Water in Malta:
Using System Dynamics Modelling for Sustainable Water Management

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Declarations

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02.2023

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Sincerely,
Toni Tonchev

Abstract

Malta, the most water stressed country in Europe, is faced with a future rife with challenges such as those caused by population growth, climate change, and overexploitation of groundwater resources. This paper uses a System Dynamics modelling approach to simulate and analyse Malta's water infrastructure over a 100 year period (2000-2100) and tackle the problem of how water resources in Malta can be effectively managed over the coming decades. The model is built using Stella Architect and validated through historical data, expert consultation, and sensitivity analysis. Multiple scenarios are tested including climate change projections based on the RCP pathways as well as various water management strategies. Results indicate that without policy change, groundwater levels are likely to decline sharply, especially under scenarios with high-emissions or with a large agricultural sector. However, utilising a combination of targeted policies, such as increasing reclaimed water (New Water) use in agriculture and shifting Water Services Corporation's freshwater blend further towards desalination, groundwater levels can be stabilised and in some cases even recover. This research aims to offer actionable insights for an effective water policy strategy in Malta and demonstrate the utility of System Dynamics analysis in complex environmental decision-making.

1. Introduction

Malta, a small Mediterranean country with a limited freshwater supply, has long struggled with water scarcity and is projected to remain among the most water-stressed regions both in Europe (ERA 2015; Hartfiel, Soupir and Kanwar 2020) and globally (Papadimitriou et al. 2019). This is primarily due to its scant surface water resources which, combined with a semi-arid climate with lower rainfall and high summer evapotranspiration, result in a heavy reliance on groundwater abstraction and energy intensive desalination through the use of reverse osmosis plants. Groundwater abstraction has risen at an average rate of 4% per year, partly due to unregulated private borehole use (Papadimitriou et al. 2019; MESDC 2018) and the current abstraction rate for the mean sea level aquifers exceeds sustainable levels by up to 50% (ERA 2024; Papadimitriou et al. 2019). These issues are all compounded by a reduction in rainfall and consecutive drought years, a trend which is projected to continue into the future as the effects of climate change are felt more strongly (Galdies and Meli 2022; Giorgi and Lionello 2007). In the Maltese context, such freshwater shortfalls are made up for by the use of reverse osmosis plants, however these are power intensive and expensive, with electricity constituting around 75% of operating costs (Goldstein 2010). Consequently, dependence on desalination imposes both economic and environmental burdens on Malta, increasing its carbon footprint as population and water demand continue to grow (Hartfiel, Soupir and Kanwar 2020).

Due to the social and economic significance of water use and allocation, it is important for policy makers to consider both present and future allocation needs. This can be challenging in a complex dynamic system where factors are interconnected and drivers such as population, rainfall and the agricultural sector's relative size all change year to year. The aim of this paper is to explore how Malta can manage its freshwater resources over the coming decades and better understand what the potential impacts of various policy decisions and scenarios will be with regards to the groundwater aquifers and overall demand. In order to explore this System Dynamics modelling will be used. A system dynamics approach can be used to model potential long term impacts of different water resource policies (Baskoro, Hermawan and Permadi 2021) such as by simulating how the behaviour of the system, or part of the system, can be changed. Such an approach is useful in building understanding of system structure and exploring feedback effects within the system in order to inform water management strategies (Park, Vahideh Sahleh and Jung 2015). System dynamics models allow for a kind of simulation and analysis quite suitable for water infrastructure problems, and numerous studies have conducted this form of analysis to gain insights into complex water infrastructure system behaviours (Sahin, Stewart and Porter 2015). To the author's knowledge, no such modelling approach has been used to examine the Maltese context.

This paper will present the work done towards building a model to tackle the water resource management problem that Malta will face over the coming years. Feedback effects will be demonstrated and scenarios incorporating population growth, climate change driven reductions in rainfall, and alternative policy interventions (such as a reduction of the agricultural sector's water abstraction) will be analysed to assess its long-term impacts on groundwater sustainability, desalination demand, and overall system resilience.

2. Background / Literature Review

2.1 Malta as a water stressed country

Malta is a small Mediterranean country which is designated as the most water stressed country in Europe (ERA 2015; Hartfiel, Soupir and Kanwar 2020). As a country with a semi-arid climate, Malta has historically received around 550 mm of rainfall per year on average though most tends to occur between October and February; on the flipside during the summer months Malta receives very little rain. This pattern matches up with Malta's peak tourism months being July and August, and as this is also the peak period for agricultural irrigation, these compound into further stressing the already high water demand of the island (MRA 2013).

