Author Response – EGU Sphere – 2022-617

Developing a Bayesian network model for understanding river catchment resilience under future change scenarios

Kerr J. Adams, Christopher (Kit) A. J. Macleod, Marc J. Metzger, Nicola Melville, Rachel C. Helliwell, Jim Pritchard, Miriam Glendell

Referee Comments #2

Dear Dr Ibrahim Alameddine,

Where appropriate we have referenced material in our response to referee comments below, we make reference the specific comment for clarity. Table and figure numbers correlate to numbers provided in our responding comment posted on the discussion page on the 5th of April 2023.

Comments

3) How did you ensure that when you were eliciting the model from the stakeholders that you did not end up with cyclical pathways?

Figure 1: Bayesian Network model section headings

7) The authors need to explain more their adopted methodology that they used to model LULC change over time. Was the change over time assumed to be linear? Did they track the change as a function of what the original LULC class was?

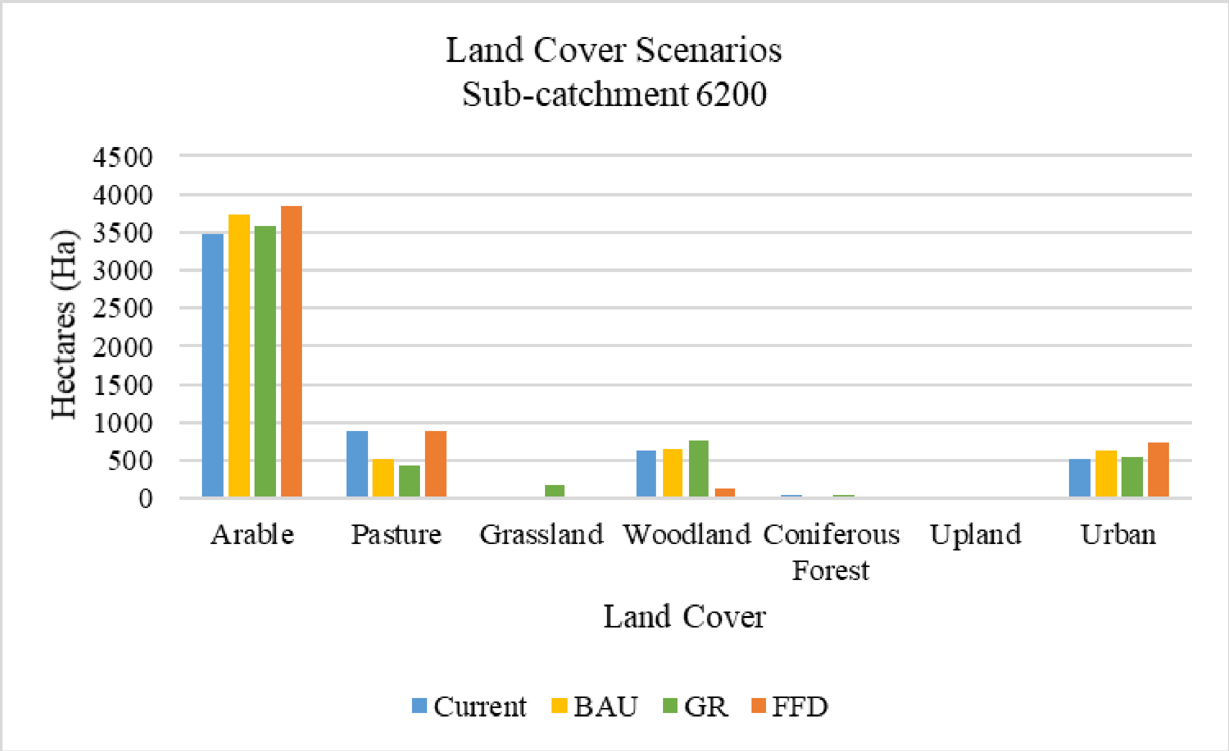


Figure 2: Land cover type hectare (Ha) differences in waterbody sub-catchment 6200 for Business as Usual (BAU), Green Road (GR) and Fossil Fuelled Development (FFD) scenarios

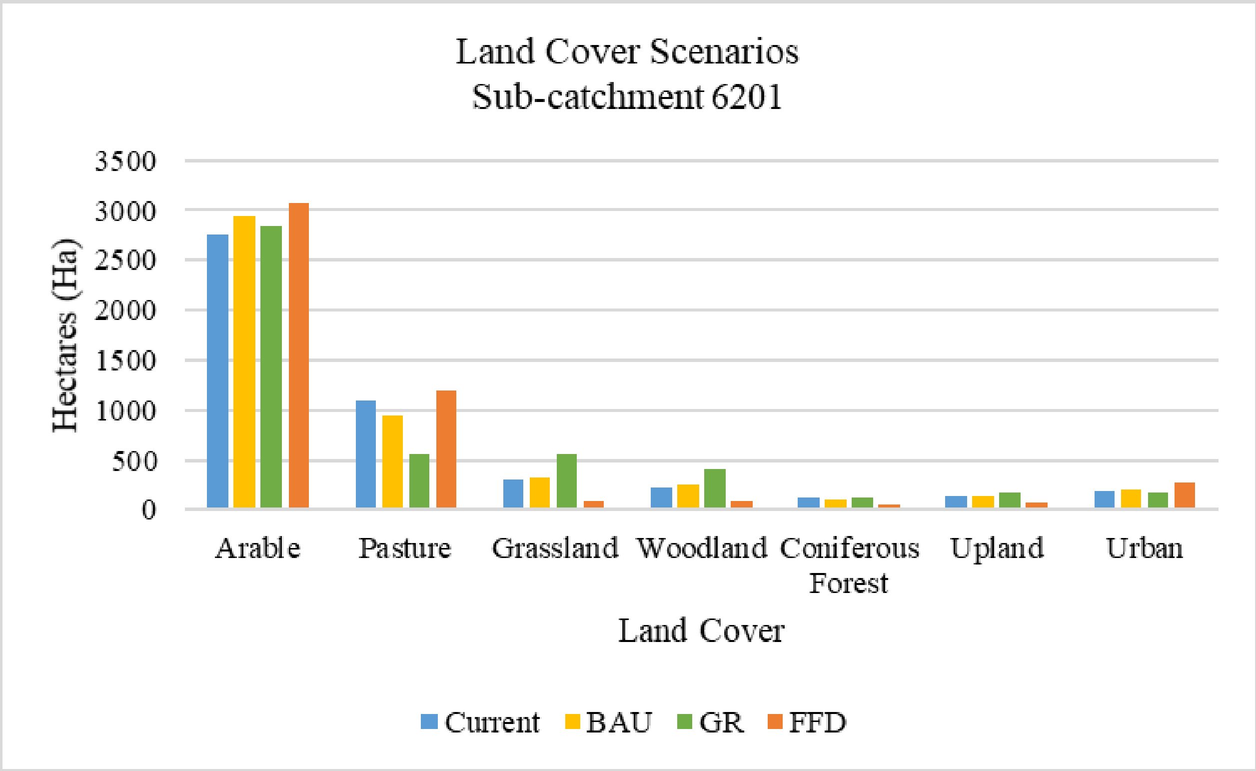


Figure 3: Land cover type hectare (Ha) differences in waterbody sub-catchment 6201 for Business as Usual (BAU), Green Road (GR) and Fossil Fuelled Development (FFD) scenarios

