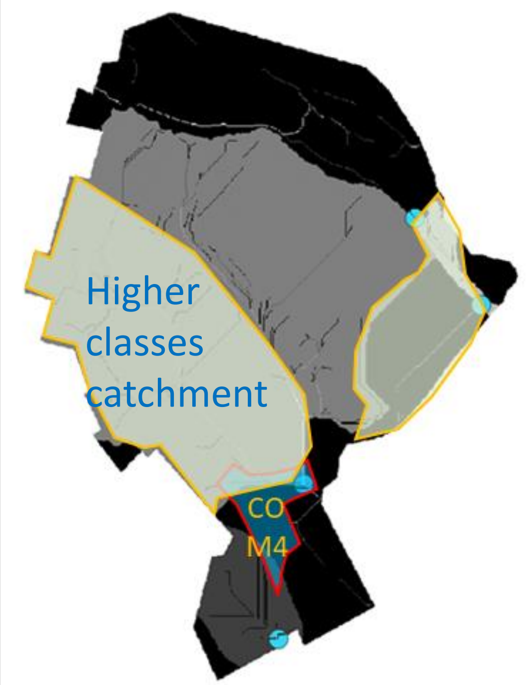
- **Changes in sub-catchment & river**

1. In the new catchment map: an **increase from 3 to 4** sub-catchments and outlets were likely a result of the QGIS scripts.
2. The COM4 DEM affects the model response by the changes of map.

- OLD: KR map with **3 outlets**



- NEW: map with **4 outlets**



No.	Map	Old_catch	New_catch	Note
1	dem	24.5~78.4 m	1.0~78.4 m	More elevation data (COM4 area)
2	river	4~8	4~7	More branched drainage
3	outlet	3	4	The sub-catchment calculations to succeed the **gauges that determine the outlets** must be on a river grid cell.
4	subcatch	0~3	0~4	

2. Running the Simulation

Selection of 3H + 1L Rainfall Events

Selected events based on shape of hydrograph and peak rainfall intensity:

- High1: **1 peak** (3.6 mm/min)
- High2: **2 peaks** – **larger** peak, followed by **smaller** peak (3.8 mm/min)
- High3: **2 peaks** – **smaller** peak, followed by **larger** peak (3 mm/min)
- Low: Intensity < 0.4 mm/min

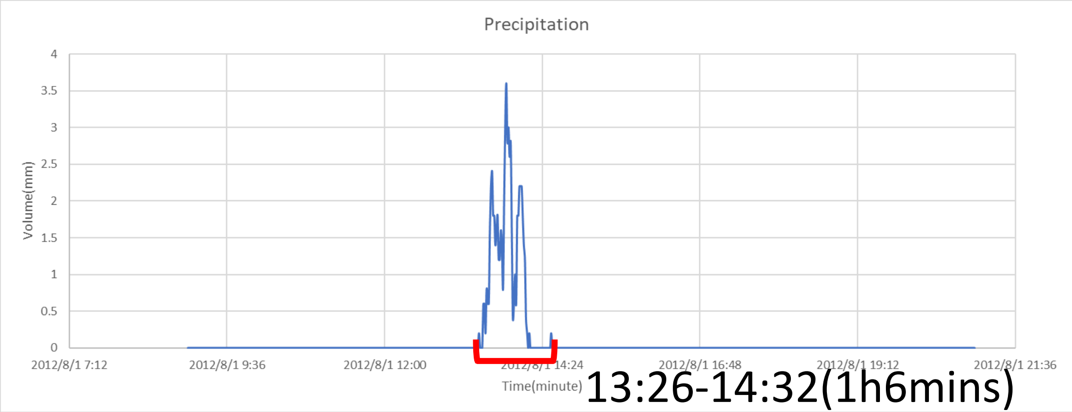
Optimised Simulation Duration

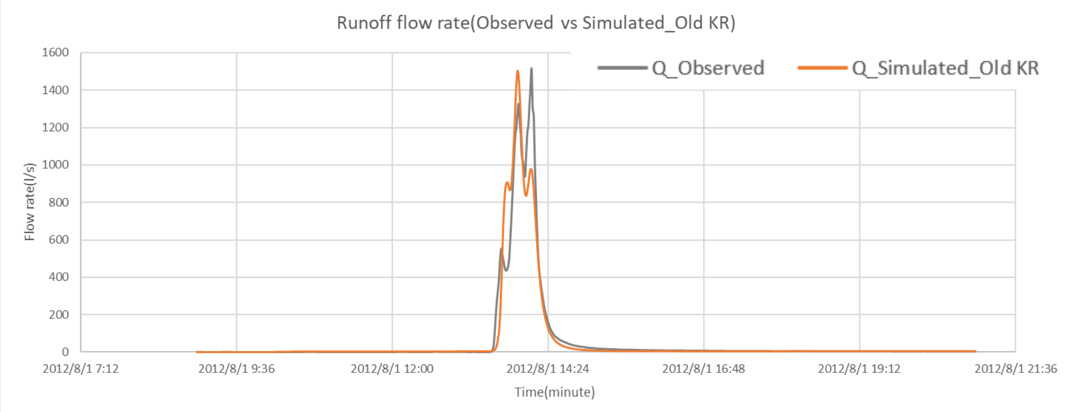
- Spin-up time: 4hrs before rainfall event
- Post-rainfall: 6 hrs after rainfall event

Preparation of Precipitation and Evapotranspiration Input .tss Files → **Run the Model** → **Compare Observed vs Simulated (Old KR)** → **Compare Simulated (Old KR) vs Simulated (New KR)**

3.1 Results: **High Intensity 1** – 1 Aug 2012

- Simulated Duration: 2012/8/1 9:00-20:59





Rainfall characteristics:

- Multiple smaller peaks occurring within short duration
- Relatively short duration

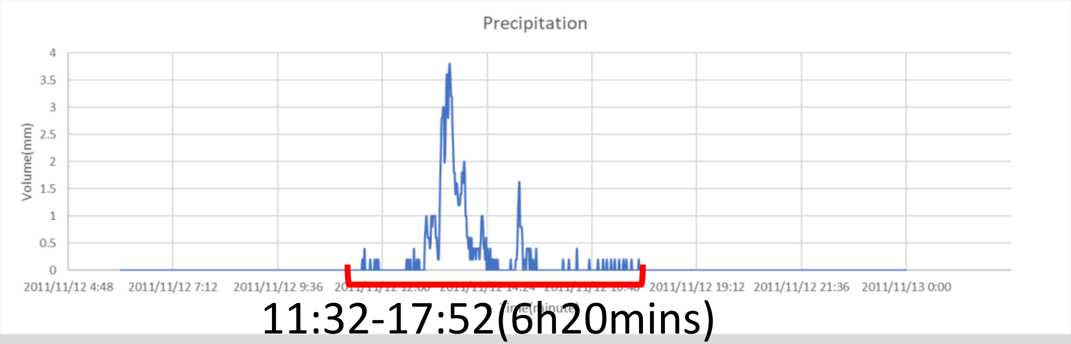
	Q_Observed	Q_Simulated (Old KR)	Difference
Time(Peak 1)	13:57	13:56	+179.624
Max Q	1324.918	1504.542	(13.56%)
Time(Peak2)	14:09	14:08	-533.755
Max Q	1512.671	978.916	(-35.29%)