Due to a lack of surface water resources, from the 1980s, Malta's freshwater supply was already very reliant on saltwater desalination (FAO 2006), a pressure which has only grown with Malta's population and tourism growth. The increased reliance on energy intensive desalination also means that Malta has its freshwater production tied to natural gas and oil imports. The other primary source of freshwater for the country is groundwater, whose abstraction has risen at an average rate of 4% per year, in part due to unregulated private borehole use (Papadimitriou et al. 2019; MESDC 2018). Much of the groundwater abstraction is attributed to Malta's agricultural sector which consumed 46% of total freshwater between 2003 and 2013 (Papadimitriou et al. 2019). Groundwater is easily accessible and significantly cheaper than desalination, making it very appealing to those in the agricultural sector, however the current abstraction rate for the mean sea level aquifers exceeds sustainable levels by up to 50% (ERA 2024; Papadimitriou et al. 2019), increasing the risk of saline intrusion, which would degrade both soil and crop yields (Daliakopoulos et al. 2016).

These challenges are further exacerbated by climate change, which has seen Malta suffer an increase in consecutive drought years and a reduction in average yearly rainfall (NSO 2022). Moreover, climate projections based on the Representative Concentration Pathways (RCP) scenarios indicate that by 2050 and 2070, the Maltese islands will be more arid, have a higher rate of evapotranspiration, undergo increased heat stress and receive less precipitation (Galdies and Vella 2019).

2.2 Malta's current water resource management

According to ERA's 3rd River Basin Management Plan for Malta (2022), henceforth "RBMP", 54% of Malta's freshwater production came from groundwater and 35% from desalination with the remainder coming from non-conventional water sources; 9% from rainwater harvesting and 2% from reused water. The 3rd RBMP also outlined projections for an increase in the use of non-conventional water sources by 2025 and onward with the intent of reducing pressure on Malta's groundwater. According to the The 2nd Water Catchment Management Plan (ERA 2015), 77% of groundwater was used for agriculture and only 23% went to non-agricultural sectors. Agriculture was also shown to have accounted for 50% of Malta's total freshwater consumption for that year 2014, amounting to around 31 million m^3 of freshwater.

Freshwater for non-agricultural sectors in Malta consists of a mixture of desalinated water (~65%) and abstracted groundwater (~35%), according to public figures made available by Water Services Corporation (Water Services Corporation 2023). The exact ratio has gradually shifted over time as water demand has grown, shifting to a higher proportion of the mixture coming from desalinated water.

As previously mentioned, groundwater abstraction in Malta is currently at an unsustainable level. Natural groundwater recharge comes from rainfall, with around 27% of rain falling on the island ending up as recharge for the aquifers (ERA 2015). As long as abstraction rates remain higher than the average rainfall recharge, Malta's groundwater level will gradually shrink over time. When one takes together projections which show increased population growth, increased irrigation demand and reduced rainfall, it becomes apparent that Malta's groundwater resources face certain risks. Such projections would mean that groundwater abstraction is liable to increase, while natural recharge is liable to decrease, and this could result in the groundwater level plummeting over the coming decades.

2.3 System dynamics for water resource management

Water resource management in a context such as Malta's is a complex problem. Water demand and production have many interconnected variables which affect or constrain them, and feedback effects present in the system may not be readily apparent. The objective of this paper is to attempt to provide an answer to the following problem: *"How can Malta effectively manage its water resources over the coming decades?"*. Due to the complex nature of the problem, behaviour over time may also be non-linear if certain thresholds or tipping points are exceeded in various scenarios. Since system dynamics is a good approach for simulating complex behaviours over time (Sterman 2000, Forrester 1971) it appears to be a good fit for water resource management as well.

A system dynamics approach has been used in many studies for assessing long term impacts of different water resource policies by building understanding of system structure and exploring feedback effects within the system in order to inform various strategies, simulating how the behaviour of the system, or part of the system, can be changed (Baskoro, Hermawan and Permadi 2021; Gohari, Madani and Mariño 2009; Mirchi and Madani 2017; Park, Vahideh Sahleh and Jung 2015). As mentioned explicitly by Madani and Mariño (2009), a common problem for arid to semi-arid environments is the difficulty of balancing variable water supply to meet the demand imposed by a growing population and irrigated agriculture. The study points out the importance of having an understanding of the interactions of various drivers as without this, management decisions can fall short of providing a solution. A systems approach involves a kind of analysis that sees interrelationships and patterns of behaviour rather than individual independent variables. System dynamics has been used to analyse numerous water management problems (Simonovic and Li 2004; Tidwell et al. 2004; Xu et al., 2002) as well as for environmental sustainability analysis (Forrester 1971; Saysel, Barlas and Yenigün 2002).

