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Supplementary Materials for

What will it take to stabilize the Colorado River?

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The PDF file includes:

Materials and Methods
Fig. S1

Additional Figure

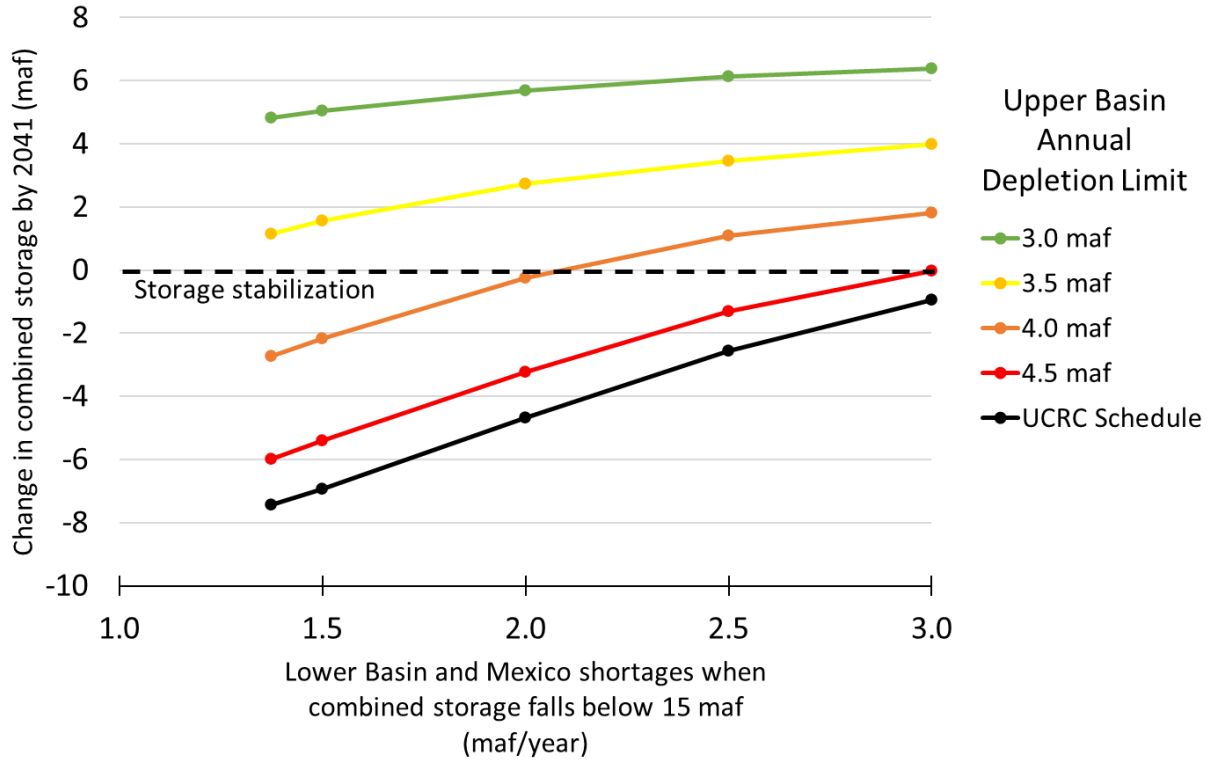


Figure S1. Average change in combined Lake Powell and Lake Mead storage in 20 years assuming hydrologic conditions of the Millennium Drought continue. Colored lines show how a range of Upper Basin consumptive use limits interact with different Lower Basin maximum consumptive use reductions (i.e., shortages shown along the x-axis) triggered when the combined storage falls below 15 maf. All water use and shortage values are annual volumes (maf/year).

Materials and Methods for Reproducing Model Results

This document provides step-by-step guidance to adapt the original model provided by Reclamation to produce the results from this study.

All materials can be found in the repository file:

Supplementary Materials and Methods_Models and Outputs.zip

https://www.hydroshare.org/resource/a065c17a6a02463ca9e7d69f22baed10/

This includes the original RiverWare model acquired from the US Bureau of Reclamation, additional elements developed for the study to be incorporated into the original model, an updated model with all adaptations, saved model versions with each configuration, outputs from each model run, and plots developed from the outputs.

Step 1: Download and Install RiverWare and RiverSmart

- RiverWare overview: https://www.riverware.org/riverware/overview.html
- RiverSmart overview: https://www.riverware.org/HelpSystem/!RiverSMART-Help/index.html#page/RSmartHelp/RSmart_Overview.03.2.html#
- RiverWare and RiverSmart could be downloaded from:
- https://cadswes2.colorado.edu/downloads/riverware/releases/index.html
- RiverWare Installation and License Guides
- https://www.riverware.org/guides/index.html
- License could be purchased from: https://www.riverware.org/riverware/LicensingRW/index.html
- This research was conducted based on RiverWare 8.23 and RiverSmart 8.23. Later versions of RiverWare and RiverSmart should work too.

Step 2: Set Up Environment

Download CRSS from:

Download the JUN 2021 official CRSS from repository above.

Setting up the environment variable for CRSS

1) Copy the CRSS directory and the sub-directories to a local computer, maintaining the existing directory structure.

2) Create an environment variable **CRSS_DIR** that points to the contents of the copied CRSS directory. For example, if the CRSS directory is copied to C:\Modeling\ then the environment variable value should be C:\Modeling\CRSS

3) The environment variable can be used in RiverWare to reference the path to different files. Ex: $CRSS_DIR\ruleset\CRSS-IG.rls.gz is the path to a ruleset. Please note the $ in front of the

environment variable, which is necessary to resolve the environment variable to a path in RiverWare.

a. Please note there cannot be any blank spaces in the **CRSS_DIR** path.

4) Environment variables can be created by either method listed below:

a. Launching the "1.SetCrssDirecotry.bat" script provided in the CRSS package. This will automatically set **CRSS_DIR** to the location of the unzipped directory. Be sure this location has no spaces in the path.
or

b. Going to properties of the computer by typing "Control Panel" in the search bar. Click the "System" icon  , and select "Advanced system settings" from the menu on the left side of the window. Click the Environment Variables button. The new environment variable will not take effect if it is set while RiverWare is open. With RiverWare closed, set the environment variable, before launching RiverWare.

Step 3: Changes to the Jun 2021 version of CRSS model

1) Make a copy of the existing model in "$CRSS_DIR\model" folder. Name One as **CRSS.V5.1.2.2022.Jun2021_Baseline_2000_Resample.mdl** and name the other one as **CRSS.V5.1.2.2022.Jun2021_Updated.mdl**

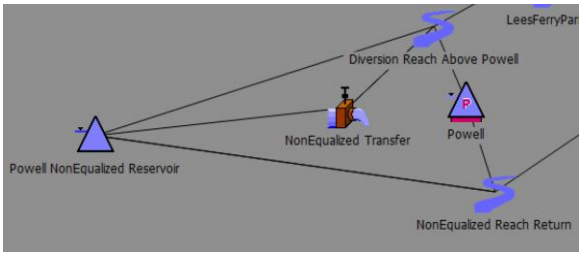
2) Open RiverWare and load **CRSS.V5.1.2.2022.Jun2021_Updated.mdl**

3) Import the **Powell_NonEqRes_Jun2021CRSS_04082022.obj** set and sew in the links into and out of Powell

a. Take out the Powell Object from this set and sew in the Powell Object from the current model. This keeps the Powell references in the sub-basins.