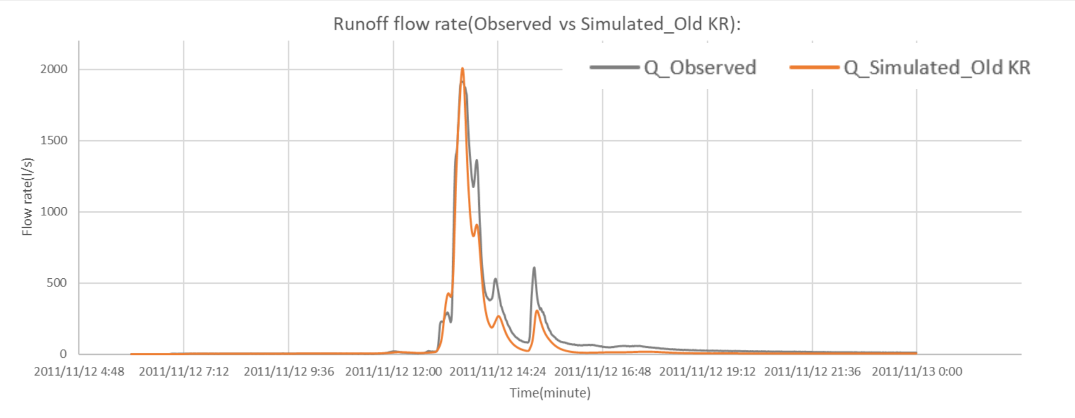
Observed vs Simulated (Old KR):

- Simulated flow is more similar to rainfall pattern as compared to the observed flow rate
- The *second peak flow is not evident* in the simulation results → The model may be insensitive to this rainfall pattern

3.1 Results: High Intensity 2 – 12 Nov 2011

- Simulated Duration: 2011/11/12 6:00-23:59





Rainfall characteristics:

- Very high peak rainfall intensity of 3.8 mm/min
- Very long duration
- A second smaller peak occurs after the first peak rainfall

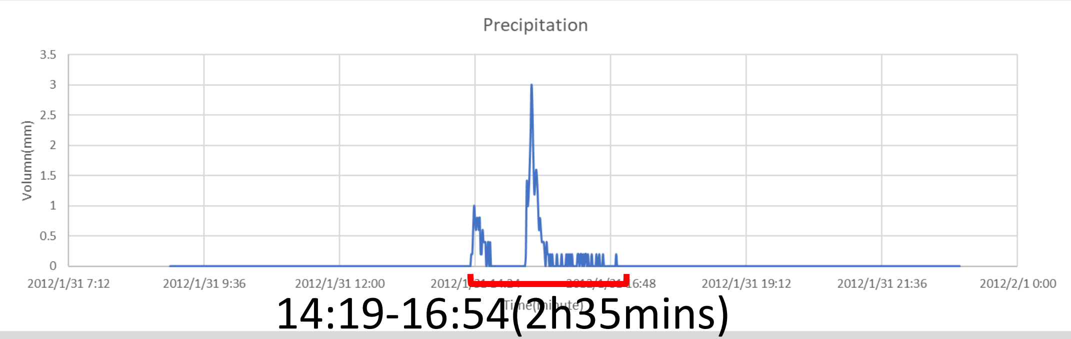
	Q_Observed	Q_Simulated (Old KR)	Difference
Time(peak 1)	13:34	13:35	+91.721
Max Q	1918.164	2009.885	(+4.78%)
Time(peak 1)	15:14	15:18	-305.515
Max Q	610.978	305.464	(-50.00%)

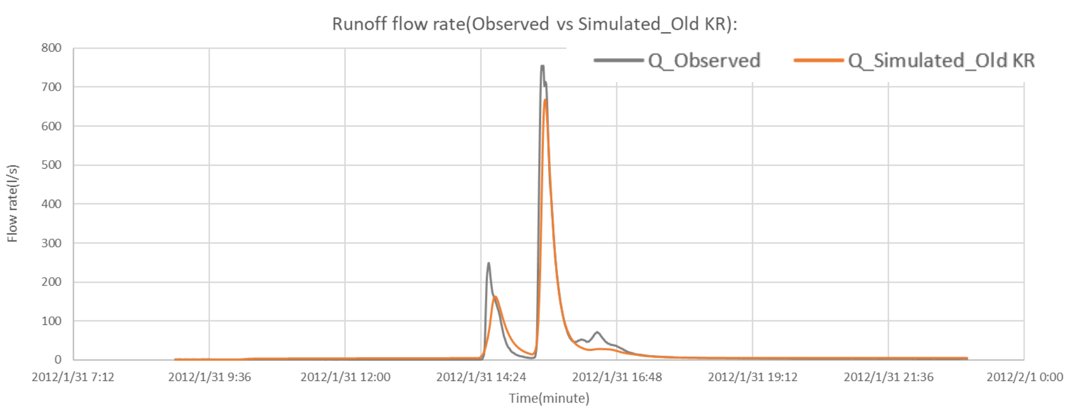
Observed vs Simulated (Old KR):

- Performance well in terms of shape
- Underestimates all subsequent flow peaks after the 1st peak

3.1 Results: High Intensity 3 – 31 Jan 2012

- Simulated Duration:2012/11/31 9:00-22:59





Rainfall characteristics:

- Two rainfall events about 30 min apart
- Continuous low-intensity rainfall after the second rainfall event

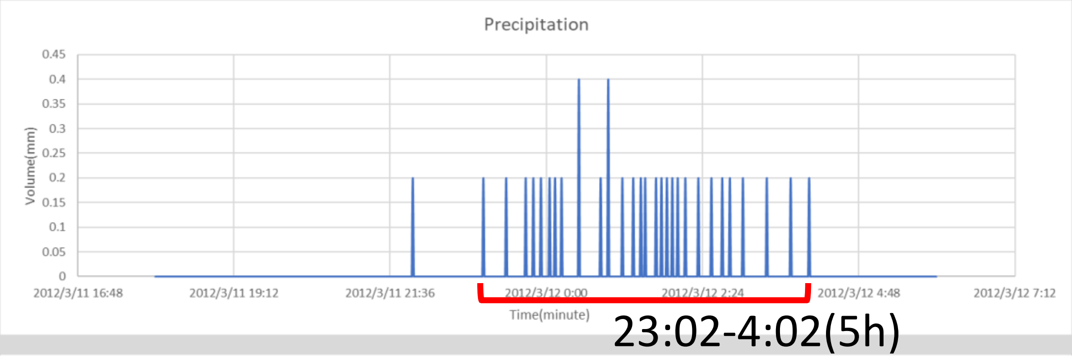
	Q_Observed	Q_Simulated (Old KR)	Difference
Time(Peak1)	14:32	14:39	-86.987
Max Q	249.415	162.428	(-34.88%)
Time(Peak2)	15:28	15:32	-85.509
Max Q	753.361	667.852	(-11.35%)