3. Methodology

System Dynamics (SD) is a method one can use in order to better understand the behaviour of complex systems made up of interconnected, interactive variables and feedback effects (Sterman 2000; Sterman 2006; Meadows 2008). As discussed in the previous section, water resource management is a complex problem, involving consumption from numerous sectors, shifting demand, fluctuating rainfall patterns and much more. In order to develop the SD model used in this study the principles of Forrester’s (1958) methodology were broadly applied. Namely, this was an iterative process of building the model from the ground up while maintaining the model's purpose as a means to solve a problem rather than purely gaining general insight. As such, the first step of building the model was establishing the problem statement concretely. This was useful in establishing the model’s scope, specifically keeping the modelling work focused around Malta’s water production and consumption and the relevant factors which impact these primary components. From this process, key variables were established for the system and some key hypotheses were established as to the problem: water demand would be higher than the natural recharge of Malta’s natural freshwater sources and thus the freshwater reserves would decrease over time. This problem formulation and scope was achieved through a mix of literature review on water management in Malta as well as consultation with an expert in the sector. Expanding and iterating the model based on historical data was next, where the model was built such that it could correctly replicate the historic behaviour up to the present time, before being run out into the future.

As the model was iterated and grew over time, an expert in the field was consulted as a form of face validity to ensure that the model’s linkages, structure and behaviour were accurate to the real world mechanisms. Resources such as the 3rd River Basin Management Plan (ERA 2024), the 2nd Water Catchment Management Plan (ERA 2015) and publications made by the Water Services Corporation were used to build an understanding of the mechanisms behind Malta's water infrastructure as well as to obtain relevant historic data. The simulation's time horizon spans 100 years from 2000 to 2100 and was built in Stella Architect version 3.8.1.

In addition to expert consultation, the model was also validated through a series of tests as described by Sterman (2000) and Richardson and Pugh (1981). These included verifying that historic behaviour was correctly reproduced as well as extreme condition tests, such as demand drastically increasing and the aquifer running completely dry, or rainfall becoming extremely erratic. This is important to ensure the model behaves as it should - if the aquifer is empty, no more water can be drawn from it. If water demand has increased dramatically, desalination must have increased. If rainfall has dropped to zero, the agricultural sector must use more water to irrigate crops. Testing also included variable validation in terms of the correct use of units. As such, the model is tested to ensure that it does not violate the laws of physics. Based on the understanding built during the creation of the model and on climatic projections, several scenarios and policies were developed and their impacts and consequences tested. These can be found in section "*5. Results and Discussion*".

4. Model

4.1 Model Sectors

The simulation model consists of a series of interconnected sectors, comprising around 100 variables and 9 stocks, with a total of 19 feedback loops emerging from the resulting structure. Stocks in such a model represent an accumulation over time, for example, the groundwater stock represents the total amount of water estimated to be present in Malta's groundwater across its aquifers at any given time. Based on its net flow change, i.e. the groundwater abstraction versus its recharge, such a stock will either increase or decrease as the model runs. Mathematically, the integral equation below is how the calculation for the groundwater stock is performed. Similar integral calculations are performed to calculate the changes of the other stocks in the model.

$$x(t) = x(0) + \int_0^t (bx - fx)\, dt$$

Where:
x(t) is the groundwater at time t
x(0) is the groundwater at the time before
bx is rainfall additions
fx is the withdrawals of groundwater, discharges to the sea, and agricultural withdrawals.
dt is the time interval between calculations.
$\int_0^t$ is the interval over which the calculation is done.

This section of the paper will detail the various sectors of the model and how they function, as well as detail, where relevant, the various assumptions that were made and the validation that was performed.

4.1.1 Population Sector

Figure 1 below shows the sector of the model simulating population growth over time in the Maltese islands:

