Quantifying the effect of climate change on aquatic ecosystems using Eco Risk Projector

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Key Points

- The potential impact of a drying climate on aquatic ecosystems needs to be quantified to ensure that water resources are managed in a sustainable way.
- We have developed a web application to model the ecological risks to 30+ species and process models under alternate water use scenarios, with a focus on spatial risk through multiple simultaneous failures.
- We have extended this application to efficiently and robustly handle large volumes of hydrological scenarios generated from climate models.
- We have tested this functionality against refuge waterholes as a flow dependent aquatic asset.
- We have developed a generalised solution that can be universally applied.

Abstract

- A key challenge for water resource planning is the quantification of the potential impacts of a drying climate on aquatic ecosystems. Global climate models are now routinely downscaled and applied to hydrological simulations to allow the production of an ensemble of potential flow scenarios. The Eco Risk Projector application is used by the Queensland Government to model ecological risks to 30+ species and ecological processes under different water resource development scenarios.
- We implemented functionality in Eco Risk Projector to automatically ingest 44 alternative hydrological scenarios generated from downscaled climate models which were subsequently applied to 130-year daily time step water planning hydrological models. Those scenarios are batch run across ecological species and process models and the results summarised and visualised to allow the interpretation of potential climate change impacts. The models are run at a site level, and the results aggregated across locations for a given species and scenario to explore the spatial risk of multiple failures across the landscape for a given scenario.
- We have learned that it is difficult to summarise and visualise large volumes of data in a way that is easy to interpret. We have also learned the value of quantifying the broader spatial/system impact of climate change scenarios over and above considering single locations.
- The approach and computational capacity can be universally applied to any water planning area where daily flow data is generated to represent potential future climates, and the ecohydrological needs of dependent ecosystems are similarly structured.

Keywords

Climate change, aquatic ecosystems, spatial risk, water resource development

Introduction

In a rapidly changing climate, it is an ongoing challenge to ensure that water resources are managed in a sustainable way. Climate change impacts on water availability are relevant across all ecological assets, and there is a clear need for inclusion of climate change projections in hydrological simulations at scales relevant to water planning. The Queensland Government uses an ecohydrological risk-based approach to assess the impacts of water resource development to flow-dependent species and ecological processes (McGregor et al. 2018). This risk assessment is conducted using Eco Risk Projector (Truii, 2022). Eco Risk Projector is a web application with a growing library (currently 32) of time series analysis models that define the hydrological requirements of important species or processes (environmental assets). Eco Risk Projector is used to quantify the ecological risk under alternative water use scenarios and to report the change in ecological opportunities at a given location between the scenarios.

In this paper we present enhancements to Eco Risk Projector that permit integration of hydrological scenarios generated from downscaled climate models. We tested the new approach using refuge waterholes as a flow dependent aquatic asset. We discuss the challenges encountered in managing the data and adjusting the computational architecture, and we present our innovative approach to visualising large amounts of complex results.

Waterholes and climate change

In dryland regions of the state, refuge waterholes are environmental assets which represent critical habitat, particularly during prolonged no flow spells. These waterholes are sensitive to management regimes which reduce baseflow and increase the return interval of flows which maintain the quantity and quality of these habitats. They are also particularly sensitive to climate change as their persistence and habitat quality are profoundly influenced by rainfall and evaporation rates.

Methodological approach

To assess the impact of a drying climate on the persistence of refuge waterholes, we considered 11 general circulation models (GCMs) that best represent Queensland's climate. The GCMs are different representations of the atmosphere and oceanic processes responsible for climate regulation. Models were downloaded from the Future Climate Dashboard (https://www.longpaddock.qld.gov.au/qld-future-climate/dashboard/) and represent IPCC CMIP5 with CCAM 10km downscaling.

Two future climate projections were applied: RCP 4.5 and RCP 8.5, with both projected to the year 2050. Whilst a number of representative concentration pathway (RCP) scenarios exist (Figure 1), the two applied represent firstly a moderate case in which emissions peak around 2040 and then decline (RCP 4.5), and a worst-case where emissions continue to rise throughout the 21st century (RCP 8.5).