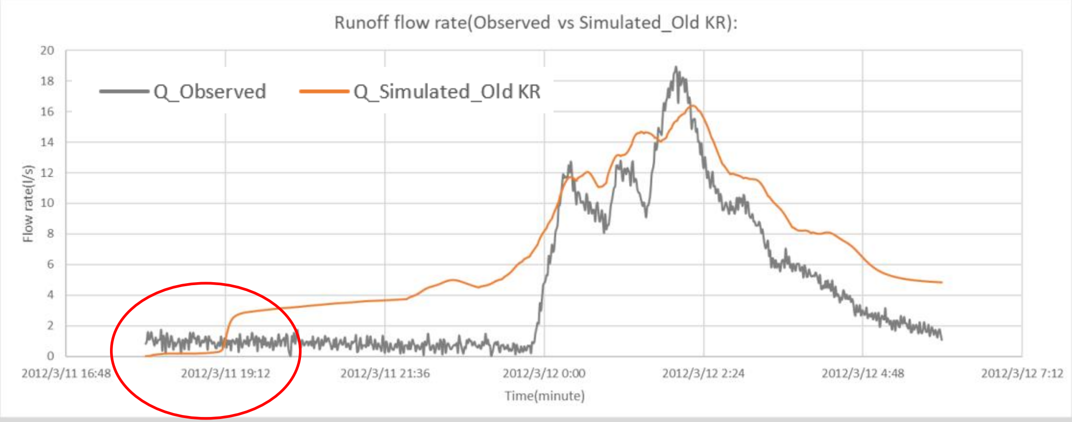
Observed vs Simulated (Old KR):

- Performance well in terms of shape
- Underestimates flow rate almost all the time, unable to model the low-intensity rainfall after the 2nd peak
- Delay of the peak time

3.1 Results: Low Intensity – 11 Mar 2012

- Simulated Duration: 2012/03/11 18:00-12 5:59





Rainfall characteristics:

- Continuous low intensity rainfall
- Long duration

	Q_Observed	Q_Simulated (Old KR)	Difference
Time	13:59	14:14	-2.555
Max Q	18.925	16.370	(-13.50%)

Observed vs Simulated (Old KR):

- Poor performance in terms of shape
- Sudden elevated values in the simulation flow
- Smoothened overall curve
- Overestimates the flow rate before the start of the rainfall event
- Underestimates the peak flow

3.2 Performance Evaluation of Model

1. Correlation Coefficient (r)

$$r = \mathrm{Cor}(Q_{\mathrm{mod}}, Q_{\mathrm{obs}}) = \frac{\mathrm{cov}(Q_{\mathrm{mod}}, Q_{\mathrm{obs}})}{\sigma_{\mathrm{mod}} \cdot \sigma_{\mathrm{obs}}},$$

- Measures the **strength** and **direction of linear relationship** between modelled flow Q_{mod} and observed flow Q_{obs}.

2. Nash-Sutcliffe Efficiency (NSE)

$$\mathrm{NSE} = 1 - \frac{\sum_{t=0}^{n}\left(Q_{\mathrm{obs}}^{t} - Q_{\mathrm{mod}}^{t}\right)^2}{\sum_{t=0}^{n}\left(Q_{\mathrm{obs}}^{t} - \overline{Q}_{\mathrm{obs}}^{t}\right)^2},$$

- Measures how well the model output reproduces the observation outputs **in comparison** with a **model that only uses the mean of the observed data**.

3. Coefficient of Regression (β)

$$\beta = \frac{\mathrm{cov}(Q_{\mathrm{mod}}, Q_{\mathrm{obs}})}{\mathrm{var}(Q_{\mathrm{obs}})},$$

- Distinguishes whether the model **overestimates/underestimates** the observed flow

4. Peak Flow Relative Error (δr)

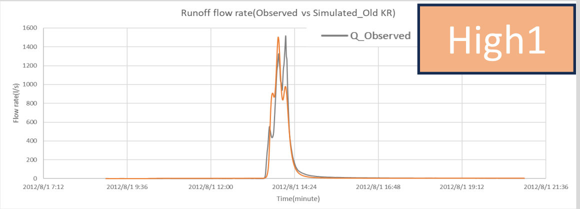
$$\delta r = \frac{Q_{\mathrm{mod}}^{\mathrm{max}} - Q_{\mathrm{obs}}^{\mathrm{max}}}{Q_{\mathrm{obs}}^{\mathrm{max}}},$$

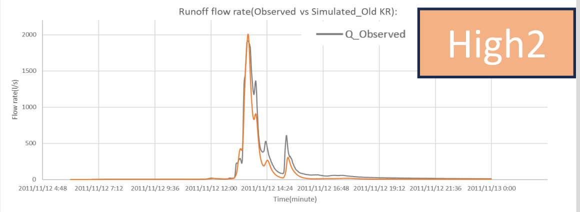
- Used to assess changes in the modelled peak flow rate.

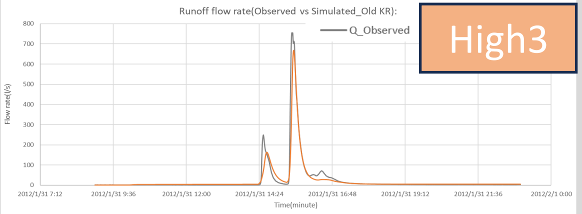
Source: Ichiba et al., 2018
https://doi.org/10.5194/hess-22-331-2018

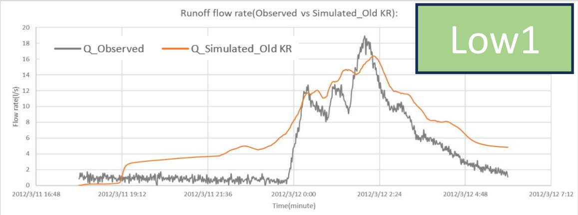
3.2 Performance Evaluation of Model

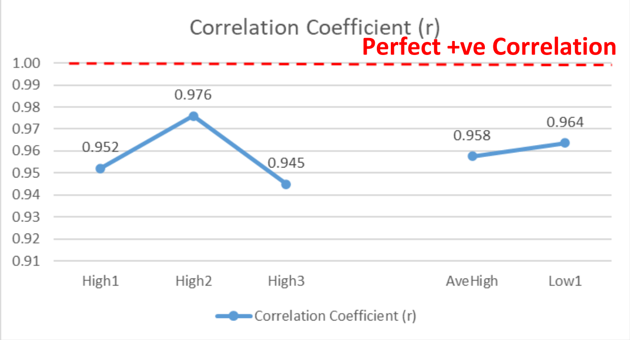
- **Model performs well**, with a **higher model performance** for high rainfall intensity (RI) events, as compared to the low rainfall intensity event.
- **Strong linear correlation, above r=0.95 for all events (strong = r>0.8)** between modelled and observed flow for all precipitation events.
- Model using High RI Events were found to perform **relatively well**.
    - ➢ High RI Event (NSE = 0.901) reproduces the observation outputs relative to a model using the mean of the observation data better than that of Low RI Event (NSE = 0.583).