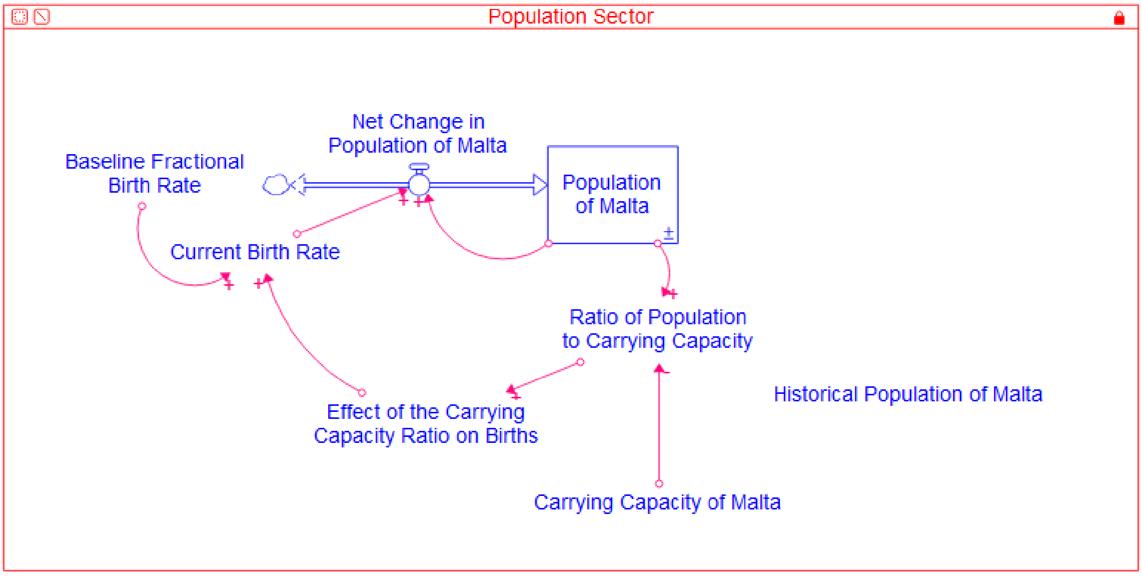

Figure 1: Population sector as modelled

Population of Malta is a stock, changing over time based on the *net change in the population of Malta* year to year. A *carrying capacity of Malta* variable was also introduced in order to ensure that population cannot grow indefinitely as there exist physical limits for the island. As the current population approaches the carrying capacity, this ratio has a detrimental effect on birth rate as it grows, slowing population growth down. As such, the current birth rate is a product of the *effect of the carrying capacity ratio on births* and the *baseline fractional birth rate* for the island.

As part of the validation process, historical data on Malta's population over the last 25 years was obtained and compared to the simulated results, as can be seen in figure 2 below.

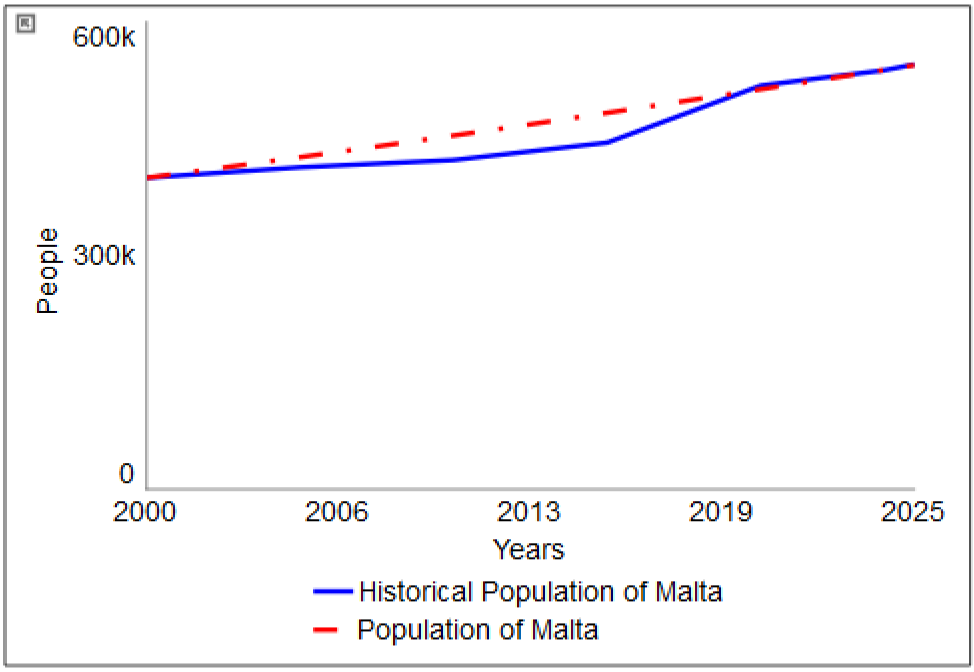

Figure 2: Historical population of Malta (blue) vs model simulated population (red)

4.1.2 Non-Agricultural Water Demand

Water consumption in Malta, as described in the 2nd Water Catchment Management Plan (ERA 2015) is broken down into four primary sectors: Agricultural, Domestic, Commercial and Public. Agricultural water consumption is more complicated and thus will be discussed in its own dedicated section. The model structure for the latter three however may be seen in figure 3 below:

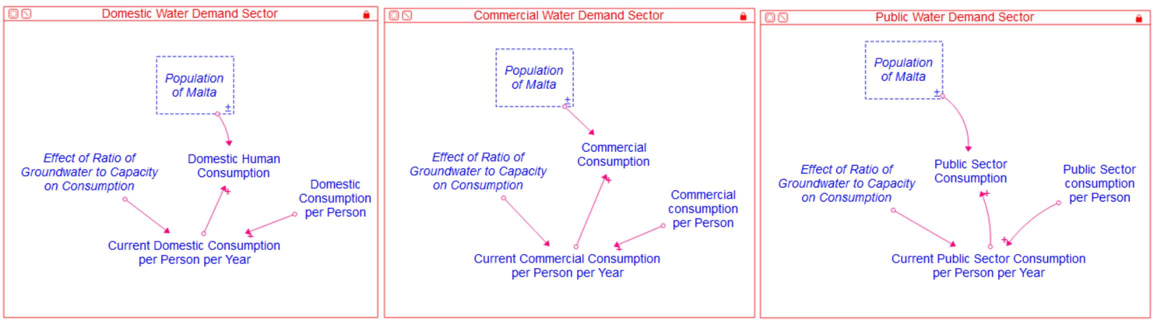

Figure 3: Non- Agricultural Water Demand as modelled

All three sectors follow the same structure due to the same underlying assumption: as all else being equal, as population grows, the water consumption of each of these sectors will also increase. In order to simulate this, historical data published by ERA (2015) on the water consumption of each sector was found. This was used to generate an estimation for the consumption per capita for each sector. The implementation was validated by running the model and observing a given year where the total water consumed by the sector was known and comparing how the simulated behaviour matched up to the historical data.