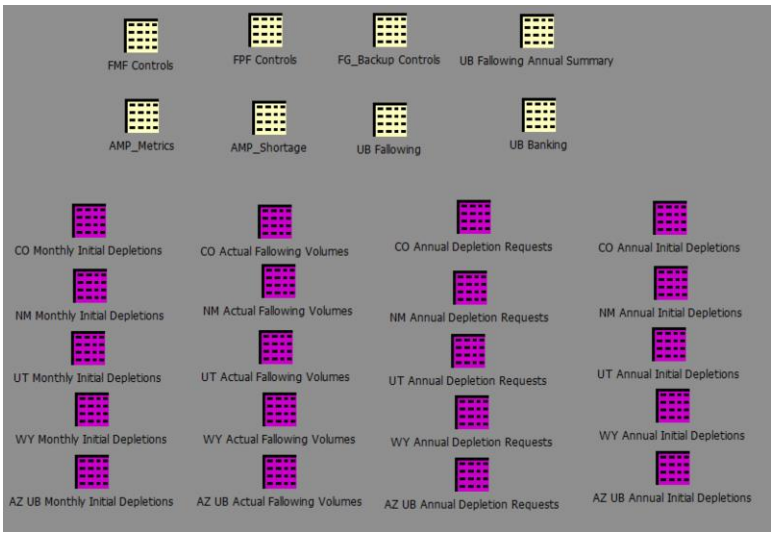
b. Diversion Reach Above Powell. Inflow <---> SanJuanPowell. Outflow

c. NonEqualized Reach Return. Outflow <---> ColoradoAtLeesFerry. Gage Inflow



*Note: not all objects and data added are used in the analysis presented in the current manuscript

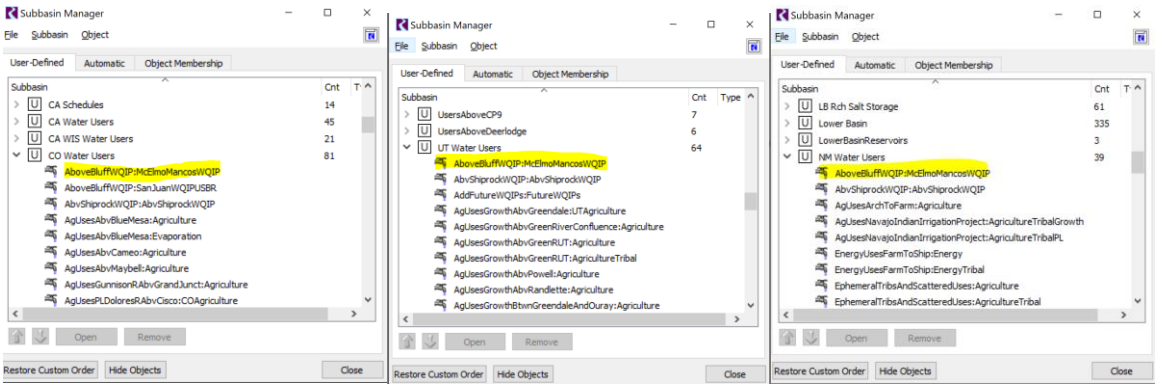
4) Import the **FMF_FPF_Controls_Jun2021CRSS_04082022.obj**, which include a comprehensive list of UB water users in the model and some control data objects.



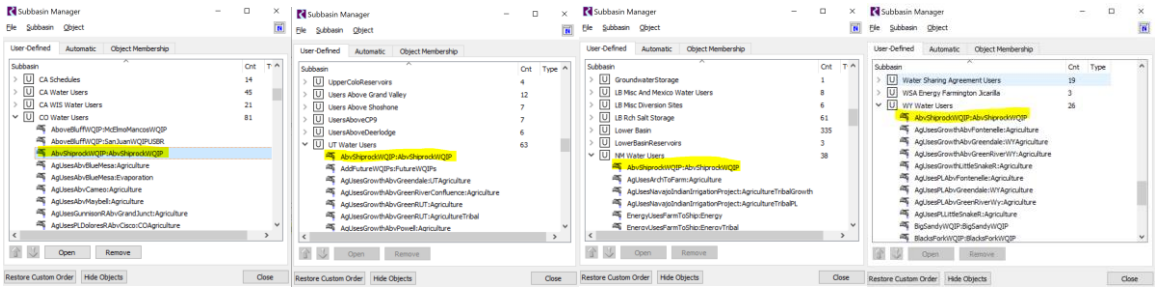
*Note: not all objects and data added are used in the analysis presented in the current manuscript

a. Remove water users that belong to different state water users at the same time.

- remove **AboveBluffWQIP:McElmoMancosWQIP** from **UT** Water Users, **NM** Water Users in RiverWare **Subbasin Manager**



- Remove **AbvShiprockWQIP:AbvShiprockWQIP** from **UT**, **WY** and **NM** Water Users in RiverWare **Subbasin Manager**



5) Other changes

a. Add these two slots that allows these two major California water users to take shortages:

- **LBShort.CoachellaSpecifiedShortage**. Unit set to acre-ft
- **LBShort.MWDSpecifiedShortage**. Unit set to acre-ft

b. Add the following slot and set the following parameters to it.

- **Shortage.LowerBasinMexicoShortageAmount_KGW**

	Shortage.LowerBasinMexicoShortageAmount_KGW					
	Arizona	Nevada	Mexico Assumed	Mexico Minute 319	Coachella	MWD
	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet
0	512	21	999999	80	0	0
1	640	27	999999	146	0	200
2	720	30	999999	275	0	350

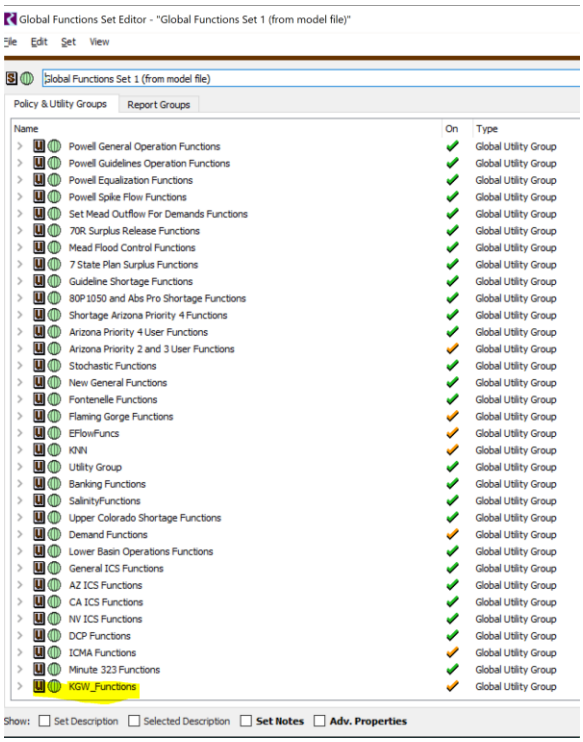
*Note: shortages applied in this analysis are on representative Lower Basin uses and not intended as policy recommendations

c. Change the Input slots to output slots for:

- **COMiscUsesAbvShiprock:Lease.Diversion Requested**
- **COMiscUsesAbvShiprock:Lease.Depletion Requested**
- **COMiscUsesBlwShiprock:Lease.Diversion Requested**
- **COMiscUsesBlwShiprock:Lease.Depletion Requested**
- **AddFutureWQIPs.TotalDiversionRequested**
- **AddFutureWQIPs.TotalDepletionRequested**

6) Import the function group **KGW_Functions_JUN2021CRSS_04082022.gfs** to Global Functions Set. Import the Rule Groups **PolicyGroup_Jun2021CRSS_04082022.rls** to the latest ruleset

a. Open **Global Function Set Editor**, import **KGW_Functions_JUN2021CRSS_04082022.gfs,** and then you will see a KGW_Functions group as below.