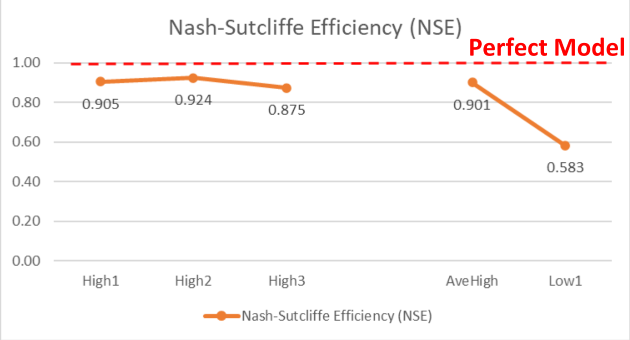






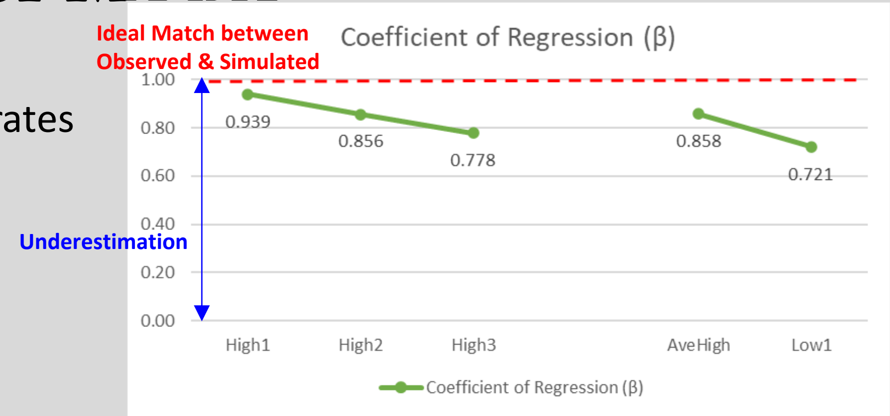




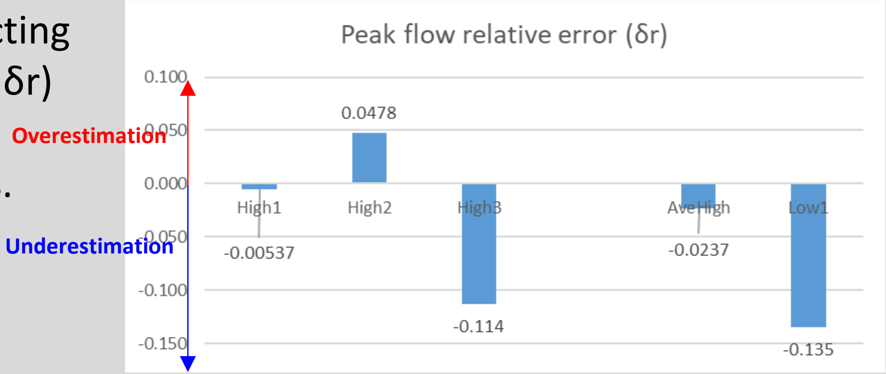


3.2 Performance Evaluation of Model

- **Underestimation** (**β<1**) of the observed flow by the model, for all events. High RI Events (β = 0.858) generates an output that is closer to the observed flow, as compared to when Low RI Event (β = 0.721) is used.

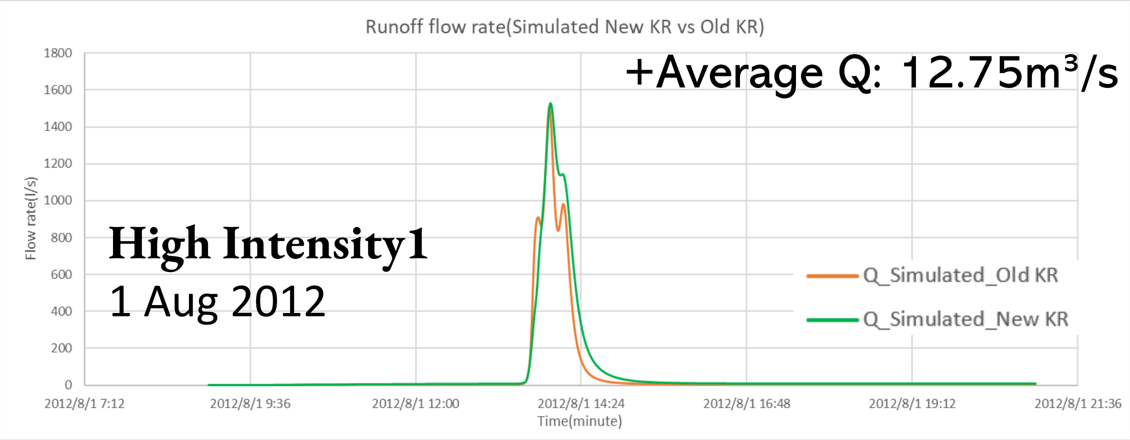


- Model seemed to be **inconsistent** in accurately predicting the peak flow. Magnitude of peak flow relative error (δr) for High RI events varied greatly: ranges from small errors, overestimation, and underestimation of errors.



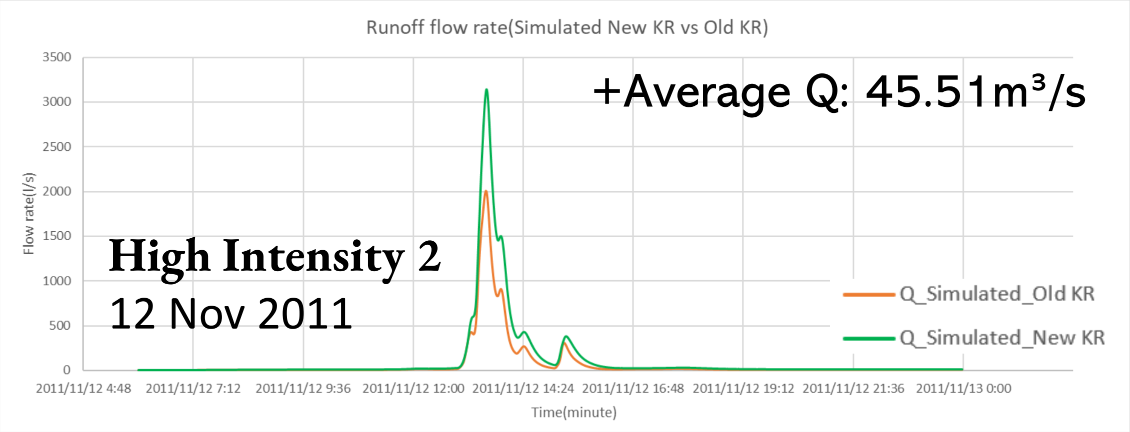
	High1	High2	High3	High Average	Low1
	1-Aug-12	12-Nov-11	31-Jan-12		11-Mar-12
Correlation Coefficient (r)	0.952	0.976	0.945	0.958	0.964
Nash-Sutcliffe Efficiency (NSE)	0.905	0.924	0.875	0.901	0.583
Coefficient of Regression (β)	0.939	0.856	0.778	0.858	0.721
Peak Flow Relative Error (δr)	-0.00537	0.0478	-0.114	-0.0237	-0.135