For example, the historical data reports an estimated 24.8 million cubic metres for the year 2014 (ERA 2015). Estimating a freshwater *Domestic consumption per person* of 52m^3 based on Malta's population at the time, the model simulates a total yearly consumption for the domestic sector of around 24.9 million cubic metres for that same year. This sort of fine tuning and verification was performed for the other two sectors.

The final structure of the model is a variable exerting an effect on the consumption of these sectors. This variable will be discussed in more detail in section "*4.1.5 The Groundwater Sector*". To put it simply, the variable exerts a small effect on the amount of water consumed by these sectors as water scarcity increases, slightly reducing their consumption.

The total demand for these three sectors were taken to calculate a total pumping demand for freshwater, as can be seen in figure 4:

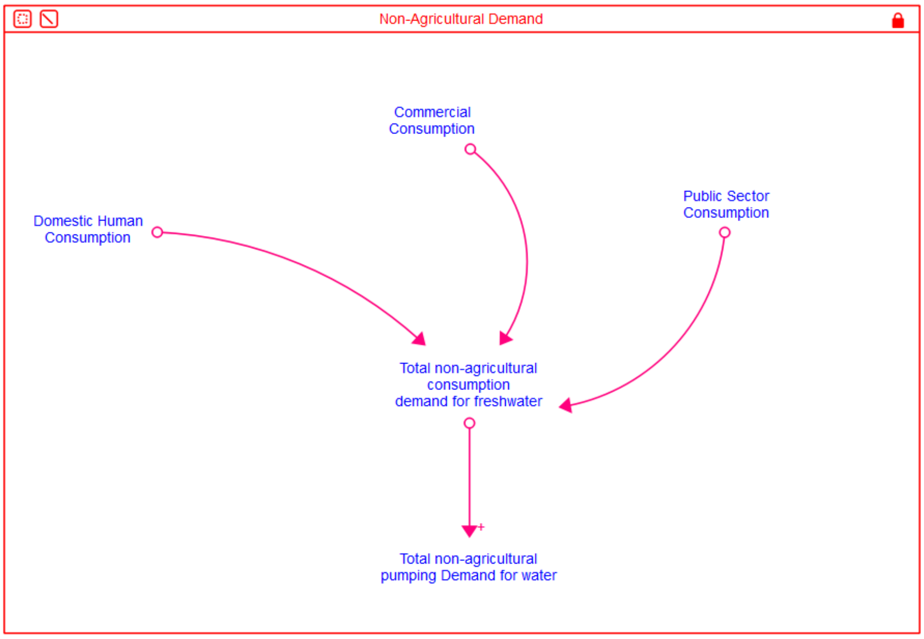

Figure 4: Total non-agricultural freshwater demand

4.1.3 Agricultural Demand

This sector attempts to calculate the amount of freshwater consumed by the agricultural sector, as can be seen in figure 5 below. The structure differs greatly as unlike the previous sectors, agricultural water consumption is not directly linked to population. In addition, unlike the previous sectors which satisfy their water demand through the freshwater blend provided by Water Services Corporation, agriculture depends primarily on groundwater abstraction for irrigation.