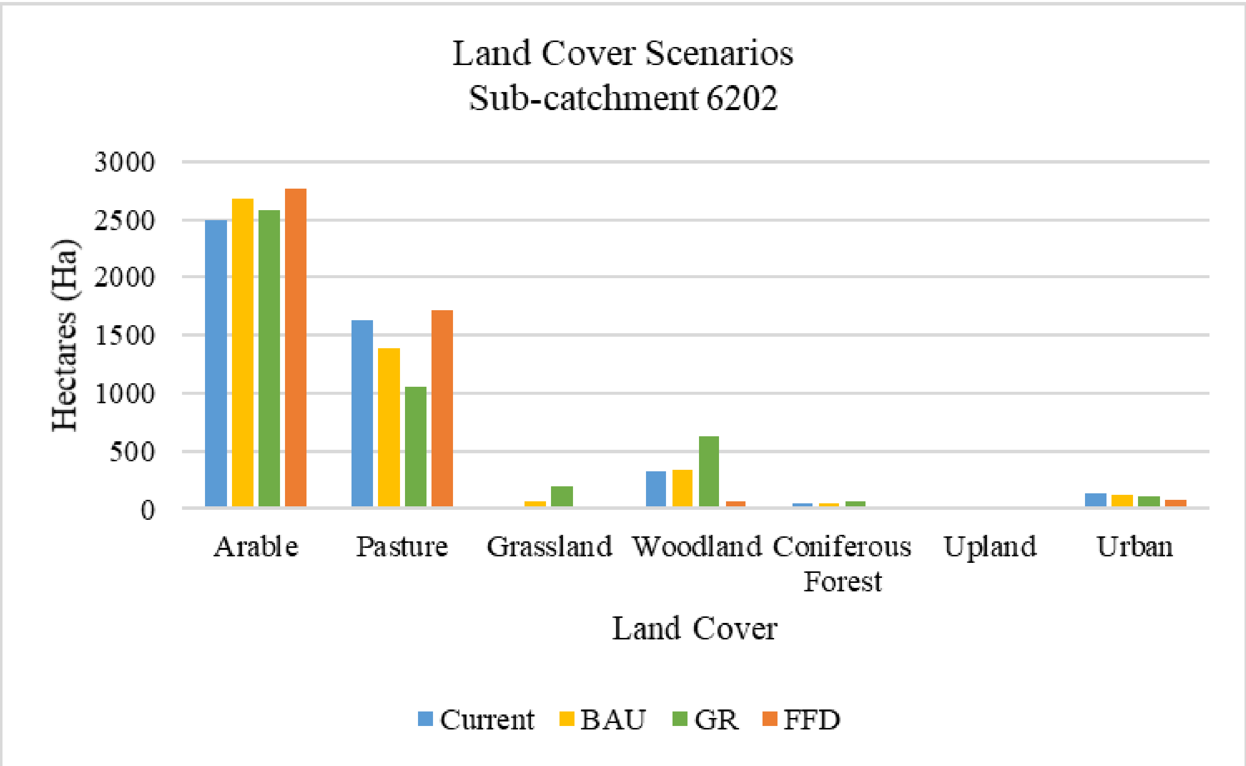


Figure 4: Land cover type hectare (Ha) differences in waterbody sub-catchment 6202 for Business as Usual (BAU), Green Road (GR) and Fossil Fuelled Development (FFD) scenarios

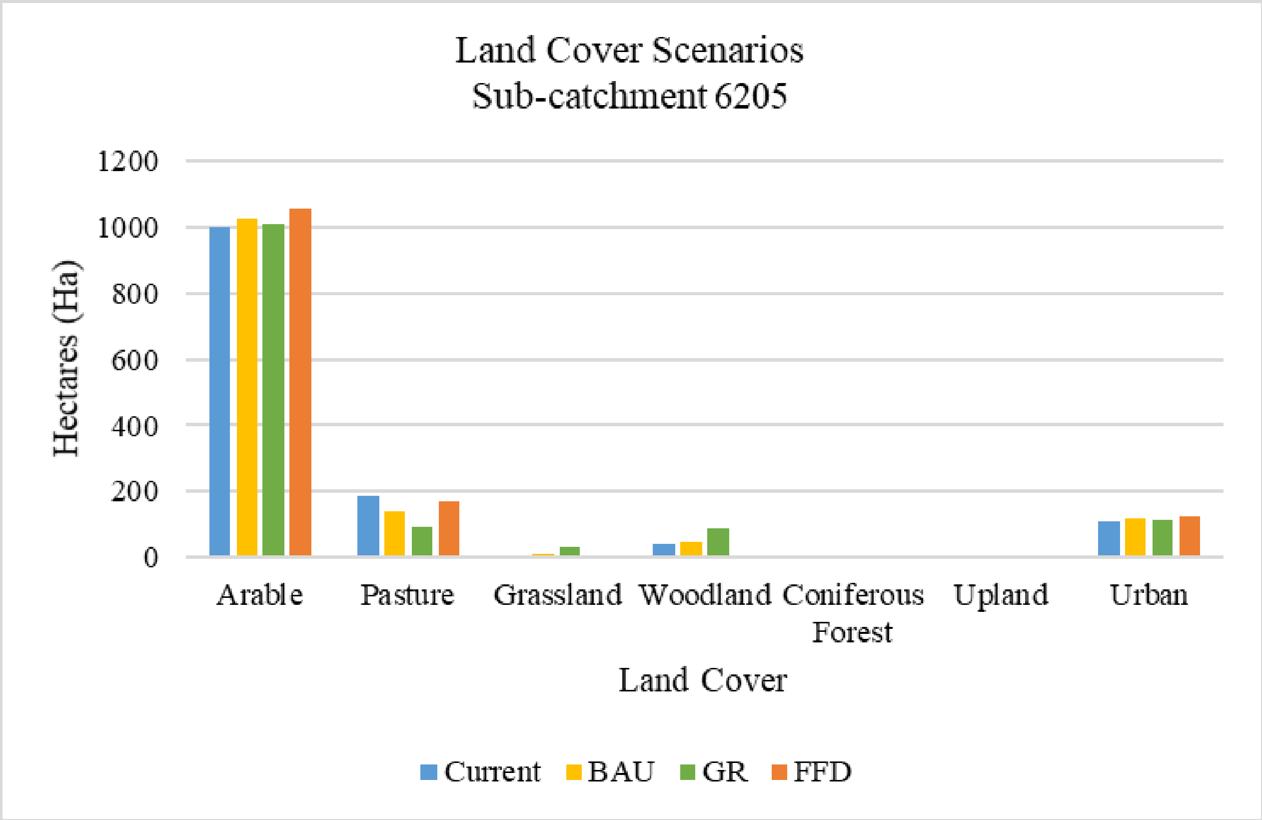


Figure 5: Land cover type hectare (Ha) differences in waterbody sub-catchment 6205 for Business as Usual (BAU), Green Road (GR) and Fossil Fuelled Development (FFD) scenarios