3.3 Results: Simulated Old KR vs New KR



	Q_Simulated (Old KR)	Q_Simulated (New KR)	Difference
Time(Peak 1)	13:56	13:57	+22.525
Max Q	1504.542	1527.067	(1.50%)
Time(Peak2)	14:08	14:08	+164.335
Max Q	978.916	1143.251	(16.79%)

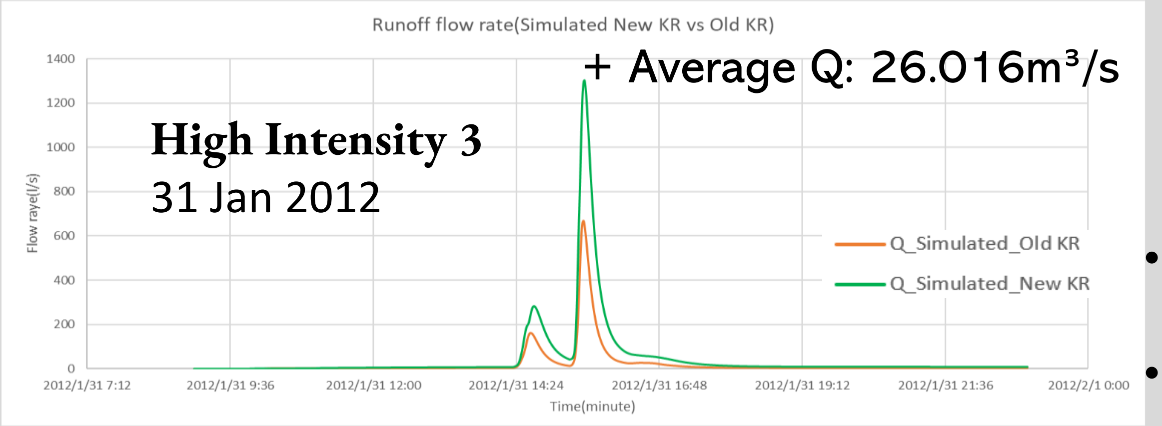
- 1st Peak flow increased slightly by 1.5%
- Flow decreases slowly, thus the second peak not as distinct

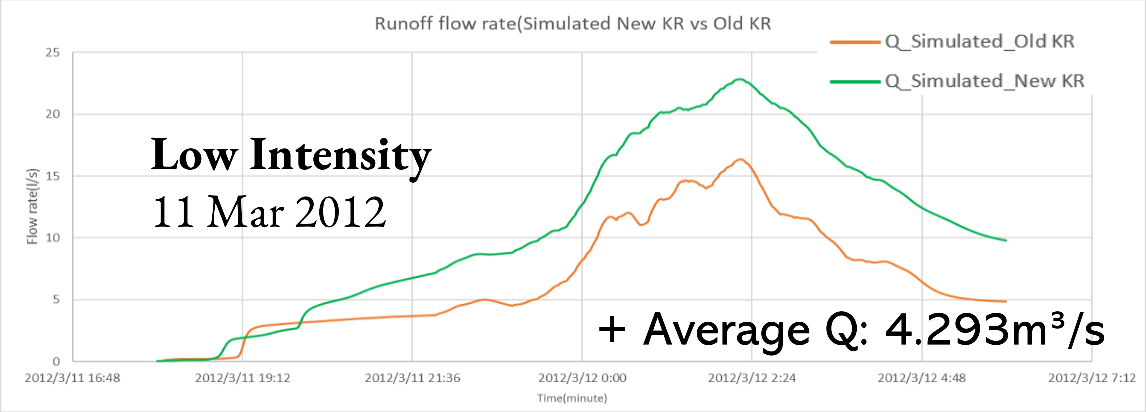


	Q_Simulated (Old KR)	Q_Simulated (New KR)	Difference
Time(peak 1)	13:35	13:36	+1131.320
Max Q	2009.885	3141.204	(56.29%)
Time(peak 2)	15:18	15:20	+74.174
Max Q	305.464	379.638	(24.28%)

- Significant increase (+56.29%, +24.28%) in 1st and 2nd peak flow rate
- Both graphs generally have a similar shape

3.3 Results: Simulated Old KR vs New KR





	Q_Simulated (Old KR)	Q_Simulated (New KR)	Difference
Time(Peak1)	14:39	14:42	+120.937
Max Q	162.428	283.365	(74.46%)
Time(Peak2)	15:32	15:33	+634.940
Max Q	667.852	1302.791	(95.07%)

- Significant increase (+74.46%, +95.1%) in 1st and 2nd peak flow rate
- Both graphs generally have a similar shape

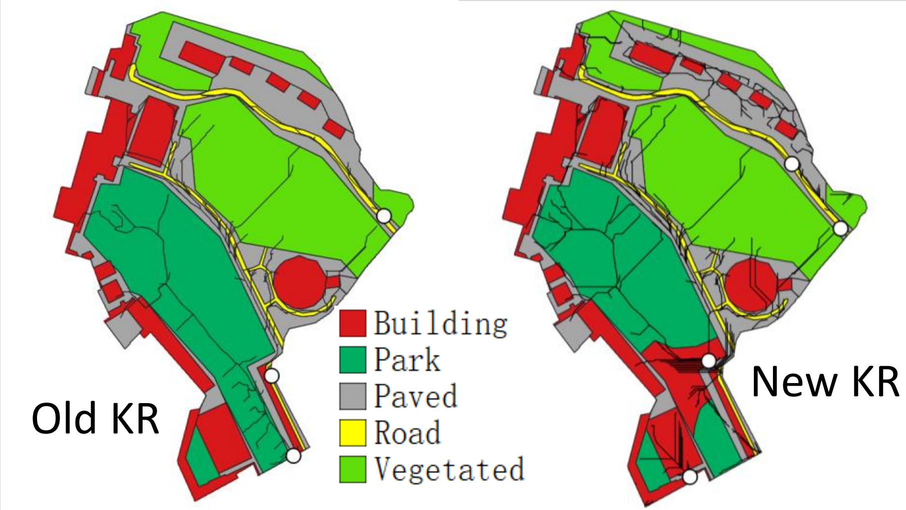
	Q_Simulated (Old KR)	Q_Simulated (New KR)	Difference
Time	14:14	14:14	+6.468
Max Q	16.370	22.838	(39.51%)

- Flow started to increase earlier compared to 'Old KR'
- Increase in overall runoff flow rate, increase in peak flow rate by 39.5%

3.3 Results: Summary

Overall:

- Small difference in the timing of peaks
- Smoothing of simulation curve
- Model tends to follow precipitation peaks. But observed flow may have other factors affecting it. → Not always have the same trend.



Observed vs Simulated (Old KR):

- *Underestimation* of peak flow rate in old KR
- Model response at the beginning of the flow is *delayed* from the observed flow in high-intensity rainfall events
- After the peak, the simulation curve declines faster in the runoff flow rate
- Model typically underestimates the subsequent peaks, after the initial 1st peak.