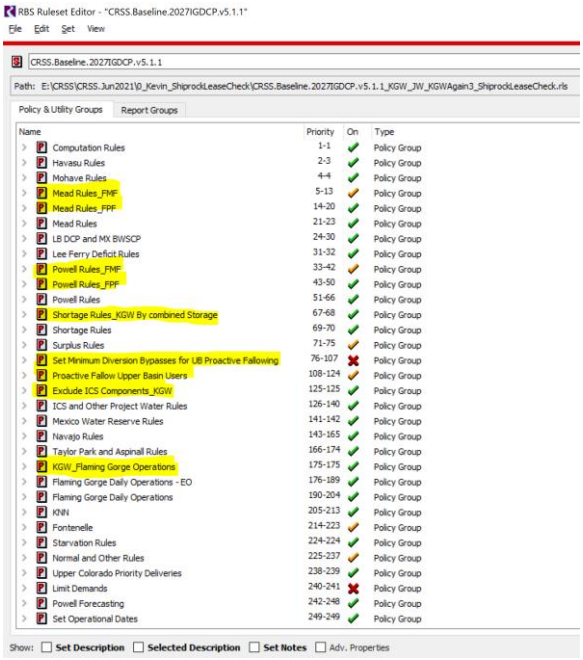


*Note: not all functions added are used in the analysis presented in the current manuscript

b. Make a copy of the existing policy **CRSS.Baseline.2027IGDCP.v5.1.1.rls** in "$CRSS_DIR\ruleset" folder, name one as **CRSS.Baseline.2027IGDCP.v5.1.1_Original.rls**, and name the other one as **CRSS.Baseline.2027IGDCP.v5.1.1_Updated.rls**

c. Load **CRSS.Baseline.2027IGDCP.v5.1.1_Updated.rls**

d. Import **PolicyGroup_Jun2021CRSS_04082022.rls,** then move the highlighted Policy Groups to certain positions shown as below.



e. Add a constraint to each rule in **the LB DCP and MX BWSCP policy group** that only makes these rules fire before the FMF Controls.AMP Combined Storage Start Date

- @"t" < FMF Controls.AMP Combined Storage Start Date
- This allows the user to switch the date of this value to 2026, thereby disengaging this rule group

f. Add a constraint to each rule in the **Shortage Rules** rule group that only makes these rules fire before the FMF Controls.AMP Combined Storage Start Date

- @"t" < FMF Controls.AMP Combined Storage Start Date
- This allows the user to switch the date of this value to 2026, thereby disengaging this rule group and allowing only the Shortage Rules_KGW by combined Storage rule group to fire

g. Add a constraint to each rule in the **Powell Rules** rule group that only makes these rules fire before the FMF Controls.AMP FMF Start Date

- @"t" < FMF Controls.AMP FMF Start Date
- This allows the user to switch the date of this value to 2026, thereby disengaging this rule group and allowing only the Powell Rules_FMF or Powell Rules_FPF to fire
- The fact that it uses the FMF Start Date as opposed to the FPF Start Date is inconsequential.

h. Add a constraint to each rule in the **Mead Rules** rule group that only makes these rules fire before the FMF Controls.AMP FMF Start Date

- @"t" < FMF Controls.AMP FMF Start Date
- This allows the user to switch the date of this value to 2026, thereby disengaging this rule group and allowing only the Mead Rules_FMF or Mead Rules_FPF to fire
- The fact that it uses the FMF Start Date as opposed to the FPF Start Date is inconsequential.

7) Save the **CRSS.V5.1.2.2022.Jun2021_Updated.mdl** and save the **CRSS.Baseline.2027IGDCP.v5.1.1_Updated.rls**

Step 4: Add the Millennium Drought hydrological scenario to the model

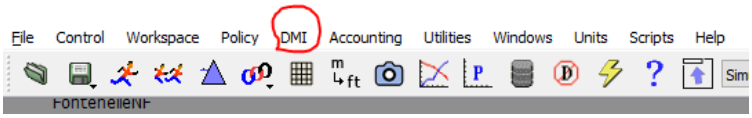
1) Copy and paste the "DataPreparations\2000_Resample" folder to "$CRSS_DIR \dmi" folder

2) Copy and paste "DataPreparations\2000_Resample.control" file to "$CRSS_DIR \control" folder. Replace the "Output. Control" file in this folder with the "DataPreparations\Output. Control" file.

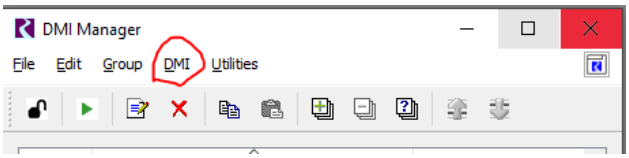
3) Create the Millennium Drought DMI within the model.

a. Load **CRSS.V5.1.2.2022.Jun2021_Updated.mdl**.

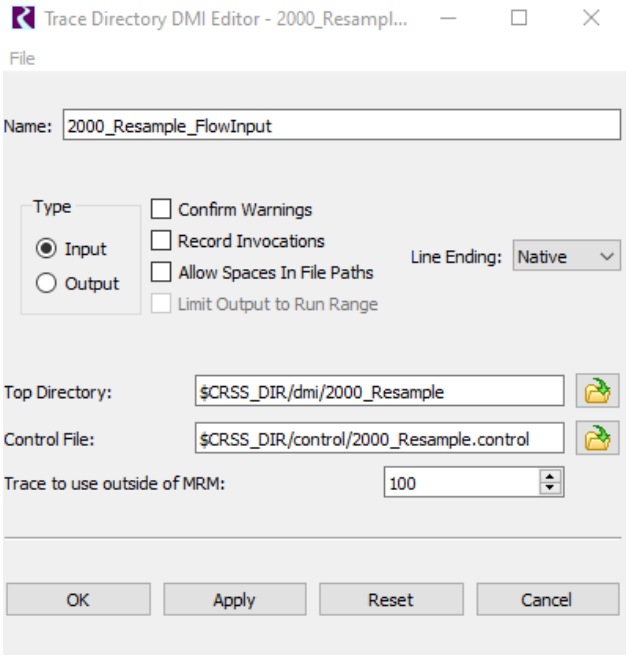
b. Click DMI → DMI manager



c. Within the DMI Manager, click DMI → New DMI → Trace Directory DMI



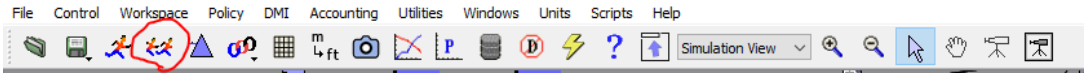
d. Within the Trace Directory DMI Editor, set parameters for **Name**, **Type**, **Top Directory** and **Control File**, and **Trace to use outside of MRM** as below. Then click Apply → OK.