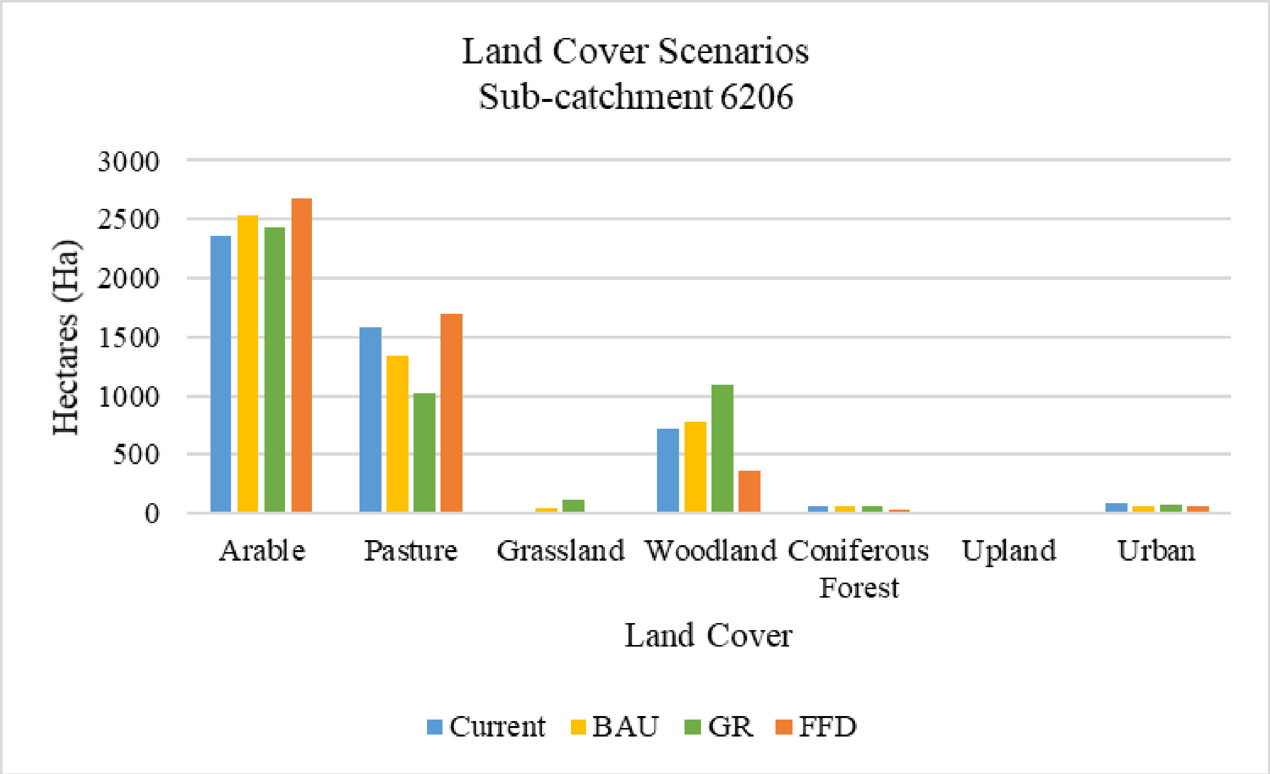


Figure 6: Land cover type hectare (Ha) differences in waterbody sub-catchment 6206 for Business as Usual (BAU), Green Road (GR) and Fossil Fuelled Development (FFD) scenarios

11) Lines 278-281: Expand on how the model valuation was done. Did you compared the mean? Did you averaged concentration values over time? If so over which period? Did you see the sd? Was this done for all subwatersheds? What metric did you use to evaluate?

$$\boldsymbol{Eq1}: \quad \%\boldsymbol{Bias} = \frac{\boldsymbol{X_{sim}} - \boldsymbol{X_{obs}}}{\boldsymbol{X_{obs}}}$$

Table 1 Summary statistics of observed and modelled current reactive phosphorus concentrations (ug/l) at the Eden catchment outlet waterbody sub-catchment 6200

Summary Statistics	Observed Simulated Reactive Phosphorus (µg/l) 6200 Outlet	Model Simulated Reactive Phosphorus (µg/l) 6200 Outlet
Median (µg/l)	168.82	157.63
Standard Deviation	109.34	361.65

Table 2: %Bias of modelled vs observed reactive phosphorus concentrations (ug/l) at catchment outlet

% Bias	% Probability
Under	26%
Optimal	43%
Over	31%

12) The authors are encouraged to do a sensitivity analysis (sensitivity to findings and sensitivity to parameters)

Table 3: Sensitivity analysis of selected diffuse and point source input variables and their influence on reactive phosphorus concentrations in sub-catchment 6200

		Variable			
		Diffuse Arable Phosphorus Sources	Diffuse Pasture Phosphorus Sources	Diffuse Septic Tank Phosphorus Sources	Wastewater Phosphorus Sources
Scenario	Current Median Reactive Phosphorus Concentration (μg/l)	157.63			
	+20% Source Load Increase Median Reactive Phosphorus Concentration (μg/l)	165.82	160.04	163.41	172.21
	% Change	4.9	1.5	3.5	8.4
	-20% Source Load Reduction Median Reactive Phosphorus Concentration (μg/l)	148.15	154.39	153.49	145.94
	% Change	-6.5	-2.1	-2.7	-8.1

13) Figure 6: Discuss why the change in 6202, 6205, 6206 is so high and different from the rest under scenario (d).