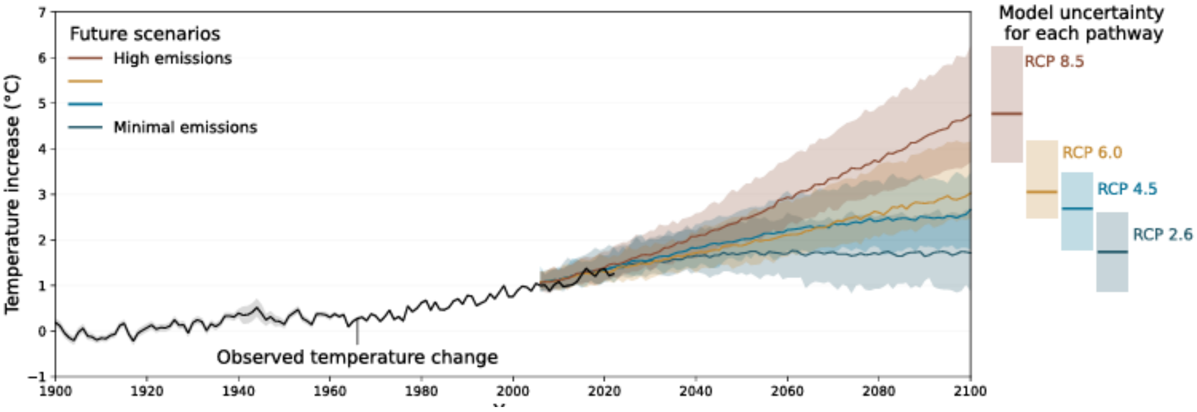


Figure 1. Global projected temperature change for Intergovernmental Panel on Climate Change (IPCC) AR5 Representative Concentration Pathways

Within each climate projection, two alternative scenarios of water resource development were also applied. The full entitlement (FE) scenario includes existing planned levels of water take. The pre-development (PD) scenario has the same hydrological parameterisation as the FE scenario but with all infrastructure and water extraction removed.

Ultimately, this process produced 44 alternative climate scenarios to consider. For each of these scenarios, waterholes were associated with local climate data (rainfall and lake evaporation) from SILO PatchPoint, and a flow series based on the closest node in the associated Source model.

Outputs

The result of this climate and hydrological modelling is 130 years of daily time series data from 22 climates for two water use scenarios (44 scenarios). The current climate is also run for both water use scenarios to allow comparison (two scenarios). This gives a total of 46 scenarios combining climate and water use. Each scenario can have tens of reporting locations where data is exported. The output from this modelling exercise is a rich but large volume of daily timeseries modelled flow/rainfall/evaporation for different RCP/GCM/water use combinations. It is difficult to interpret simple statistics of changes to flow regime across 46 flow records across tens of locations, let alone the aquatic ecosystem implications of different scenarios.

We used the waterhole persistence model in Eco Risk Projector as a case study for addressing the challenges associated with incorporating climate scenarios into existing water planning environmental risk assessments. The waterhole persistence model is a water balance model combining measurements of waterhole morphology (i.e. bathymetry), water inputs (i.e. surface-water hydrology, rainfall and groundwater discharge) and losses (i.e. evaporation, seepage, and water extraction) to predict daily waterhole depth in periods where no-flow occurs.