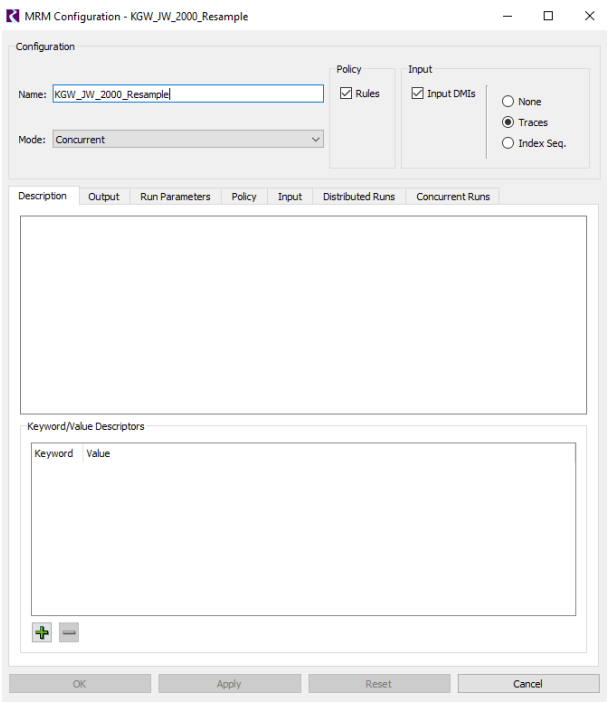
e. Click Apply, OK, and then Save **CRSS.V5.1.2.2022.Jun2021_Updated.mdl**.

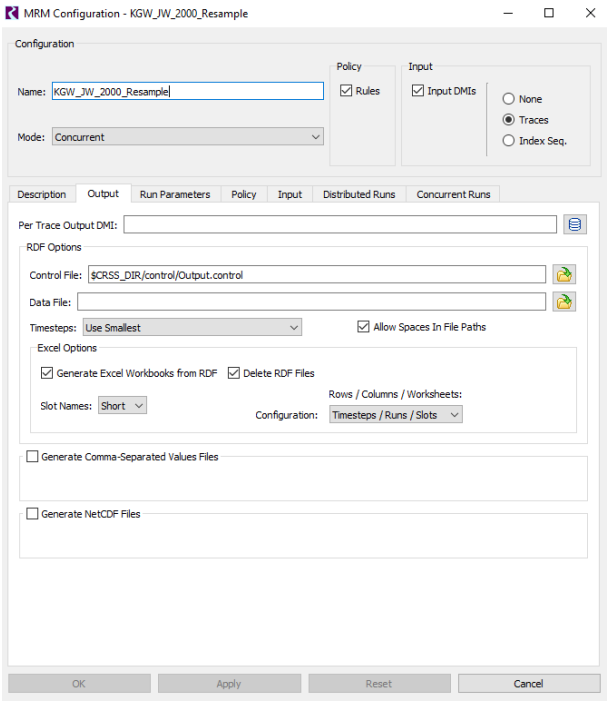
4) Create a **Multiple Run Management (MRM)** configuration for the Millennium Drought scenario.

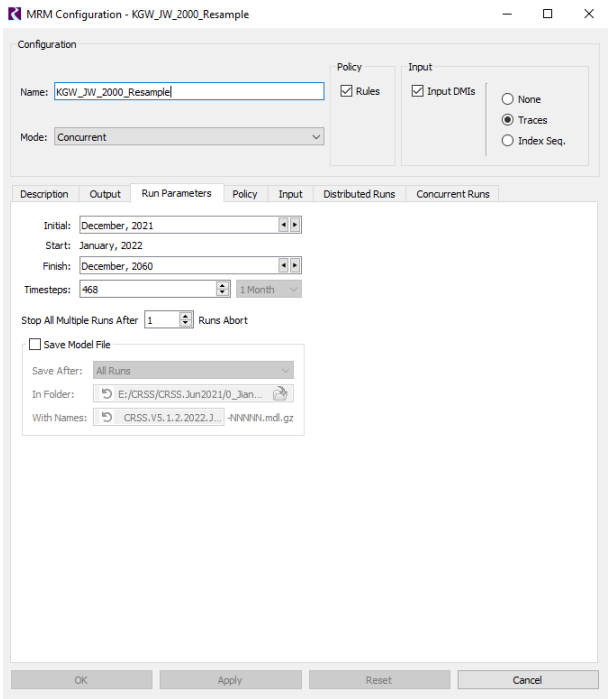
a. Click the icon shown below and then create an MRM configuration

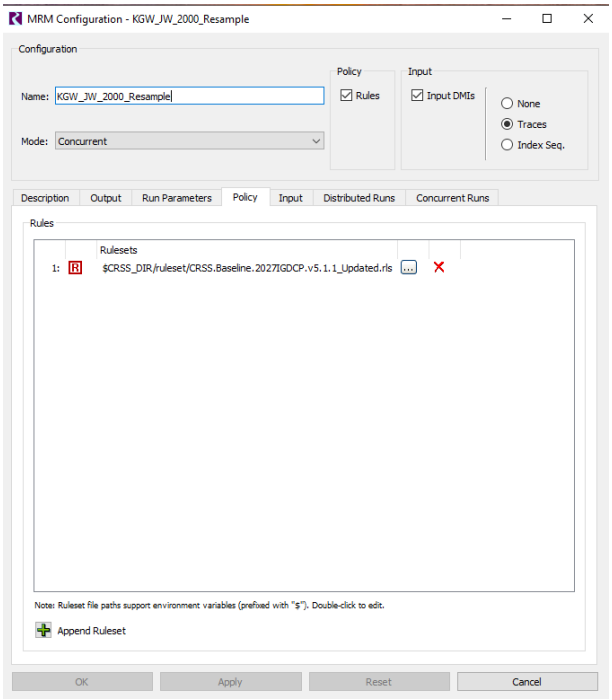


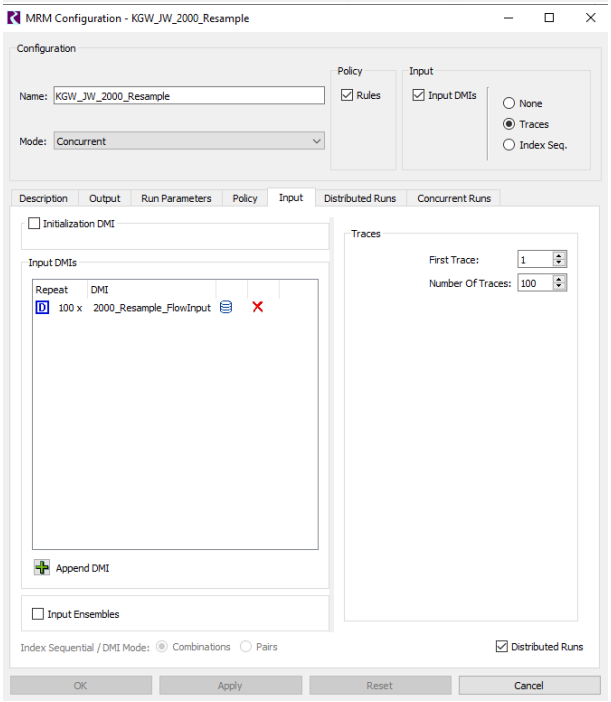
b. Set the configuration parameters according to the following figures. Note that **Run Parameters**, **Distributed Runs** and **Concurrent Runs** tabs are set automatically, users don't need to make any changes.