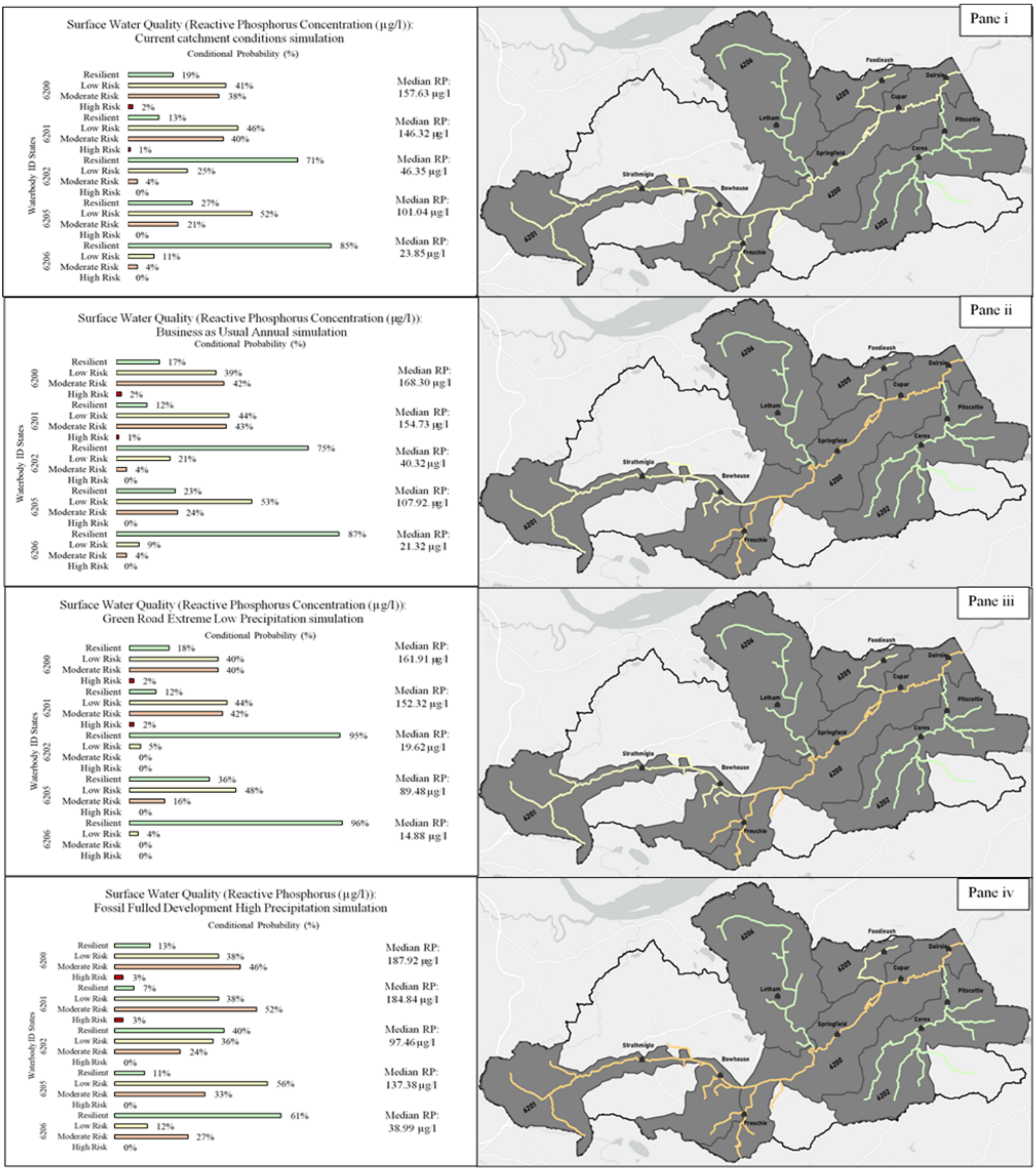


Figure 7: Conditional probabilities of resilient-high-risk states and median reactive phosphorus concentrations in micrograms per litre in each water body sub-catchment under (i) current conditions scenario, (ii) future Business as Usual scenario to 2050, (iii) future Business as Usual scenario to 2050, (iii) Green Road extreme low precipitation scenario to 2050 and (iv) Fossil Fuelled Development extreme high precipitation scenario to 2050. Acknowledgements: Acknowledgements: catchment boundary provided by the National River Flow Archive. River network provided by the EU-Hydro River Network Database (Gallaun et al., 2019). Map created in ArcGIS Pro (Esri Inc, 2021)

14) Bar charts 7 and 8 need to show the uncertainty bounds. Also provide similar charts for the rest of the subwatersheds in the SM

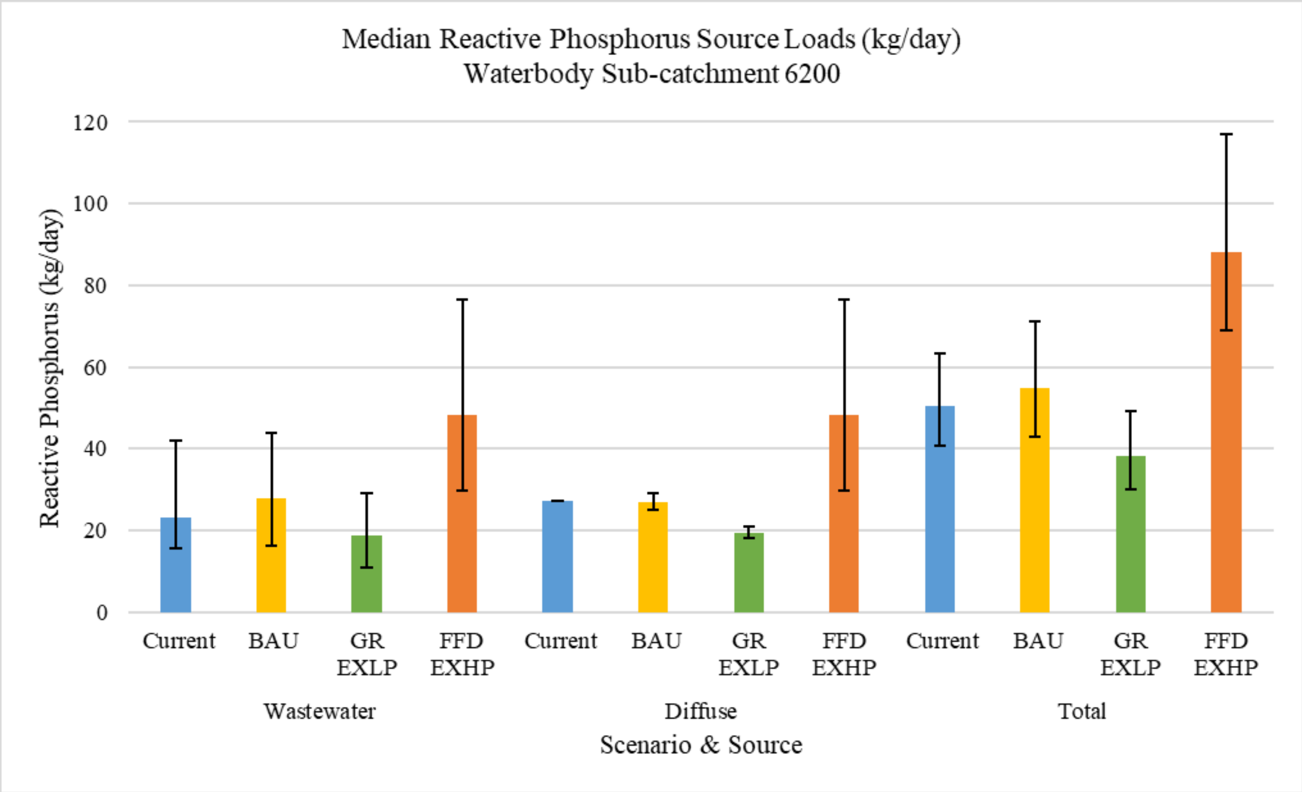


Figure 8: Median reactive phosphorus source loads (kg/day) in waterbody sub-catchment 6200 for Current, Business as Usual (BAU), Green Road Extreme Low Precipitation (GR EXLP) and Fossil Fuelled Development Extreme High Precipitation (FFD EXHP) scenarios