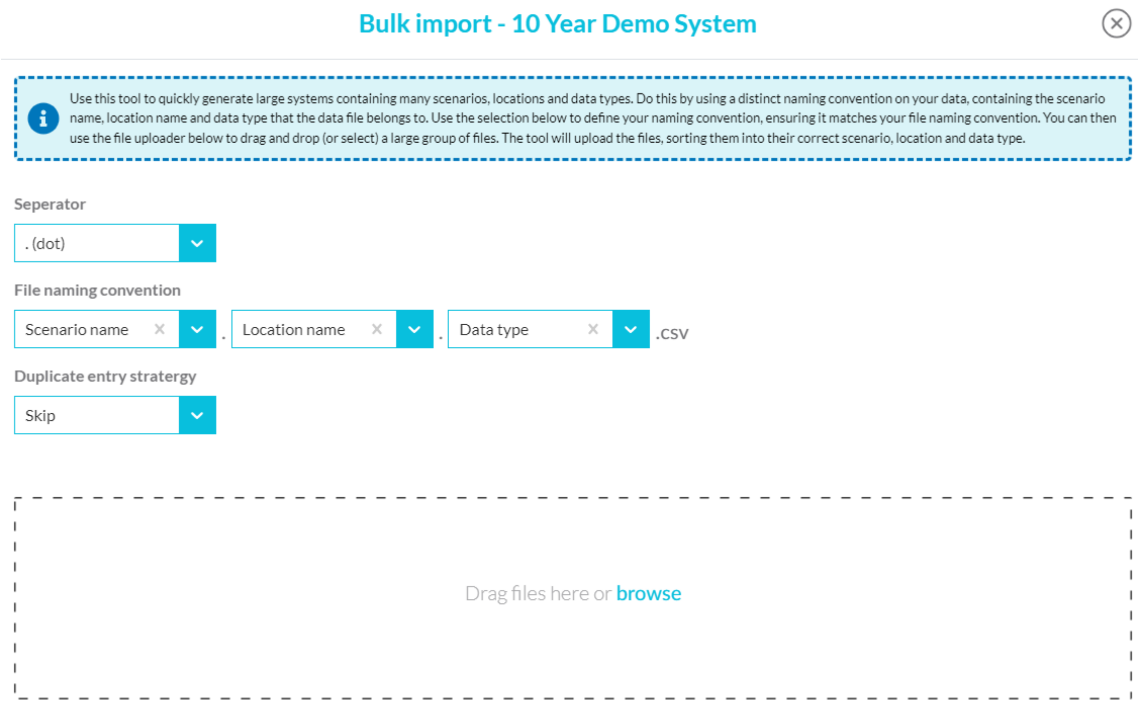
Refuge waterholes represent sensitive ecological assets when examining potential climate change impacts as they are susceptible to both changes in flow and evaporation. Whilst a change in the return frequency of flows may cause waterholes to continue to dry down for longer, changes to rates of evaporative loss may cause waterholes to dry down to critical thresholds more quickly. In combination, this could result in more frequent waterhole failure under future climate change scenarios. The waterhole persistence model requires greater amounts of input data compared to other asset models on the Eco Risk Projector platform, integrating location specific flow, evaporation, and rainfall data at a daily time step to calculate waterhole depth. The outputted daily time series of water depth can then be used to assess when a waterhole exceeds the minimum depth threshold needed to sustain aquatic life during no-flow periods.

A novel feature of Eco Risk Projector is the consideration of not only individual waterhole failures, but the integration of results across locations to report on simultaneous waterhole failures across multiple locations in the landscape. Failure at multiple locations across the landscape is significant as it may result in local extinction because of the concurrent removal of all available refuge habitat and hence removal of the potential for recolonisation during subsequent periods of higher flow. The challenge for this project was to firstly quantify the risk to refuge waterholes under different climate change scenarios, and secondly to be able to investigate those results in a timely and meaningful way.

Managing the data

A common challenge with climate studies is the efficient handling of large datasets. Eco Risk Projector has been designed to support water resource planning through the manual creation of systems where scenarios and locations are manually defined, and data is manually imported before being applied to environmental asset models. Whilst prone to human error, this manual system creation is sufficient for simple systems. However, for a full climate ensemble including hydrology, temperature, evaporation, etc. a manual import would take days and is at high risk of error through accidental omission and incorrect nomenclature. As well as setting up the system, it is important to be able to manage the data within the system, as modelling is revised and updated.

Our solution was to create a bulk file handling feature that automatically generates the system (locations and scenarios) based on a configurable structured naming convention (Figure 2). This feature can setup a climate change system with ~1000 data files in just minutes, with no chance of human error in the data handling process. Where the data already exists (i.e. updating data), the bulk import can be set to update the existing data. Additionally, version records are maintained within the application to alert the user when model results are out of date with the available system data.



Bulk import - 10 Year Demo System

Use this tool to quickly generate large systems containing many scenarios, locations and data types. Do this by using a distinct naming convention on your data, containing the scenario name, location name and data type that the data file belongs to. Use the selection below to define your naming convention, ensuring it matches your file naming convention. You can then use the file uploader below to drag and drop (or select) a large group of files. The tool will upload the files, sorting them into their correct scenario, location and data type.