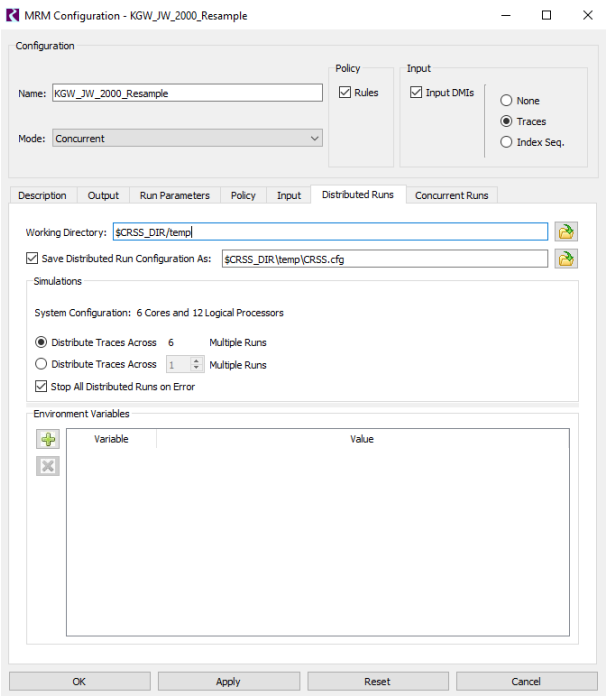

MRM Configuration - KGW_JW_2000_Resample
Configuration
Name: KGW_JW_2000_Resample
Mode: Concurrent
Policy
Rules
Input
Input DMIs
None
Traces
Index Seq.
Description
Output
Run Parameters
Policy
Input
Distributed Runs
Concurrent Runs
Keyword/Value Descriptors
Keyword
Value
OK
Apply
Reset
Cancel

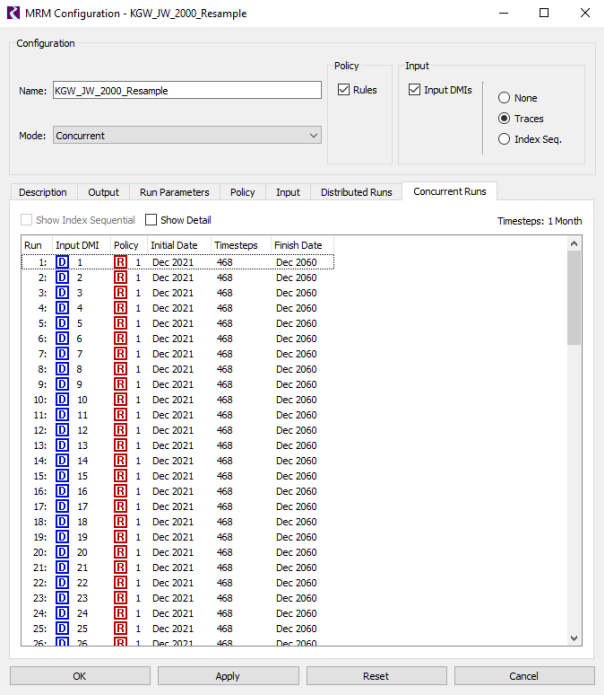

MRM Configuration - KGW_JW_2000_Resample
Configuration
Name: KGW_JW_2000_Resample
Mode: Concurrent
Policy
Rules
Input
Input DMIs
None
Traces
Index Seq.
Description
Output
Run Parameters
Policy
Input
Distributed Runs
Concurrent Runs
Per Trace Output DMI:
RDF Options
Control File: $CRSS_DIR/control/Output.control
Data File:
Timesteps: Use Smallest
Allow Spaces In File Paths
Excel Options
Generate Excel Workbooks from RDF
Delete RDF Files
Slot Names: Short
Rows / Columns / Worksheets:
Configuration: Timesteps / Runs / Slots
Generate Comma-Separated Values Files
Generate NetCDF Files
OK
Apply
Reset
Cancel


MRM Configuration - KGW_JW_2000_Resample
Configuration
Name: KGW_JW_2000_Resample
Mode: Concurrent
Policy
Rules
Input
Input DMIs
None
Traces
Index Seq.
Description
Output
Run Parameters
Policy
Input
Distributed Runs
Concurrent Runs
Initial: December, 2021
Start: January, 2022
Finish: December, 2060
Timesteps: 468
1 Month
Stop All Multiple Runs After 1 Runs Abort
Save Model File
Save After: All Runs
In Folder: E:/CRSS/CRSS.Jun2021/0_Jian...
With Names: CRSS.V5.1.2.2022.J... -NNNNN.mdl.gz
OK
Apply
Reset
Cancel


MRM Configuration - KGW_JW_2000_Resample
Configuration
Name: KGW_JW_2000_Resample
Mode: Concurrent
Policy
Rules
Input
Input DMIs
None
Traces
Index Seq.
Description
Output
Run Parameters
Policy
Input
Distributed Runs
Concurrent Runs
Rules
Rulesets
1: $CRSS_DIR/ruleset/CRSS.Baseline.2027IGDCP.v5.1.1_Updated.rls
Note: Ruleset file paths support environment variables (prefixed with "$"). Double-click to edit.
Append Ruleset
OK
Apply
Reset
Cancel


MRM Configuration - KGW_JW_2000_Resample
Configuration
Name: KGW_JW_2000_Resample
Mode: Concurrent
Policy
Rules
Input
Input DMIs
None
Traces
Index Seq.
Description
Output
Run Parameters
Policy
Input
Distributed Runs
Concurrent Runs
Initialization DMI
Input DMIs
Repeat
DMI
100 x
2000_Resample_FlowInput
Append DMI
Input Ensembles
Index Sequential / DMI Mode: Combinations Pairs
Traces
First Trace: 1
Number Of Traces: 100
Distributed Runs
OK
Apply
Reset
Cancel


MRM Configuration - KGW_JW_2000_Resample
Configuration
Name: KGW_JW_2000_Resample
Mode: Concurrent
Policy
Rules
Input
Input DMIs
None
Traces
Index Seq.
Description
Output
Run Parameters
Policy
Input
Distributed Runs
Concurrent Runs
Working Directory: $CRSS_DIR/temp
Save Distributed Run Configuration As: $CRSS_DIR\temp\CRSS.cfg
Simulations
System Configuration: 6 Cores and 12 Logical Processors
Distribute Traces Across 6 Multiple Runs
Distribute Traces Across 1 Multiple Runs
Stop All Distributed Runs on Error
Environment Variables
Variable
Value
OK
Apply
Reset
Cancel



c. click Apply, and then save **CRSS.V5.1.2.2022.Jun2021_Updated.mdl**

Step 5: Create Models with Different Upper Basin Use Limitations and Maximum Lower Basin Shortages

1) Make 25 copies of the revised model above.

2) Set parameters for each model within RiverWare.

a. Rename each model based on the following table.