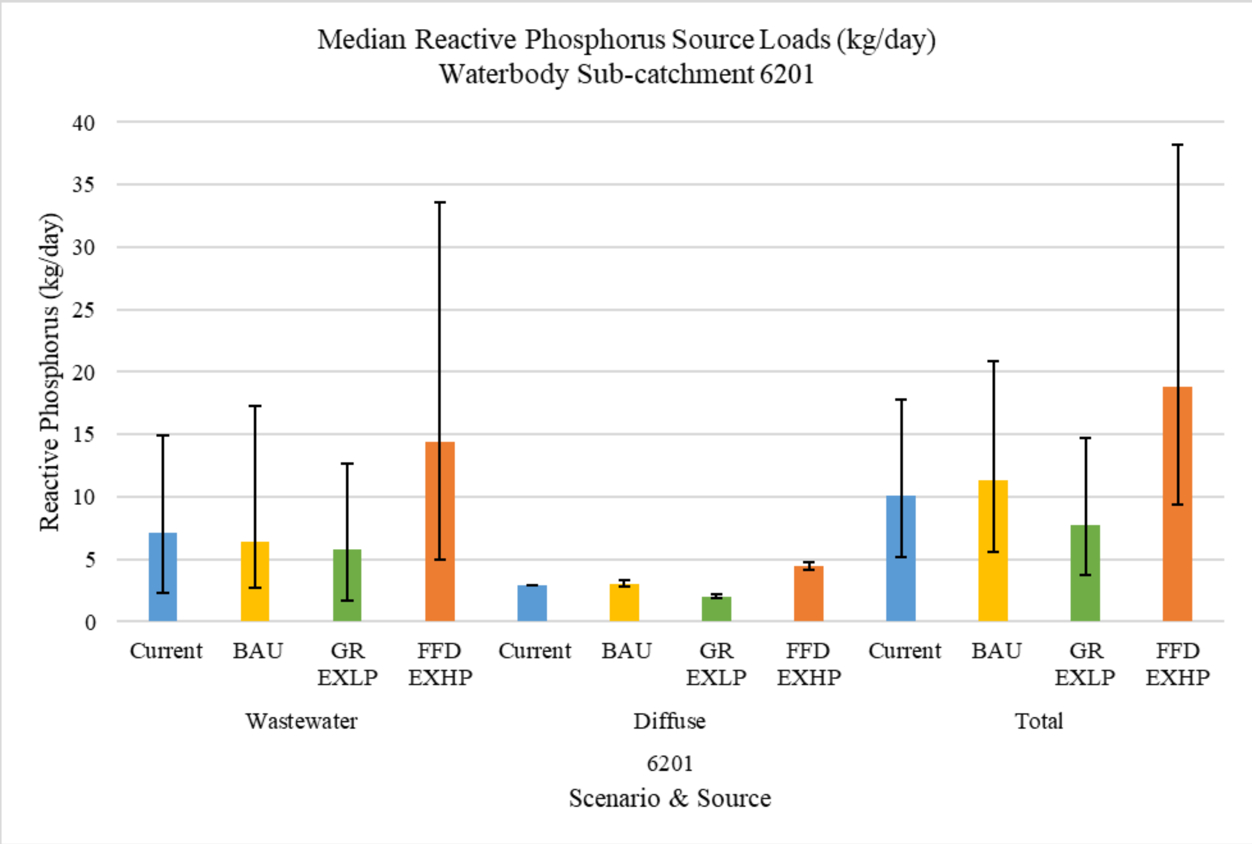


Figure 9: Median reactive phosphorus source loads (kg/day) in waterbody sub-catchment 6201 for Current, Business as Usual (BAU), Green Road Extreme Low Precipitation (GR EXLP) and Fossil Fuelled Development Extreme High Precipitation (FFD) scenarios

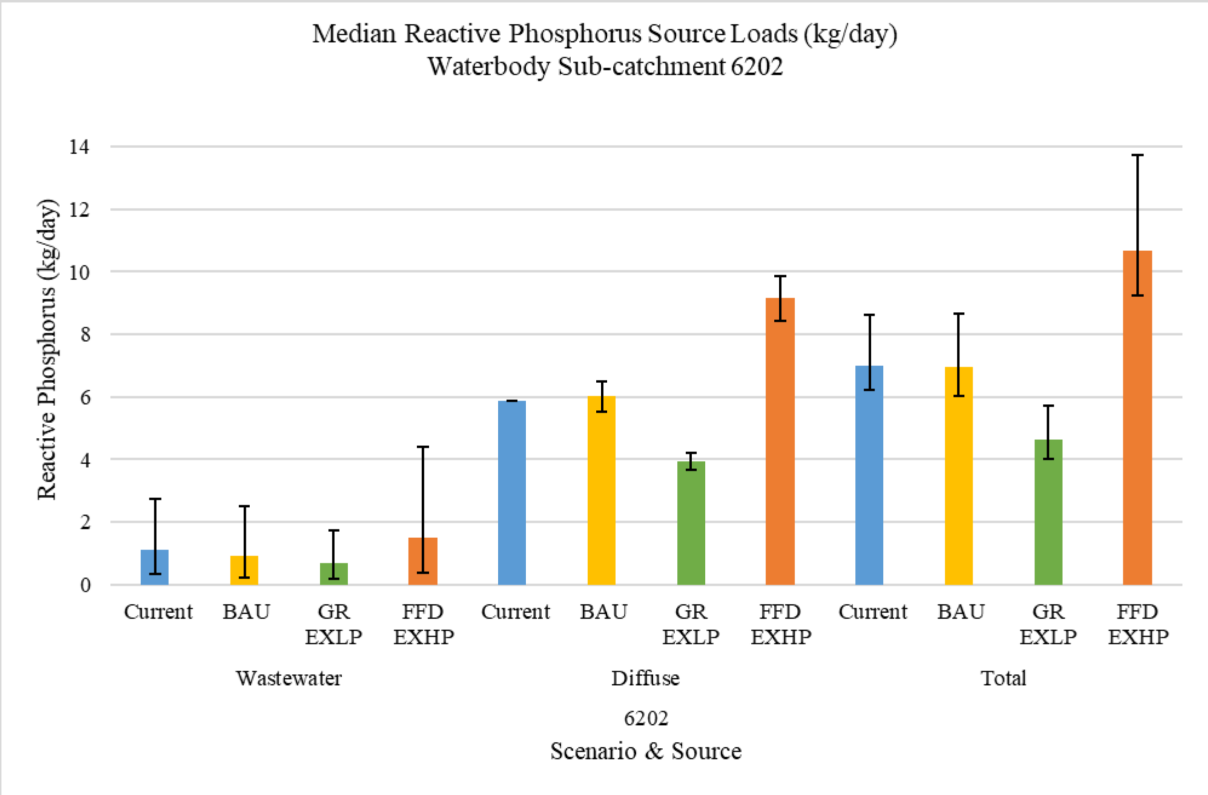


Figure 10: Median reactive phosphorus source loads (kg/day) in waterbody sub-catchment 6202 for Current, Business as Usual (BAU), Green Road Extreme Low Precipitation (GR EXLP) and Fossil Fuelled Development Extreme High Precipitation (FFD) scenarios