Seperator: . (dot)

File naming convention: Scenario name . Location name . Data type .csv

Duplicate entry stratergy: Skip

Figure 2. Bulk import feature interface

Computational challenges

For the waterhole persistence model being run across 20 locations for 46 scenarios with 3 different daily data types (flow, evaporation, rainfall) over 130 years, more than 130 million individual days of data need to be ingested and model outputs computed. The Eco Risk Projector computational architecture was originally developed around running small to moderate sized models (~10 locations, ~3 scenarios, ~100 years of daily data), with model run times in the 2 to 20 minute range and moderate resource usage. This architecture was quickly pushed past its limit when running the climate scenarios through the waterhole persistence model, with the immense volume of data causing excessive memory use (memory usage complexity was $O(n)$, with n being the total number of locations) that was often too much for the existing un-scalable infrastructure. For smaller climate runs that could be computed, the heavy resource usage slowed computation speeds and run times exceeded 12 hours. We addressed this with two major changes.

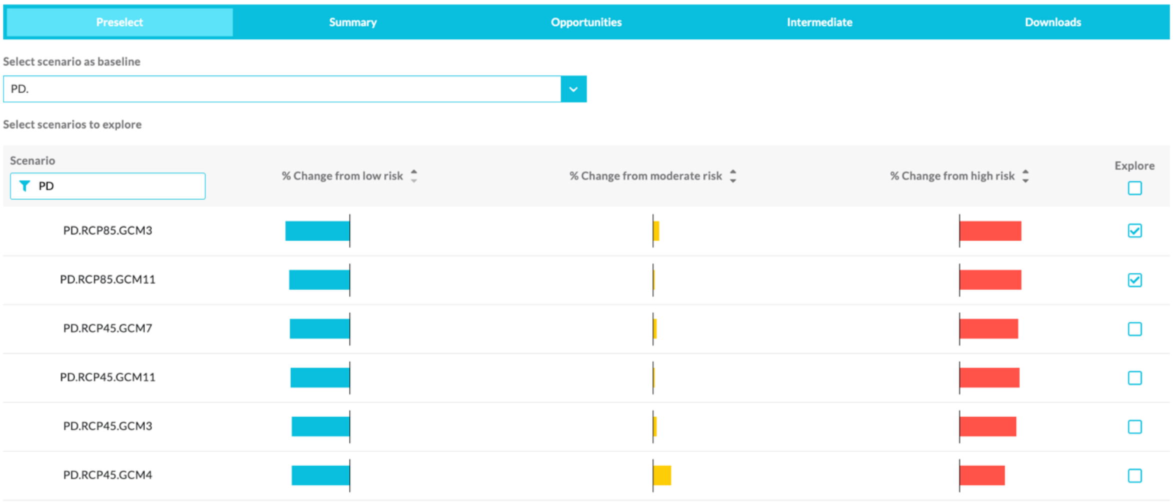
Firstly, we re-structured the memory management of the computation to a structure with an $O(1)$ complexity (constant). We did this by moving the storage of results outside of memory and onto a local database (stored on disk) that exists only for the lifecycle of the run. This means the maximum amount of memory needed is only determined by the current location being run and does not increase based on the total number of locations being computed. Secondly, we re-designed the computation architecture to move the computation into an individual, highly scalable queue-based service. This service scales to create many computation instances based on the amount of work pending, thus allowing the scenarios to be computed in a massively parallel fashion across multiple computation instances. This re-design allows even the most complex climate change model runs to compute within two hours.

Results visualisation

Eco Risk Projector reports the overall result for a scenario expressed as annual risk across locations for each year. Underlying the spatially aggregated risk score are scores for individual locations. For individual locations, there are annual and daily scores as well as the intermediate annual and daily values used to develop the scores. Depending on the model, there may be up to 10 forms of output data generated per location, each covering 130+ years. That is, there is up to 10 times the amount of output generated than the input data used to generate it. Only some of this output data is frequently interrogated as the highest-level summary is usually enough to determine that there is little difference between water use scenarios and no further investigation is required. However, where there are concerning differences between the assessment scenario (FE) and the reference scenario (PD) spatially aggregated risk, then the underlying detailed results are interrogated in order to determine the underlying reason for changes in ecological opportunity. As such, all results need to accessible through the application, but they need to be presented in a hierarchical view for users to ‘drill down’ to explore specific cases.