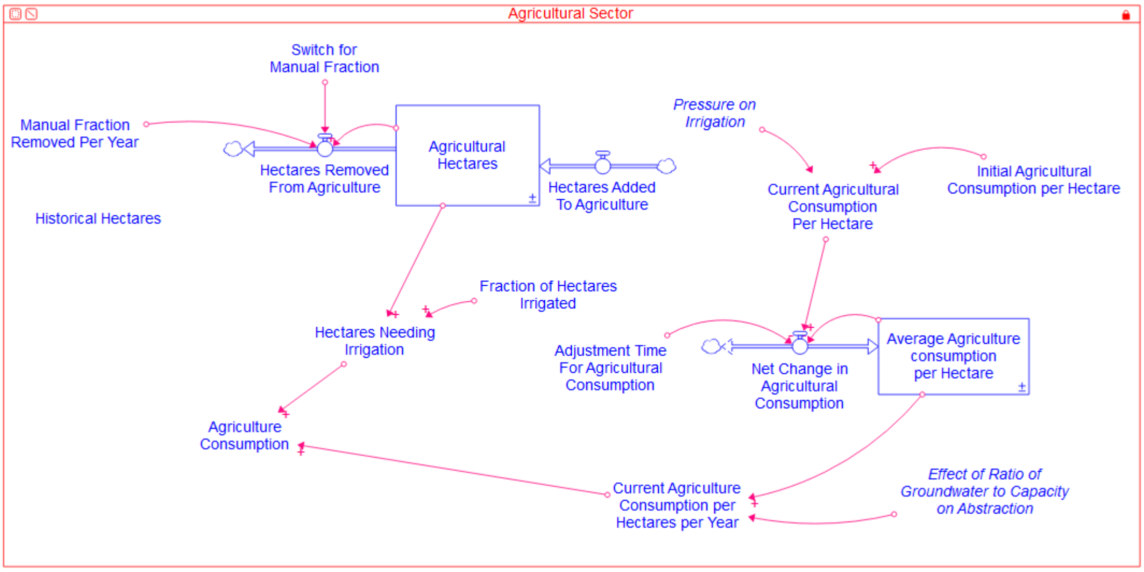

Figure 5: Agricultural demand as modelled

The right hand side of this sector of the model calculates the consumption per hectare. This section of the model used historical data from the National Statistics Office (2010) on how much water was used to irrigate a given number of hectares in Malta in 2009 and calculated an *initial agricultural consumption per hectare*. An additional variable *Pressure on Irrigation* can be seen feeding into the current consumption, and this is meant to represent the impact of fluctuations of rainfall year to year. The assumption is that during a year with a lot of rain, less irrigation will be needed while during drought years with minimal rainfall, more irrigation will be required from the baseline. The exact manner in which this variable is calculated can be seen in section *"4.1.4 Rainfall Sector"*.

The left hand side of this sector of the model simulates the actual number of agricultural hectares being farmed in a given year. As noted in the literature (NSO 2010) only 29% of hectares are actually irrigated as much of the rest is designated as forage. Together, the number of hectares requiring irrigation and the water consumption per hectare give us the yearly agricultural consumption.

The upper part of the diagram shown in figure 5, controlled by a switch, allows for a yearly fractional reduction in agricultural hectares being farmed in Malta. Historic data (NSO 2016) shows a downward trend, indicating that a reduction occurs, and this data was used to calculate the fractional decline. Validation was once again done by comparing historic data to the simulations results, as can be seen in figure 6 below:

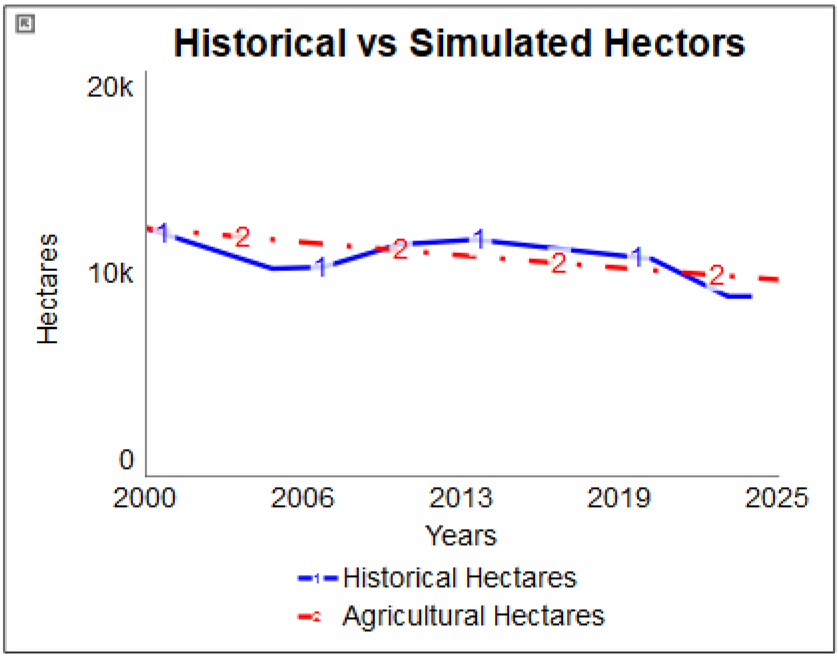

Figure 6: Historical Hectares (blue) vs Simulated Hectares (red)

4.1.4 Rainfall Sector

The rainfall sector of the model (figure 7 below) aims to generate a realistic pattern of rainfall, something challenging for the Maltese context due to great inter-year rainfall variability.