Simulated Old KR vs New KR：

- Their hydrograph have a similar shape, but typically a higher peak flow is generated by the 'New KR' model
- Due to increased impervious surfaces (i.e. COM4), higher volume of runoff generated, hence require longer time to drain out of the catchment

3.4 Assessment of High Intensity Rainfall Events

With reference to Clause 7.1.3 in the COP, for a catchment of 8.5ha size, the COP specified a **10-year return period**. Before establishing the storm hyetograph, the time of concentration (T_c) is calculated based on the rational method, using the tabulated parameters from the table listed.

Parameter/Period	12-Nov-11	31-Jan-12	1-Aug-12
Total vol of rainfall (m)	0.064	0.025	0.109
Total duration of storm(hr)	0.767	0.333	1.400
Rainfall Intensity (m/h)	0.083	0.075	0.078
Tc (min)	23.9	24.9	24.5

$$T_c = \left(\frac{L}{\alpha * (I_e)^{m-1}}\right)^{\frac{1}{m}}$$

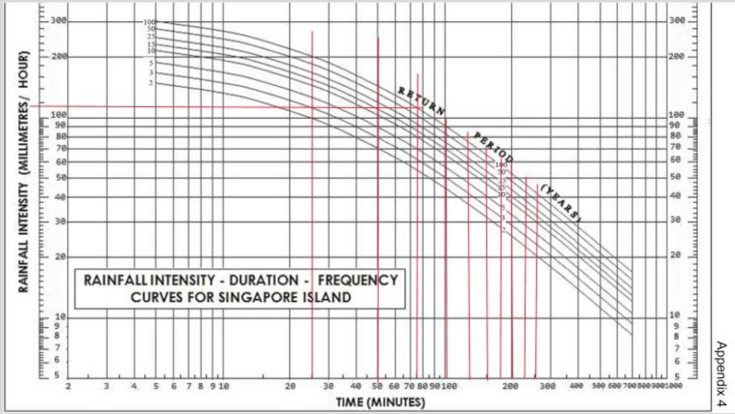
$$\alpha = \frac{(1.49 * S^{\frac{1}{2}})}{n}$$

$$I_e = Rainfall\ intensity * C$$

m = 1.67

Where:
T_c – Time of concentration (h)
L – Length of overland sheet flow (m)
I_e – Rainfall excess (mm/h) →(m/h)
S – Average catchment slope (m/m)
n – Mannings' roughness coefficient for surface = 0.02
C – Weighted Runoff coefficient

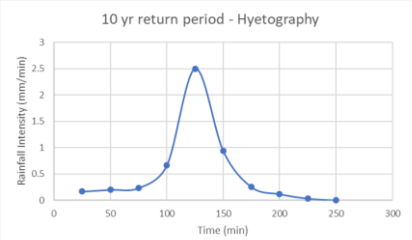
To compute the rainfall hyetograph(10-yr, 100-yr) from IDF curves, following was carried out:

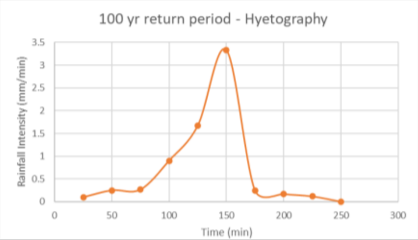


1. Obtain time intervals corresponding to the **Time of Concentration** (Tc), computed to be 25 mins.

2. **Obtain the intensity values,** tracing the 10-year curve at intervals of 25 mins.

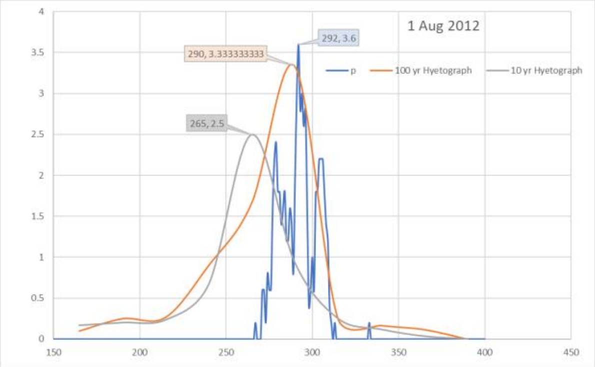
3. With the values, shift the **peak inwards and rearrange the values** to plot the storm hyetograph.

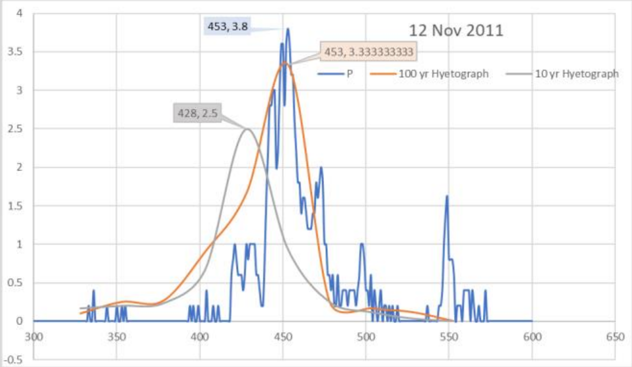


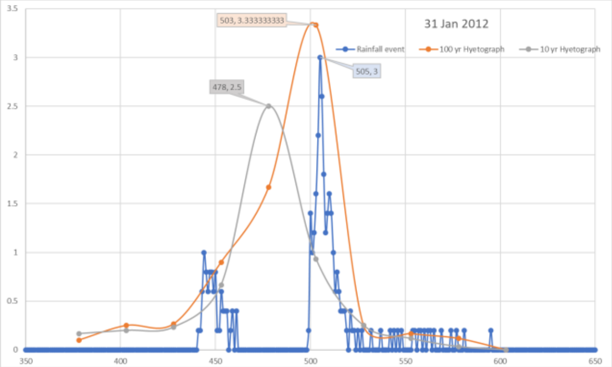


3.4 Assessment of High Intensity Rainfall Events

With the rainfall hyetograph, precipitation was plotted against each of the high intensity events for comparison.