Preselection view

To explore the results of the climate change scenarios, we have adopted a progressive disclosure approach. At the highest level, the key measure of spatially aggregated risk change is used as the basis for selecting which scenarios to explore further (Figure 3). The changes in risk relative to a baseline scenario are displayed, where the baseline scenario can be set based on the use case. For example, to show relative difference for future climate full entitlement scenarios relative to the current full entitlement scenario, or relative differences between GCMs for a given RCP. Additionally, the table is filterable by using a search on the scenario names. For example, a search of “RCP45.GCM1” will show all water use versions of the RCP4.5 GCM1 climate change scenario. The scenarios of interest identified through this process are selected for further investigation in the subsequent views.



Select scenario as baseline

PD.

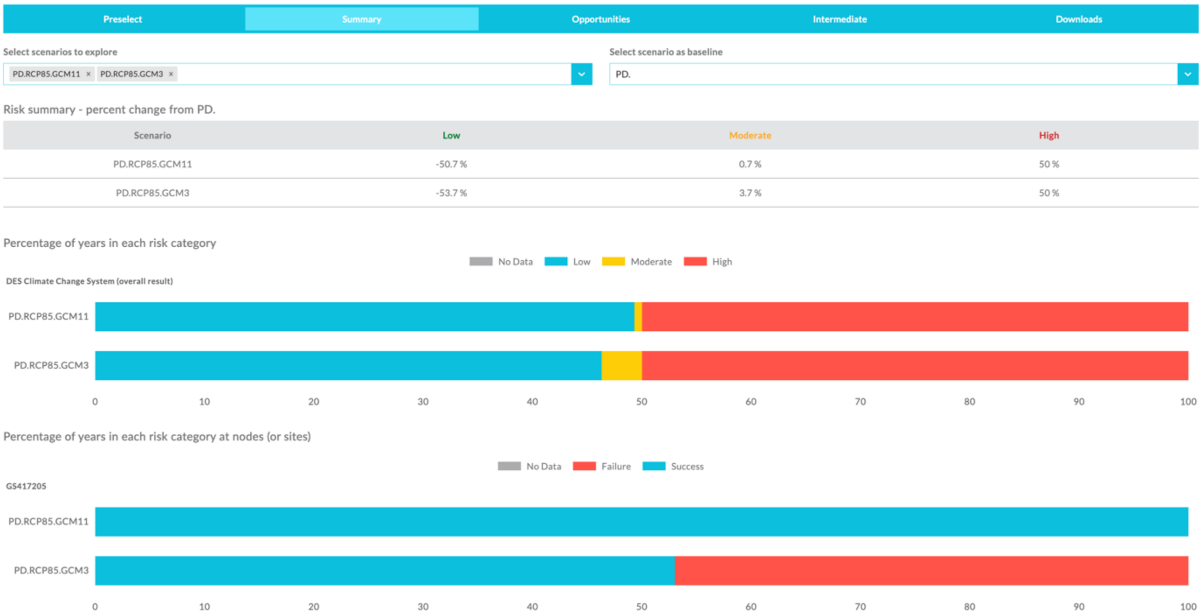
Select scenarios to explore

Scenario PD	% Change from low risk	% Change from moderate risk	% Change from high risk	Explore ☐
PD.RCP85.GCM3				☑
PD.RCP85.GCM11				☑
PD.RCP45.GCM7				☐
PD.RCP45.GCM11				☐
PD.RCP45.GCM3				☐
PD.RCP45.GCM4				☐

Figure 3. Scenario preselection results view

Summary View

Once selected, the available scenarios are summarised (Figure 4). Firstly, as a table showing overall percent change from the baseline scenario for each risk category. This is then visualised on a horizontal bar chart as the overall time in each risk category for the habitat model across all locations. Additionally, the time in either success or failure for each individual location is reported.



Select scenarios to explore

PD.RCP85.GCM11 × PD.RCP85.GCM3 ×

Select scenario as baseline

PD.

Risk summary - percent change from PD.