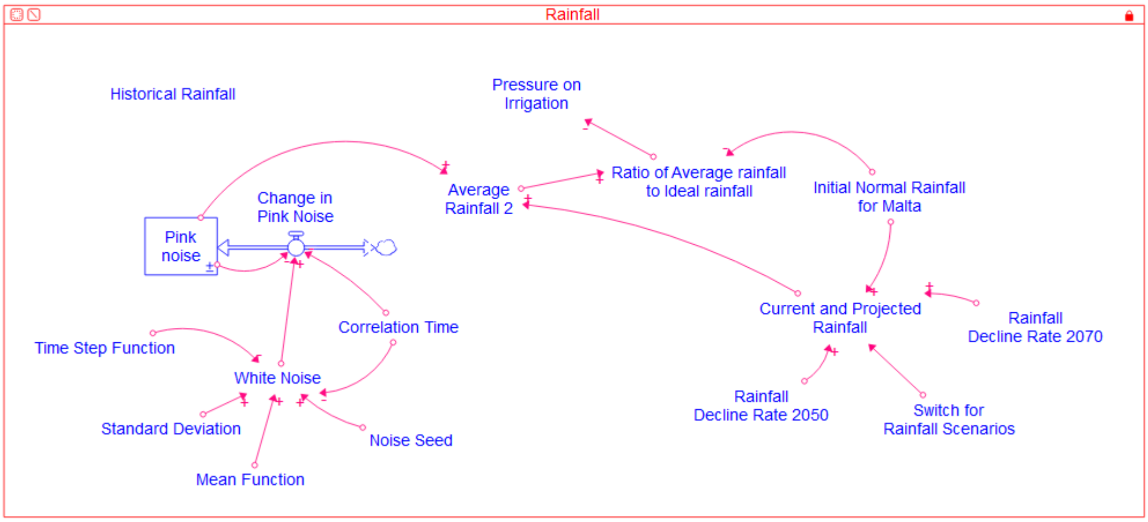

Figure 7: Rainfall as modelled

Rainfall in the model was built up on the basis of a baseline, present in the model as *Initial Normal Rainfall for Malta.* This value is based on historical data taken from the National Statistics Office (2022) and represents the average rainfall over a 20 year period, from the year 2000 to 2020. This is taken to be a baseline for 'normal' rainfall in Malta for the purposes of the model. This rainfall may be acted upon by projected decline rates based on the standard RCP scenarios, which will be further discussed in section "*5. Results and Discussion*".

As the rain experiences a lot of year to year variability, a pink noise structure, adopted from Sterman (2000) was implemented to add variation and fluctuations to the yearly rainfall. This noise was calibrated to mimic the behaviour of the historic data, as can be seen in figure 8 below with the solid blue line representing historic data while the dotted purple line represents the model's simulation.

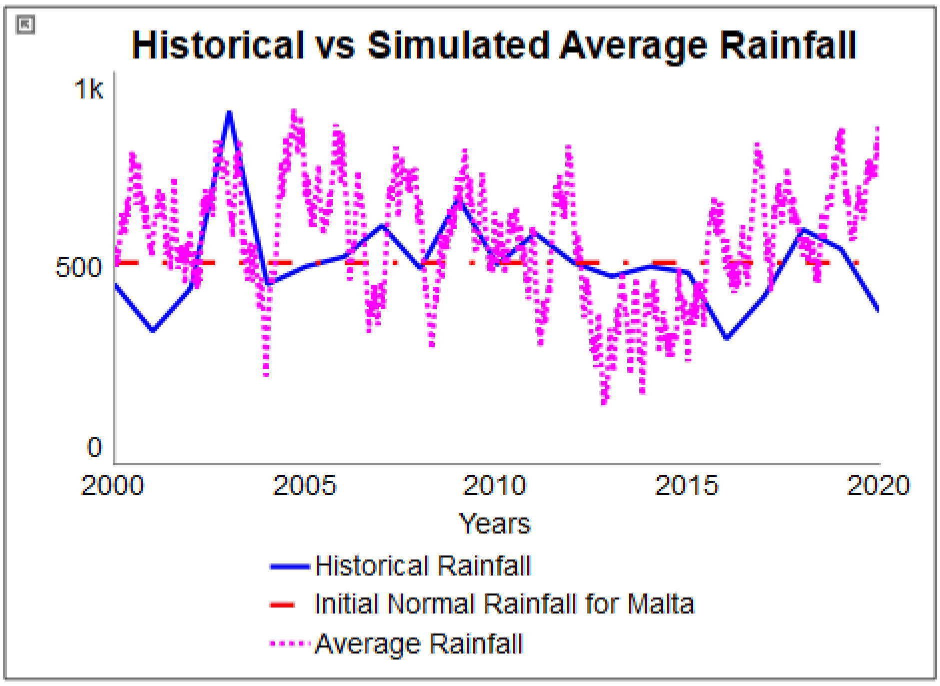

Figure 8: Historic rainfall (blue) vs Simulated Rainfall (pink)

4.1.5 Groundwater Sector

This sector aims to model all the abstractions from and additions to groundwater in Malta, including natural recharge from rainfall and subsurface discharge to the sea as well as abstractions done by WSC and by the agricultural sector. Malta's largest aquifers are mean sea level aquifers, a freshwater lens sitting on seawater which can shrink or recover based on the net flow of water. The model therefore simulates a decrease in the capacity of the aquifer to hold water in years where over abstraction occurs, and structurally allows for the capacity to recover in years where the recharge rate exceeds abstractions.