	1 Aug 2012	12 Nov 2011	31 Jan 2012
Peak rainfall Intensity (P_{event})	P_1 = 3.6mm/min	P_2 = 3.8mm/min	P_3 = 3mm/min
$P_{event} > P_{10}$	✓	✓	✓
$P_{event} > P_{100}$	✓	✓	✗

3.4 Assessment of High Intensity Rainfall Events

Method 1: Rational method to find Q

- The discharge, Q, is calculated using the rational formula for the 10-year return period (RP) and 100-year RP storm event.
- Plot the observed discharge (Q_obs), 10-year RP storm discharge (10-yr Q) and 100-year RP storm discharge (100-yr Q) on the same graph for comparison.

$$Q_r = \frac{1}{360} CIA$$

where Q_r = peak runoff at the point of design (m^3/s)

C = runoff coefficient

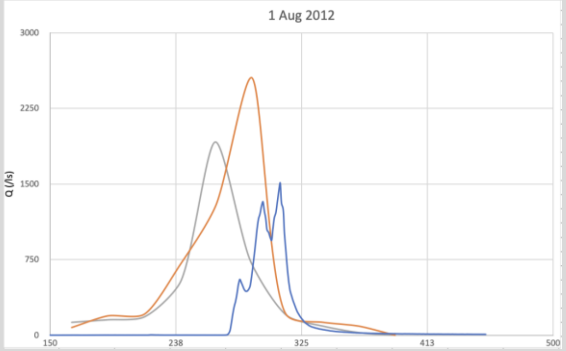
I = average rainfall intensity (mm/hr)

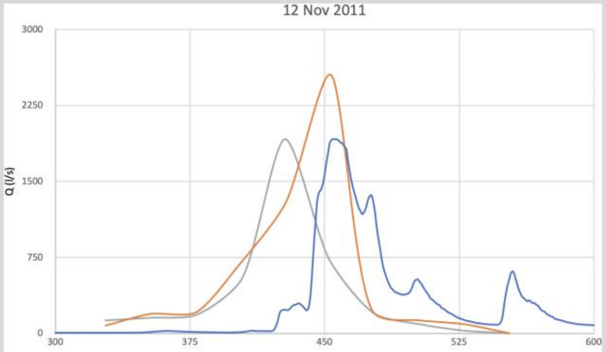
A = catchment area (hectares)

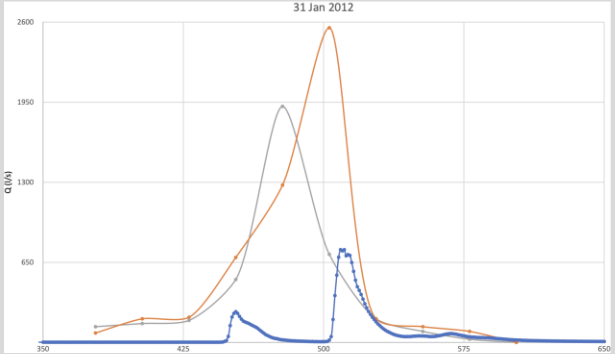
Source: PUB Code of Practice

3.4 Assessment of High Intensity Rainfall Events

Method 1: Rational method to find Q







High Intensity 1

Precipitation (on slide 19):

- High Intensity 1's peak precipitation intensity was greater than that of a 10-yr RP storm.

Discharge:

- However, the observed peak Q was **slightly lower** than the calculated 10-yr RP storm Q.

High Intensity 2

Precipitation (on slide 19):

- High Intensity 2's peak precipitation intensity was greater than that of a 100-yr RP storm

Discharge:

- However, the observed peak Q was only **equivalent** to the calculated 10-yr RP storm Q.

High Intensity 3

Precipitation (on slide 19):

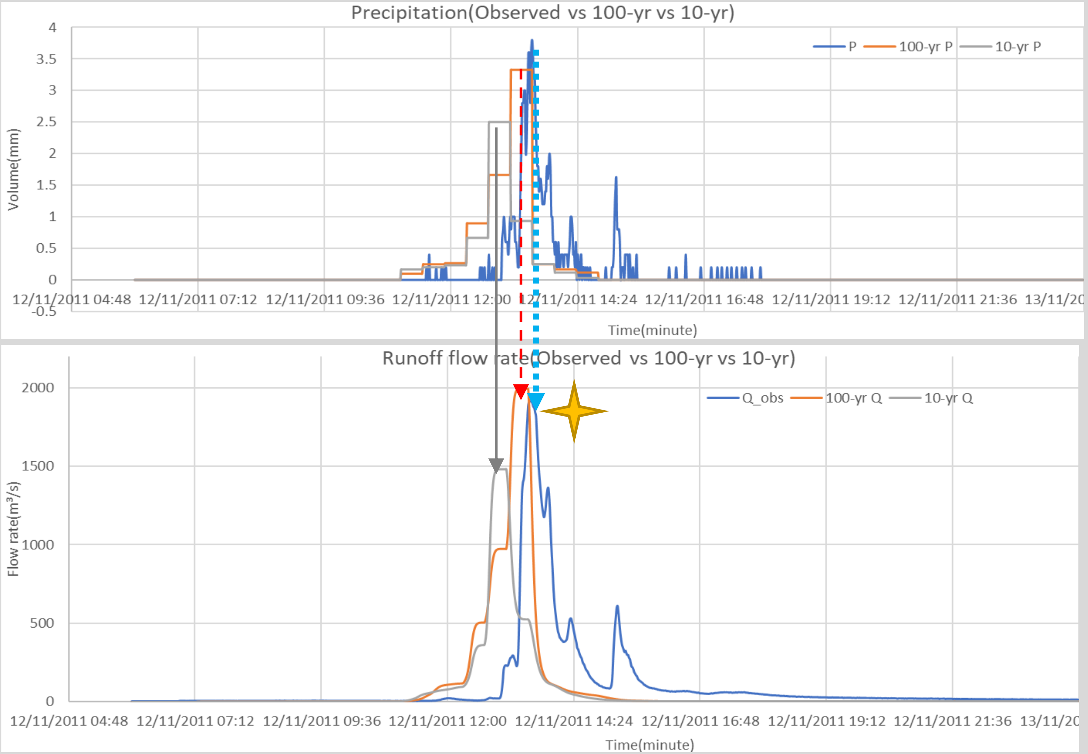
- High Intensity 3's peak precipitation intensity was greater than that of a 100-yr RP storm

Discharge:

- However, the observed peak Q was **significantly lower than** that of both 10-yr and 100-yr RP storm Q.

→ The difference in observations are likely due to the **selection of the runoff coefficient, C** and the s**teep slope of KR catchment** that the rational method is unlikely able to cater for. Hence, the rational method of calculation tends to underestimates the runoff from the old KR catchment.

3.4 Assessment of High Intensity Rainfall Events



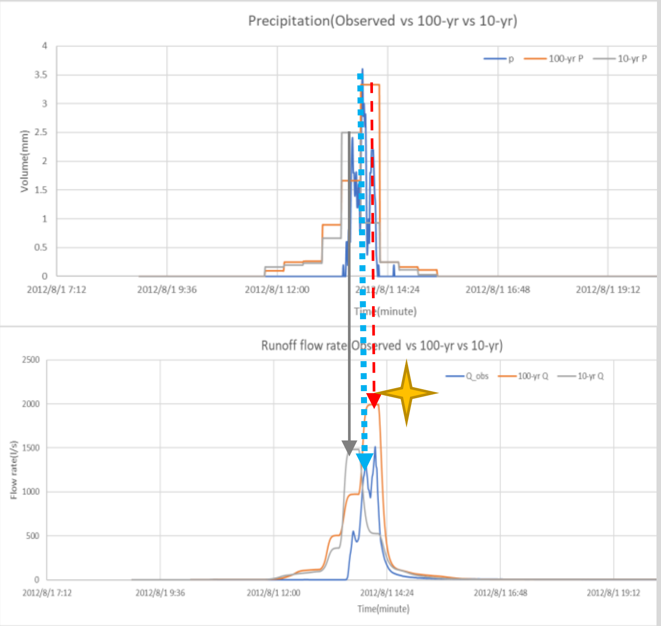
➢**High 2**: Continuous rainfall followed by a lower-intensity rainfall