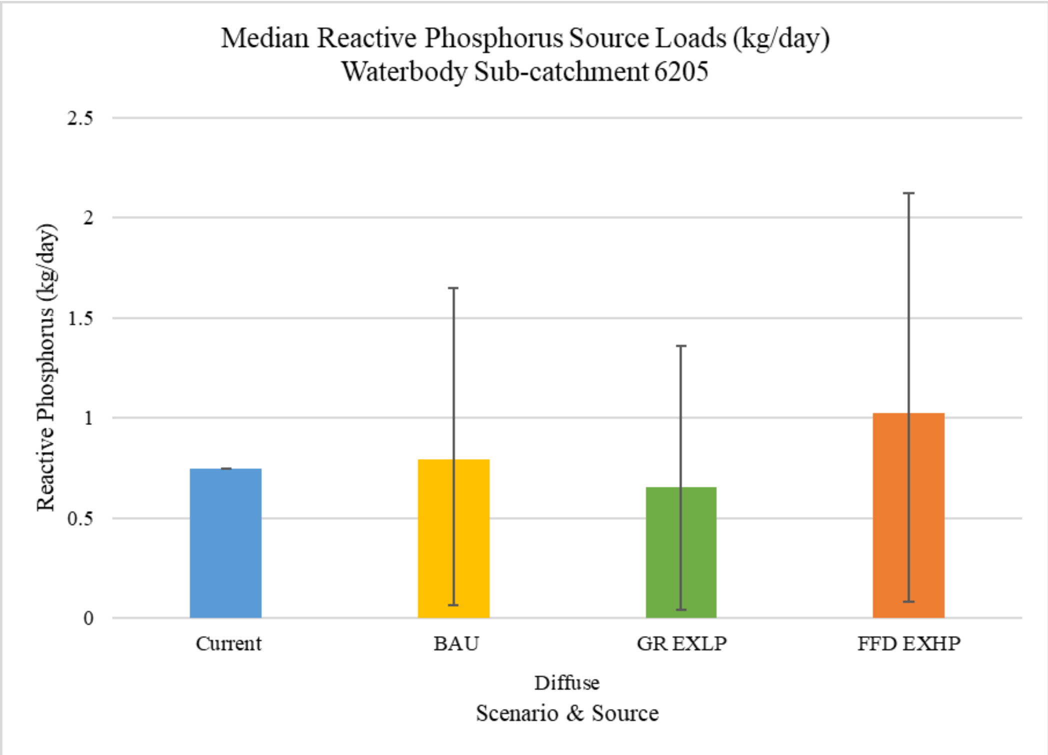


Figure 11: Median reactive phosphorus source loads (kg/day) in waterbody sub-catchment 6205 for Current, Business as Usual (BAU), Green Road Extreme Low Precipitation (GR EXLP) and Fossil Fuelled Development Extreme High Precipitation (FFD) scenarios, please note only diffuse sources are present

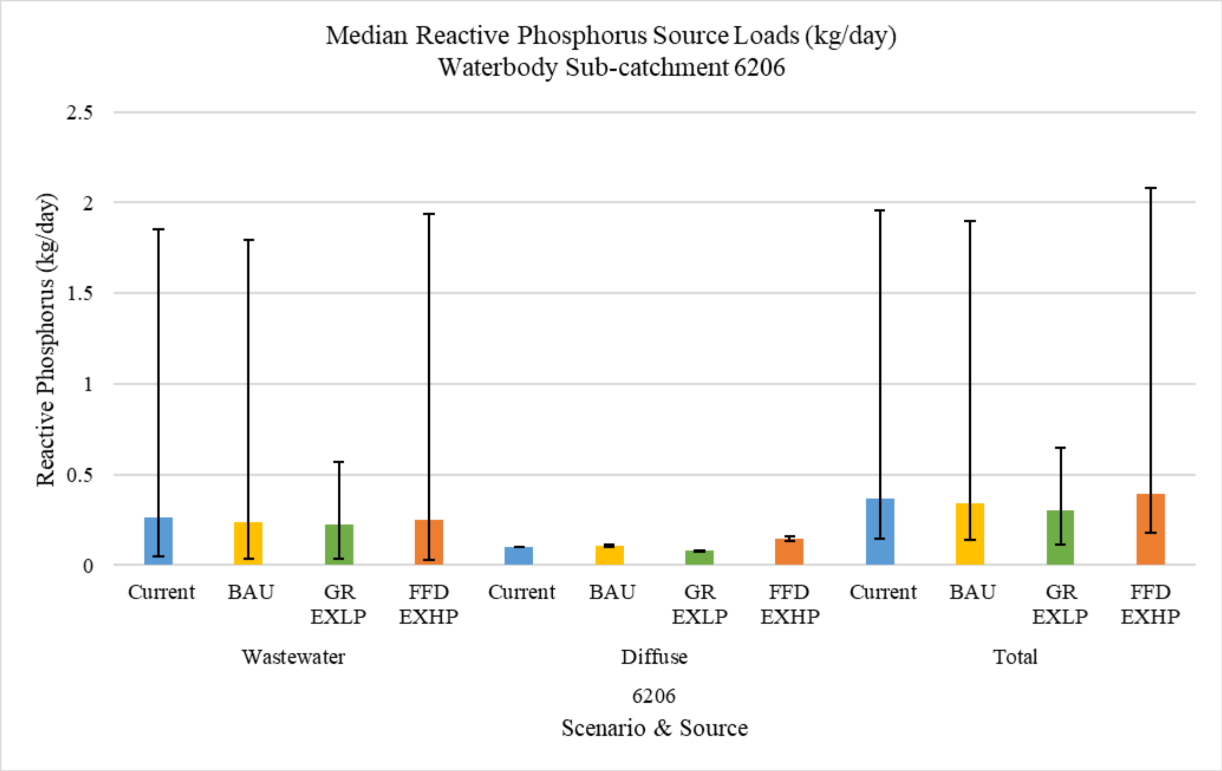


Figure 12: Median reactive phosphorus source loads (kg/day) in waterbody sub-catchment 6206 for Current, Business as Usual (BAU), Green Road Extreme Low Precipitation (GR EXLP) and Fossil Fuelled Development Extreme High Precipitation (FFD) scenarios

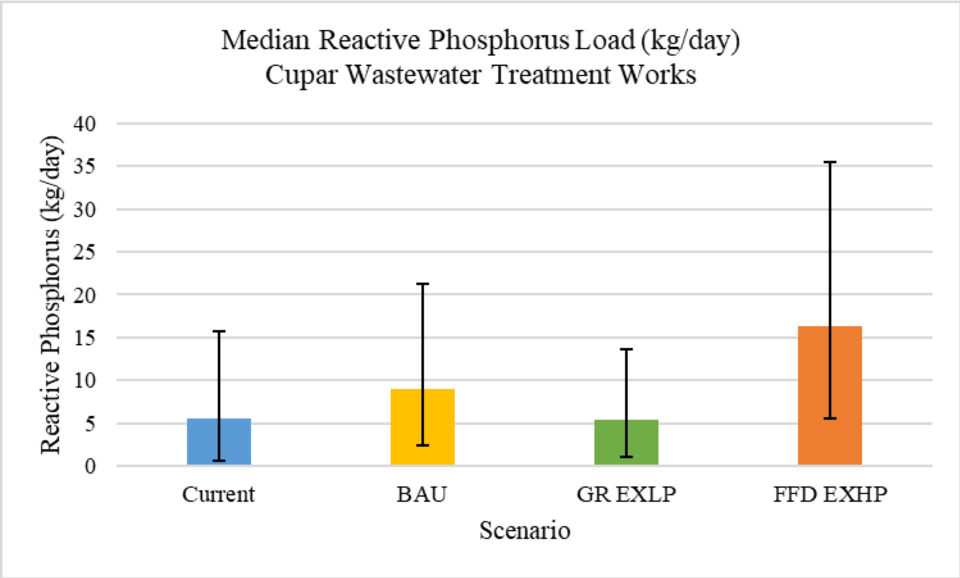


Figure 13: Median reactive phosphorus source loads (kg/day) at Cupar wastewater treatment works for Current, Business as Usual (BAU), Green Road Extreme Low Precipitation (GR EXLP) and Fossil Fuelled Development Extreme High Precipitation (FFD) scenarios

19) Table S2 in the SM is very important; yet it hard to follow. It also needs English editing