Model Parameters and Names		Upper Basin Use Limitations (maf)				
		3	**3.5**	**4**	**4.5**	**UCRC schedule**
Maximum Lower Basin Shortage (maf)	**1.375**	UB3000_LB1375	UB3500_LB1375	UB4000_LB1375	UB4500_LB1375	UBnolimit_LB1375
	1.5	UB3000_LB1500	UB3500_LB1500	UB4000_LB1500	UB4500_LB1500	UBnolimit_LB1500
	2.0	UB3000_LB2000	UB3500_LB2000	UB4000_LB2000	UB4500_LB2000	UBnolimit_LB2000
	2.5	UB3000_LB2500	UB3500_LB2500	UB4000_LB2500	UB4500_LB2500	UBnolimit_LB2500
	3.0	UB3000_LB3000	UB3500_LB3000	UB4000_LB3000	UB4500_LB3000	UBnolimit_LB3000

b. Set corresponding parameters to each model.

- For **UB3000** models, Set **UB Fallowing.UB Cap Value** to 3,000,000.
- For **UB3500** models, Set **UB Fallowing.UB Cap Value** to 3,500,000.
- For **UB4000** models, Set **UB Fallowing.UB Cap Value** to 4,000,000.

- For **UB4500** models, Set **UB Fallowing.UB Cap Value** to 4,500,000.
- For **UBnolimit** models, Set **UB Fallowing.UB Cap Value** to 10,000,000. (A large number like 10 maf allows UB to apply UCRC schedule)

- For **LB1375** models, Set **Shortage.LowerBasinMexicoShortageAmount_KGW** to the following table

	Arizona	Nevada	Mexico Assumed	Mexico Minute 319	Coachella	MWD
	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet
0	512	21	999999	80	0	0
1	640	27	999999	146	0	200
2	720	30	999999	275	0	350

- For **LB1500** models, Set **Shortage.LowerBasinMexicoShortageAmount_KGW** to the following table

	Arizona	Nevada	Mexico Assumed	Mexico Minute 319	Coachella	MWD
	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet
0	512	21	999999	80	0	0
1	640	27	999999	146	0	200
2	785.454545454545	32.7272727272727	999999	300	0	381.818181818182

- For **LB2000** models, Set **Shortage.LowerBasinMexicoShortageAmount_KGW** to the following table

	Arizona	Nevada	Mexico Assumed	Mexico Minute 319	Coachella	MWD
	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet
0	512	21	999999	80	0	0
1	640	27	999999	146	0	200
2	1047.273	43.63636	999999	400	0	509.0909

- For **LB2500** models, Set **Shortage.LowerBasinMexicoShortageAmount_KGW** to the following table

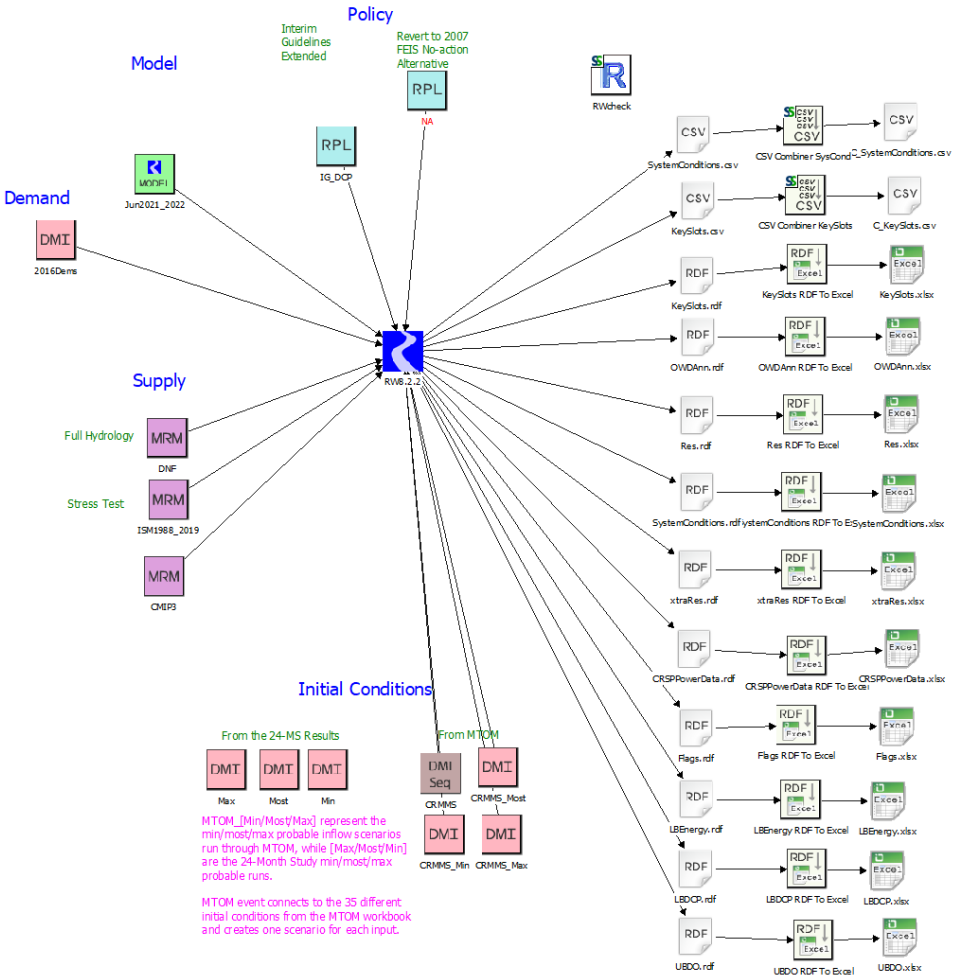
	Arizona	Nevada	Mexico Assumed	Mexico Minute 319	Coachella	MWD
	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet
0	512	21	999999	80	0	0
1	640	27	999999	146	0	200
2	1200	54.5454545454545	999999	500	109.090909090909	636.363636363636

- For **LB3000** models, Set **Shortage.LowerBasinMexicoShortageAmount_KGW** to the following table

	Arizona	Nevada	Mexico Assumed	Mexico Minute 319	Coachella	MWD
	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet	1000 acre-feet
0	512	21	999999	80	0	0
1	640	27	999999	146	0	200
2	1200	65.4545454545455	999999	600	370.909090909091	763.636363636364

Step 6: Run All these Models with RiverSmart

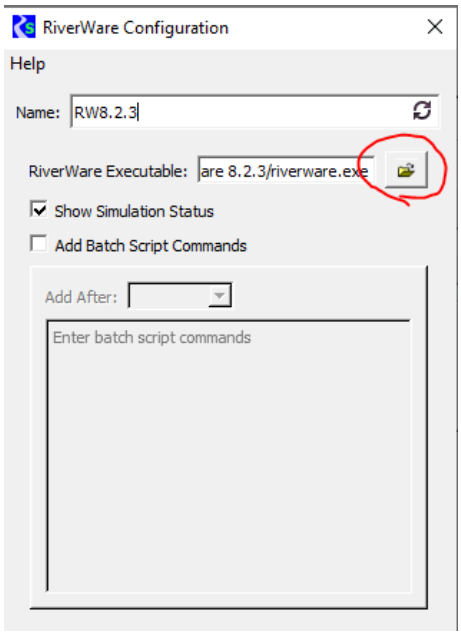
1) Open RiverSmart and load **CRSS_StudyManager_Jun2021_CRMMS.rsm**



2) Setup RiverWare

   a. Double click RW8.2.2, and Change the Name to RW8.2.3

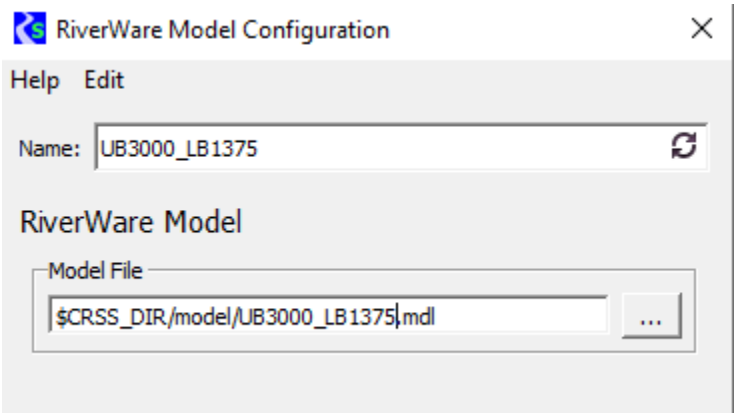
   b. Assign the RiverWare Executable to where you installed your RiverWare



3) Setup 25 models created in the previous step

   a. Make 24 copies of the **Jun2021_2022** model events.

   b. Rename each of them by double clicking the model events and then assign the directory of each model.