Scenario	Low	Moderate	High
PD.RCP85.GCM11	-50.7 %	0.7 %	50 %
PD.RCP85.GCM3	-53.7 %	3.7 %	50 %

Percentage of years in each risk category

Percentage of years in each risk category at nodes (or sites)

Figure 4, Summary results view

Opportunities View

The opportunities view allows the exploration of each year of the analysis (Figure 5). At a high level, the spatially aggregated risk across locations for the scenarios are presented. This is followed by the performance (success/failure) for each year at individual locations. These visualisations are filterable to show only a certain year range for more detailed analysis.

Select scenarios to explore: PD.RCP85.GCM11, PD.RCP85.GCM3

Years: 1889 – 2022

Figure 5. Opportunities results view

Intermediate Reporting

The intermediate reporting visualisations allows exploration of every day/year of the record for a series of model specific metrics (Figure 6). These metrics are based on the model parameters, and are calculated in the process of determining the overall success. For example, the waterhole persistence model calculates an estimated daily depth, which is then used with spell analysis methods to determine drying events (depth below a threshold). If a day is not part of a drying event, that day is a success (as visualised in the summary and opportunities results). This estimated depth, along with key spell statistics are reported in the intermediate results view. Generally, the intermediate results provide an intuitive way to interrogate model results and determine what criteria is causing a model's failure. Further, the daily intermediate results are visualised with a heat map style chart that allows straightforward identification of seasonal result patterns across years.

Select scenarios to explore: PD.RCP85.GCM11, PD.RCP85.GCM3

Select intermediate results to explore: Event (Daily)

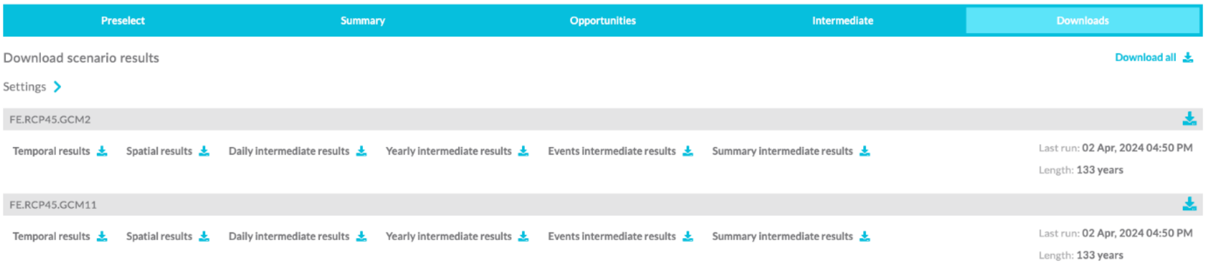
Years: 2002

Days: 1

Figure 6. Intermediate results view

Downloads

The final view provides access to a range of download summaries for further post processing (Figure 7). These downloads are highly configurable, from downloading a single result file to all model results packaged in a directory hierarchy. Additionally, there are options to allow combining all scenario results into a single file, and separating all daily results into location files which makes post processing straightforward for all use cases. Finally, a run setting log file is included in the results, which stores all model parameters that were set when the model was run.



Last run: 02 Apr, 2024 04:50 PM
Length: 133 years

Last run: 02 Apr, 2024 04:50 PM
Length: 133 years

Figure 7. Scenario downloads view

Conclusions

The Eco Risk Projector method to quantifying changes in risk to aquatic assets is a repeatable, evidence-based approach to assessing the impacts of water resource development. The spatially aggregated risk assessment is a novel way to assess broader landscape risk. We have rebuilt the software architecture to apply the approach with the high volumes of data generated to explore the impact of climate change on future water availability. The largest challenge has been enabling access to the full suite of model results for each climate scenario whilst also providing an interactive high-level interface to explore, compare, and select individual scenarios for further analysis.

The project has produced a generalised solution for handling large volumes of daily time series data for conducting hydrological analysis and the approach is scalable for large scale climate change analysis.

Application of the new method gives us the opportunity to integrate climate change scenarios into water planning. Ultimately this will lead to more accurate assessment of changing water availability at the asset scale, and improved identification of asset vulnerabilities under a warming climate.

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