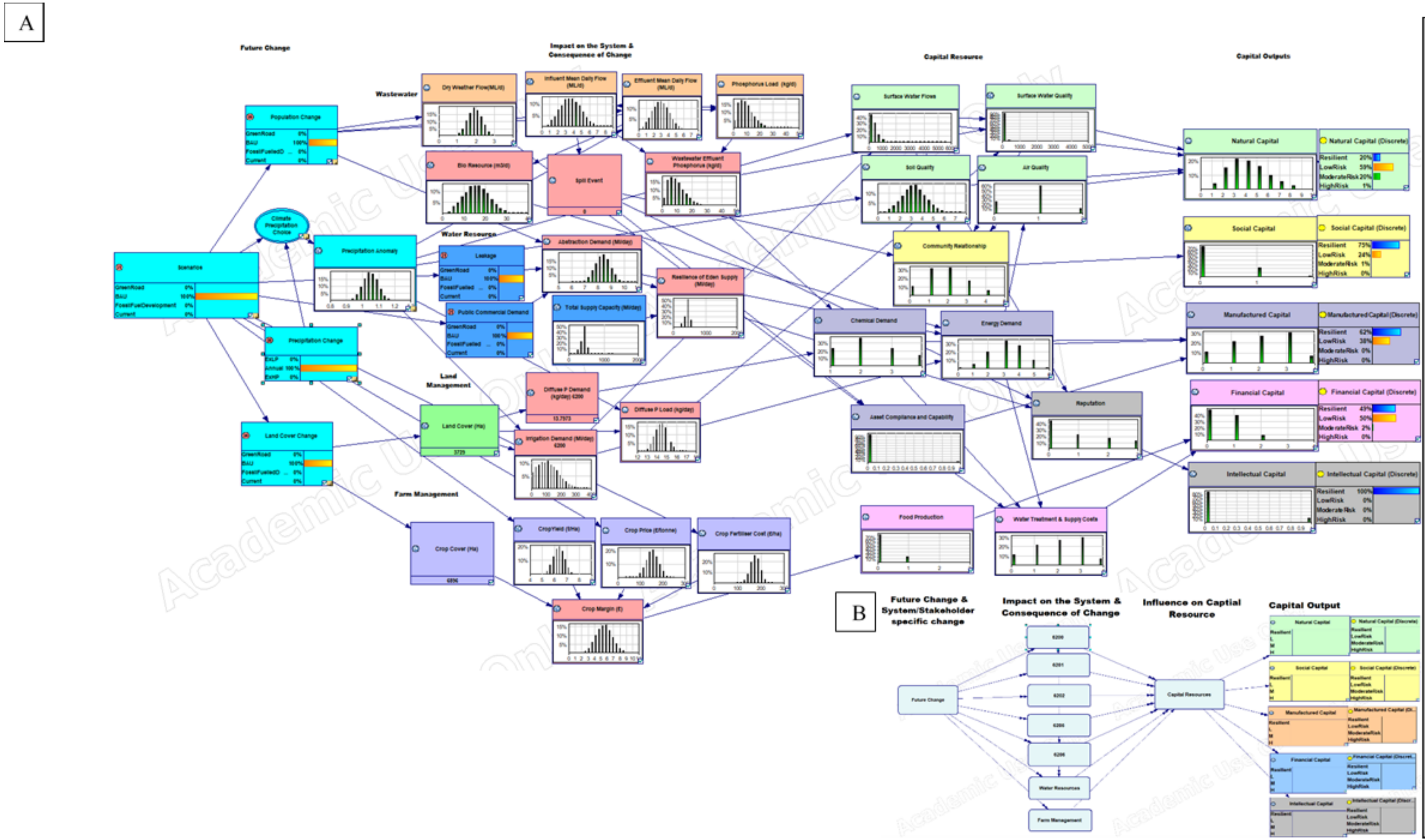
Table 4: Model variable log including node name, identifier, equations where appropriate and supporting information.

Node Name Identifier	**Equation**	**Supporting Information**
Scenario i	--	Deterministic input node for range of plausible scenario pathways.
Precipitation Change j	--	Deterministic input node for executing BAU precipitation change, and precipitation change for extreme low (Q5) and high (Q95) precipitation change.
Climate Precipitation Choice CPC	--	Deterministic node that combines Precipitation Anomaly with the Simulation node to enable the selection of precipitation anomaly scenarios under the different diverse future pathway scenarios.
Precipitation Change Anomaly (%) PA	$PA = \beta_{ij}$	Equation node that selects the precipitation change anomaly distribution β for each future simulation i and precipitation change simulation j. Values for β are derived from the UK Climate Projection User Interface product Anomalies for probabilistic projections (25km) over UK, 1961-2100 (Lowe et al., 2018). Annual temporal averages are used for Annual state to represent the incremental predicted change. To represent shocks to the system, Q95 values for seasonal winter anomalies to represent an extreme high precipitation scenario (ExHP) and the summer Q5 anomaly values are applied for extreme low precipitation scenario (ExLP). The data is selected for the 1981-2010 baseline period, in grid cell 337500.00, 712500.00, during the time slice 2040-2069 (2050's) using all sampling methods.
Population Change PC	--	Deterministic node that sets acquires population equivalent change values for scenarios i. Values are derived from the Scottish Water Population Growth Model. The Growth Model provides Real and Raw estimations of Population Equivalents (PE) to the year 2030. For the Green Road scenario (GR), the lower Real PE estimate for 2030 remains consistent for 2050 to reflect as shared-socioeconomic pathway (SSP) narrative which suggests population growth will stagnate in urban areas and migration to more rural areas will increase. For the Business As Usual (BAU) the Real PE trend for 2030 is extrapolated to 2050. For the Fossil Fuelled Development scenario (FFD), the Raw PE value for 2030 is extrapolated to 2050 as RAW PE provides an upper estimate of population growth, particularly in urban areas, which is reflected in the SSP narrative for FFD. Narratives are derived from Pedde, et al., (2021).
Land Cover Change LCC	--	Deterministic variable that sets land cover change values for i. Current and project future value are derived from UKCEH land cover vector maps (Morton et al., 2020). Extrapolations of historical land cover change, interpretations from the SSP narratives (Pedde, at al., 2021) and catchment specific knowledge provided by stakeholders were used to create projections for different land cover areas. See S4 of the supplementary material for more information.
Dry Weather Flow (Ml/d) DWf	$DWf_{ik} = \beta_k + PC_{ik} \times \gamma_k$	Dry Weather Flow, DWf, at wastewater treatment works (WwTWs), k, in the catchment are influenced by changes in PC_{ik} . The distribution β represents a truncated distribution of the current DWf at WwTW, k, derived from effluent flow summary statistics provided in the Scottish Water Strategic Study. We simulated effluent flows using the summary statistics to generate 365 data outputs, then calculated a Q80 value of the outputs, which was highlighted by stakeholders as the values used to derive asset dry weather flow values. We use the Q80 values as the mean and the standard deviations of the values to derive β_k.