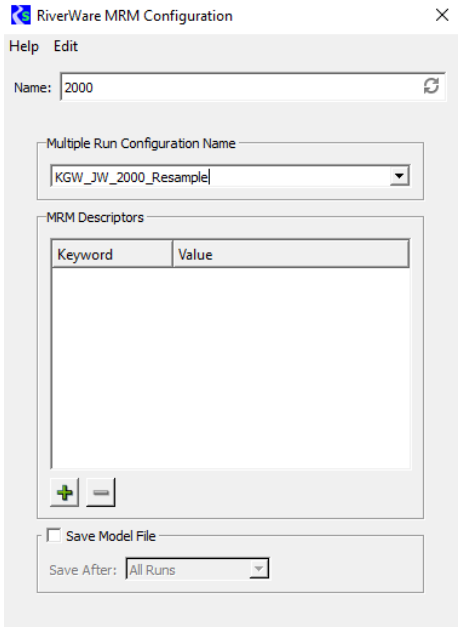


   c. Link all models to RW8.2.3

4) Setup Supply

   a. Double click one of the MRM events, change the Name of this configuration

   b. Select **Multiple Run Configuration Name** as below

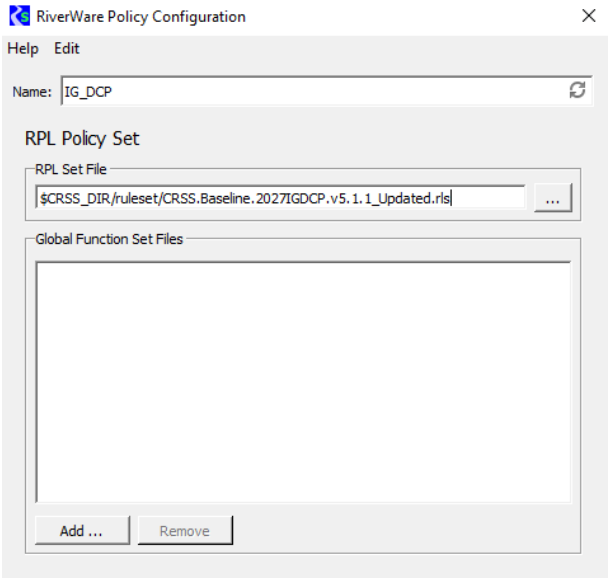


c. Delete the other two MRM configurations

5) Setup Policy

a. Double click the RPL event named “IG_DCP”