Method 2: Running wflow to find Q

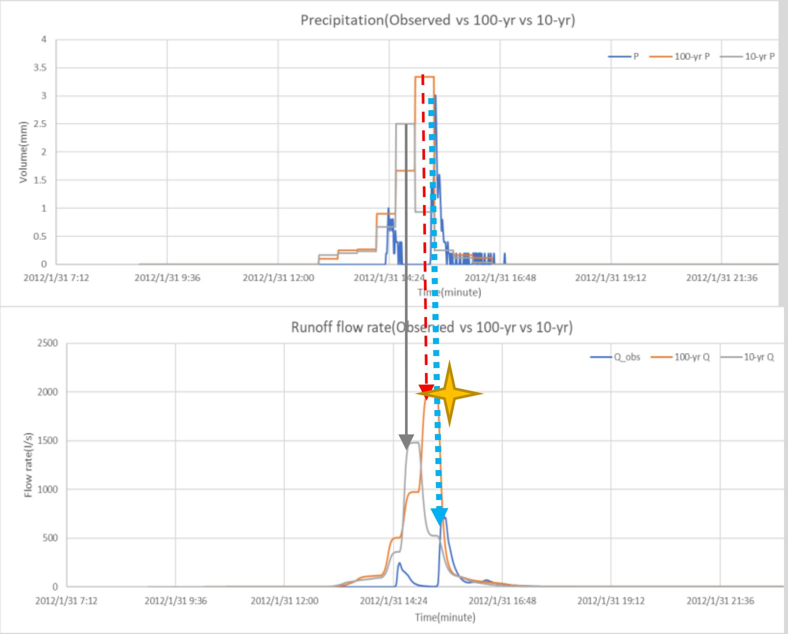
- Comparing the P_{e2}, P_{10} and P_{100} peak rainfall intensities, it is noted that P_{e2} has a higher peak rainfall intensity than both the expected P_{10} and P_{100}
- Although with a higher peak rainfall intensity, the resulting wflow simulated discharge flow rate for P_{e2} turned out to be about 30% higher than P_{10} and only slightly lower than that for P_{100}. It seems to suggest that the current design capacity of 10-yr return period may not be adequate to handle such high intensity rainfall.

3.4 Assessment of High Intensity Rainfall Events

- For Q_1, the observed peak discharge is comparable to the computed Q_{10} and about 30% lower than that for Q_{100}.
- For Q_3, the observed peak discharge is significantly lower than the computed Q_{10} and Q_{100} although the rainfall intensity is comparable. It is likely that the staggered rainfall (time gap between rainfall peaks) may have attributed to the lower than expected discharge



➢**High 1**: Continuous rainfall within a short duration.



➢ **High 3**: Staggered rainfall event(30mins apart)

4. Assumptions & Simplifications of Model

1. Soil infiltration capacity is set as constant which may not be representative of the actual ground conditions in time.

2. The wflow_sbm concept uses the kinematic wave approach for channel, overland and lateral subsurface flow, assuming that the topography controls water flow mostly. This assumption holds for steep terrain, but in less steep terrain the hydraulic gradient is likely not equal to the surface slope (subsurface flow).

3. Saturated and Unsaturated store of soil: may consider the shallow lateral subsurface flow, but not be appropriate for simulating deep groundwater.

5.1 Challenges Faced

❑ Calibration Challenges

1. How to reduce the spin-up time (hence, simulation time) and yet ensure that the spin-up effects does not spill over to the simulated results?

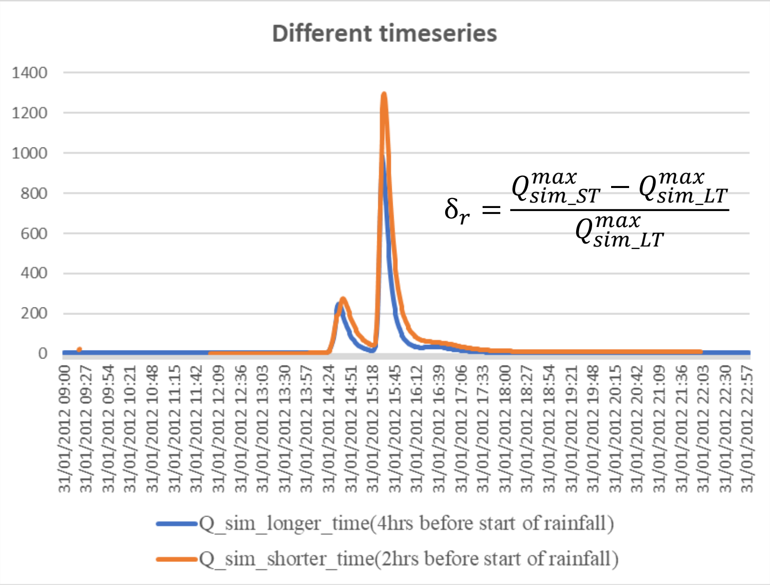
▪ **Used trial and error** to find the optimal simulation time before the start of the rainfall

2. Difficulties in identifying high intensity rainfall events, due to overwhelming large amount of data.

▪ Overcame this using different data visualisation tools such as **Tableau**.

3. Unsure on the definition of the start and end of a rainfall event.

▪ Overcame this when realising that a long spin-up time and 'time after the rainfall' is required, and therefore the precise duration of the rainfall event is not crucial for this exercise



Peak Q	Old_map	New_map
Longer Time	667.85	982.46
Shorter Time	980.67	1299.09
Peak flow relative error δr	47%	32%

- When a shorter simulation time in high intensity events is used, the peak discharge increases compared with the longer simulation time, and δr is more than 30%, indicating that the length of timeseries obviously affects simulation.
- However, the longer simulation time had generated peak flow that is a closer approximation to observed flow. Delay of peak occurs when shorter spin-up time is prescribed.

5.2 Difficulties Faced if No Examples were Provided

- **Folder Navigation:** Navigating the folders to understand the location of the input and output files.

- **Result Uncertainty:** Uncertainties to whether wflow was providing the correct discharge response to the rainfall events.

- **Modelling from Scratch:** Building model from scratch would be very time consuming and challenging, as it would require understanding the intricacies of the model within a short period of time.

- **Error and Debugging:** Having the examples meant that it was easier to debug when and error message came up, since there were fewer variables to change.

6. Conclusion

- wflow model should be used with **consideration** of the **intensity** of the rainfall event
  - e.g. Knowing that it may perform more poorly in low-intensity events than high-intensity; a larger uncertainty should be used.
- The **change in land use** can affect the runoff flow rate directly, it requires us to consider more in planning and reviewing the drainage system should there be any changes in the land use.
- Although the COP required design for 10-year period for catchment of less than 100 ha, as **extreme rainfall events increase in frequency**, it may be worthwhile to consider **innovative, smart infrastructure** to increase our flood resilience.

Thank You!