		PC_{ik} is multiplied by γ_k which is the 1 PE value of 200 litres per day wastewater sewage flow contribution (Mara, 2006) which is converted to Ml/d and added to β_k. Resilient states threshold c is the *DWf* licence condition for k. Anything three times greater than the licence condition value is set as the threshold value for high risk (H) u. Thresholds for states low (L) and moderate (M) risk, b_l uniformised between c and u Ml/d. See Table S3 for values.
Daily Effluent Flow (Ml/d) Ef	$Ef_{ik} = \beta_k \times PA_{ij} + PC_{ik} \times \gamma_k$	Effluent discharge *Ef* at WwTWs k are influenced by changes in PA_{ij} and PC_{ik} under different scenarios i To measure potential impacts on Ef_{ik} we derived the distribution β_k to represent the current *Ef* distribution for k, from the Scottish Water Strategic Study. We multiply current *Ef* distributions with the % anomaly change in PA_{ij} which is assumed to lead to a change in run-off and infiltration which currently influence *Ef*. PC_{ik} is multiplied by the 1 PE value of 200 litres per day waste sewage flow γ_k and added to β_k to represent the influence of changes in PC_{ik} on *Ef*. Discretisation of states is based on the >3 *DWf (3DWf)* licence condition at setting for storm overflow detailed in the SEPA Supporting Guidance (WAT-SG-13) document which is a standard threshold set for calculating the Flow to Full Treatment (FFT) limit for WwTWs. The FFT for values for each WwTW k is described as anything three times greater than DWF leads to the risk of the sewer overflow. The resilient threshold c is therefore set as three times the *DWf* at treatment works k. The high risk threshold u is set at six times the DWF. Thresholds for states low (L) and moderate (M) risk, b_l are uniformised between c and u Ml/d. See Table S3 for values.
Daily Influent Flow (Ml/d) If	$If_{ik} = Ef_{ik} \times \gamma_k$	Influent flow *If* is influence by PA_{ij} and PC_{ik}. We use an equation node representing the change in influent flow *If* based on the change in *Ef* using the value γ_k to represent the difference between *If* and *Ef*. The value γ_k is used due to the limited *If* data available in the catchment. The only WwTW in the catchment with *If* data available was Cupar, where a reduction in flow volume after the treatment process was evident in the annual flow returns data from 2015 – 2019 provided by Scottish Water when comparing influent and effluent flows. We calculated the difference between influent and effluent flows using annual flow returns data to derive γ_k which is applied to each WwTWs k. The *If* node is discretised using the same methods as *Ef*.
Spill Event SP	$SE_{is} = IF_{eq}(If_{ik})$	The risk of spill events *SE* under different simulations i could occur due to changes in If_{ik} in waterbody sub catchments s. Spills (SP_{is}) occur if the node If_{ik} exceeds its c resilience threshold. We use IF_{eq} statement equations to index the prior distributions of parent node If_{ik} based on their discretised state thresholds. Each prior state discrete threshold for If_{ik} resilient to high-risk, was assigned a value of zero, one, two or three based on the values of *c, u, and b*. For SP_{is} the sum of If_{ik} of prior If_{ik} values is as follows: $IF(If_{ik} \geq u, 3, IF(If_{ik} \geq b, 2, IF(If_{ik} \geq c, 1, 0)$.

		We set the resilience threshold c for SP_{is} as a value for one, as anything greater than the value of one would mean at least one treatment works k is likely to spill. The upper value u set as the maximum possible index value of all nodes (3 times the number of parent nodes). Threshold values for high and moderate risk, b_1 and b_2 are uniformised values between c and u.
Wastewater Phosphorus Load (kg/d) P	$P_{ik} = (\beta_k \times (1 + 1 - PA_{ij}) + PC_{ik} \times \gamma_k) \times Ef_{ik}$	Change in Reactive Phosphorus (P) based on the change in PC_i and change in Ef.. The current concentration of P is represented using the distribution β for each of the different WwTW k. Current effluent P concentration (mg/l) are taken from the Scottish Water Eden Water Quality Strategic Study. PC_{ik} is multiplied by the calculated P concentration (mg/l) per PE γ, based on the current PE for WwTW k. The P concentration is multiplied by Ef to provide the daily effluent P load (kg/d). The node is discretised using the current mean P load for each k as the resilient threshold, which is calculated by multiplying the current P concentration by the current Ef. Anything greater than the current P load is seen as an increased risk, as higher loads demonstrate poor outcomes for both the environment and wastewater system. The high risk (H) value u is calculated as 3 times the c. The values for L and M risk are then uniformised between c and u (kg/d). See Table S3 for values.
Bio Resource (m^3/d) BR	$BR_{ik} = If_{ik} \times \gamma_k \times 1000$	Volumes of Bio resource BR (m^3/d) is influenced by changes in If. Su et al. (2019). An increase in If_{ik} can lead to an increase in bio resource concentrations and accumulations. Sludge volumes (m^3) were provided for all wastewater treatment works in the catchment for 2019. The relationship between If and BR volume is derived by analysing the relationship between flows and sludge volumes at WwTW in the catchment to create an average BR_k volume (m^3/d) per If_k (Ml/d) to provide a (m^3/l/d) value for each k which is represented by γ_k. The γ_k value is multiplied by If_{ik}, then multiplied by 1000 to convert the value to (m^3/d). The BR_{ik} node is discretised by setting the resilient threshold c as the current volume of BR_k. The high risk threshold is set as three times the current c value. Thresholds for states low (L) and moderate (M) risk, b_1 are uniformised between c and u m^3/d. See Table S3 for values.
Total Phosphorus Load (kg/d) TPL	$TPL_{is} = \sum P_{ik} + IF(If_{ik} \geq c, 1.05, 0)$	Equation node representing the relationship between overflow spills and P_{ik} loads. As the concentration of P is higher for untreated spill events, the P_{ik} load in the event the If exceeds the $3DWf$ threshold is added to the effluent P load to generate the Total Phosphorus Load (*TPL)* of WwTWs k in water body sub-catchment s. The Scottish Water Eden Water Quality Strategic Study sets a suitable concentration of 1.05 mg/l of P for spill events, which is multiplied by the spill volume. The discretisation of the TPL_{is} sets the resilient c value as the current TPL for each water body sub catchment s which is derived from the Scottish Water Eden Water Quality Strategic Study, the high risk u value is set as three times the c value. The values for L and M risk are then uniformised between c and u (kg/d). See Table S3 for values.

Extra note: additional Figure S2 due to incase of issues for upload in response to Reviewer#1 comments:



*To reduce complexity, all sub-models (as depicted in image B) and their variables haven't been included. FigureS2 provides a simplified visualisation of each of the variables within the system. The following duplicating variables for each sub-model are not included in the visualisation:

- 10 wastewater assets (*k*) in sub-catchments *s*
- Four land management land cover types (*v*) in sub-catchments *s*
- Four crop cover types (*z*)
- Septic tanks (*ST*) in sub-catchments *s*
- Water resource supply assets (*SC*)

Fig.S2 provides a hypothetical represented of modelled outputs for the future Business as Usual (BAU) annual scenario.

** Variables in red are variables that represent a consequence of change.

***Capital output variables include both an equation node (left) and discrete child node (right). Discrete child nodes are included for all equation nodes in the model, for the purposes of clarity, they've been removed from this visualisation.

Figure 12: (A) Simplified visualisation of the Bayesian Network model, its variables and outputs for a hypothetical future Business As Usual (BAU) scenario (B) visualisation of how sub-catchments are considered using sub-models. Both models developed using GeNIe modeller (version 2.4.4601.0) (BayesFusion, 2017)