b. Setup the path for **RPL Set Policy**

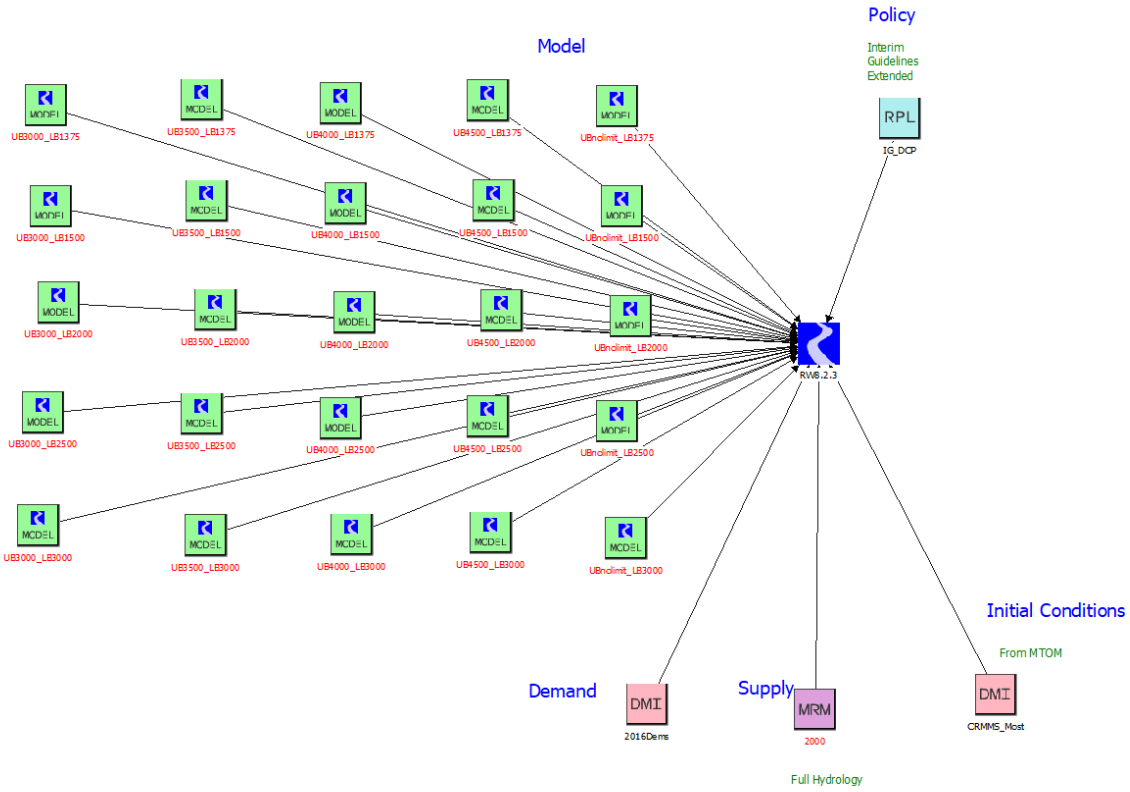


c. Remove the other RPL events

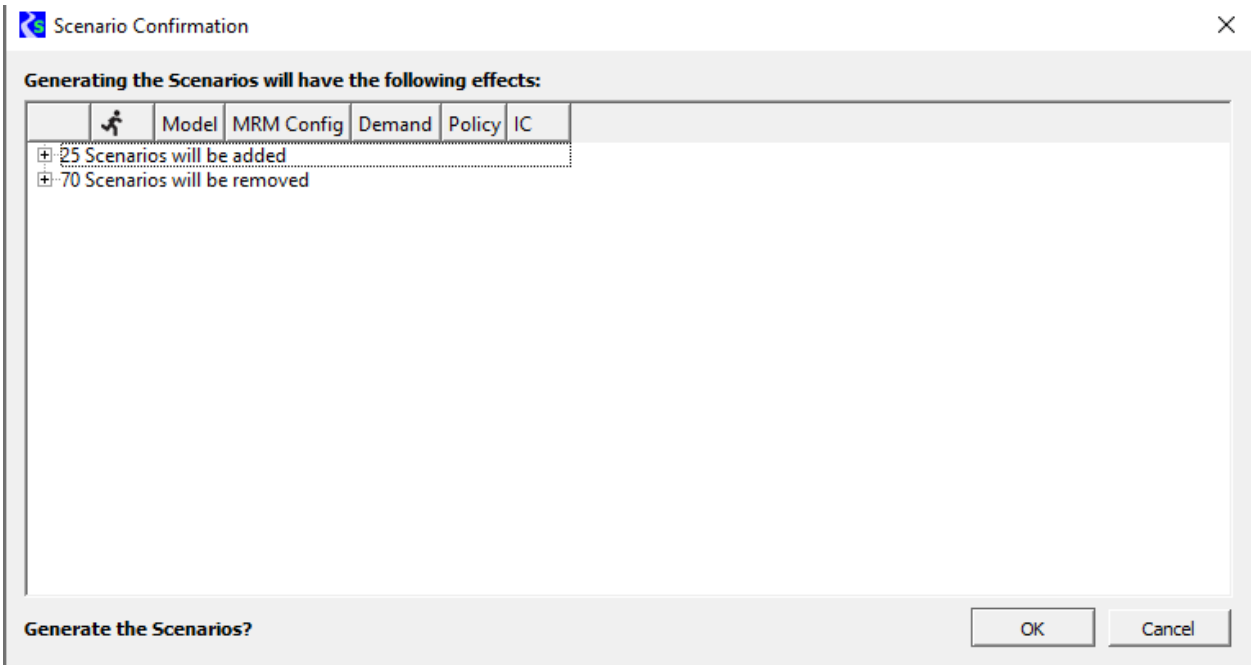
6) Setup Initial conditions

a. Keep **CRMMS_Most DMI** event and delete all other DMI events

7) The final version of RiverSmart model shown below.

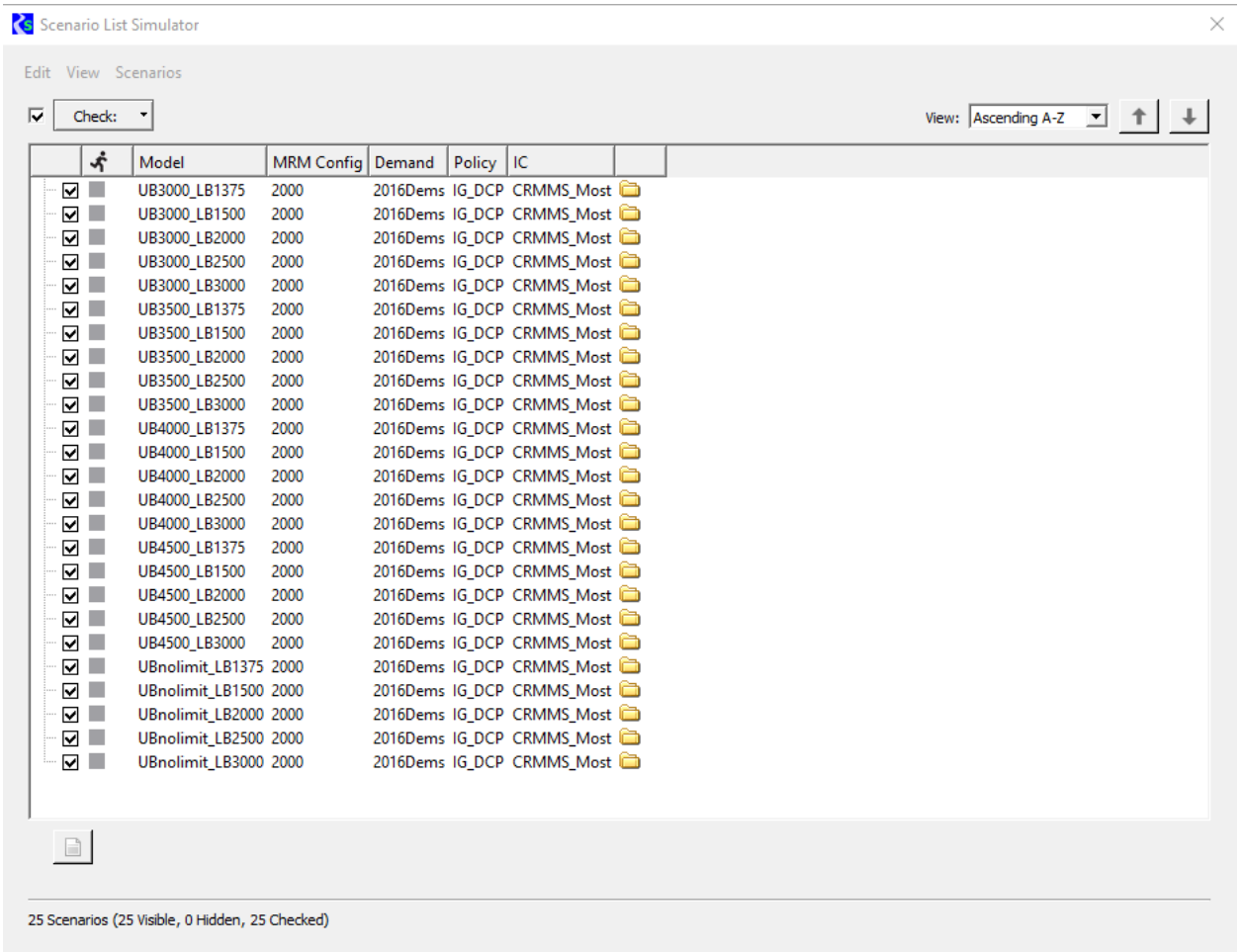


8) Scenarios → Regenerate Scenarios … and then click OK.



9) Scenarios → Simulate Scenarios …

   a. Within the Scenario List Simulator, check all scenarios, and then click Scenarios → Simulate Checked Scenario.



Step 7: Run Status Quo

1) Open RiverWare, Load **CRSS.V5.1.2.2022.Jun2021_Baseline_2000_Resample.mdl** model and
2) Create the Millennium Drought DMI within the model as shown in Step 4.
3) Create a Multiple Run Management (MRM) configuration for the Millennium Drought scenario as shown in Step 4.
4) Run in MRM mode.

Step 8: Generate Figures 1 and 2 with Results

1) Lake Powell and Lake Mead storages could be found at **KeySlots.xlsx**.
    - For the RiverSmart run (Step 6), results are all stored in "$CRSS_DIR\Scenario" folder. Combined Lake Powell and Lake Mead storage could be found at **AMP_ShrtgPwll_Md_Cmbnd_Strg** tab in **KeySlots.xlsx**

- For the RiverWare run (Step 7), results are all stored in "$CRSS_DIR\results" folder. Withing **KeySlots.xlsx**, Lake Powell storage could be found at **PwllStrg,** Lake Mead storage could be found at **MdStrg.**
- Note these results are in monthly basis, and Figures 1 and 2 only use the end of year combined Lake Powell and Lake Mead storages.

2) Calculated average combined storages using the GPAT tool and then copy them to a spreadsheet for Figures 1 and 2. (See What will it take to stabilize the Colorado River_Figures_Revision1.xlsx).