The groundwater sector of the model can be viewed below (figure 9):

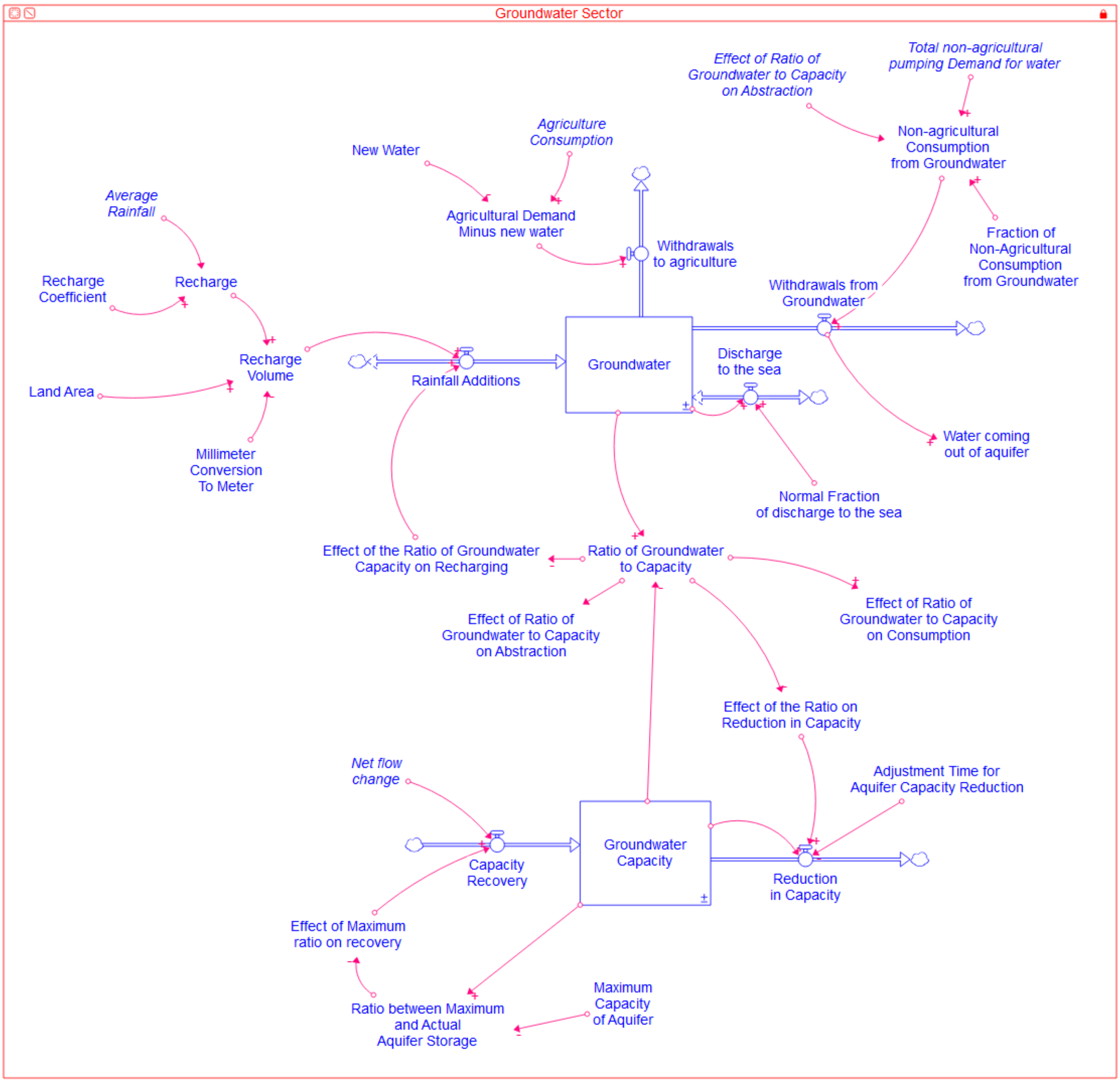

Figure 9: Malta's groundwater as modelled

According to ERA (2015) around 27% of rain falling on the Maltese islands infiltrates and recharges the aquifer, with the rest being lost to evapotranspiration or runoff. The model therefore uses this recharge coefficient along with the rainfall calculated in the "rainfall sector" and Malta's land area in order to calculate the amount of natural recharge that groundwater in Malta experiences in any given year.

Groundwater leaves the aquifer in three primary ways.

- Foremost, the agricultural sector abstracts groundwater, represented by the outflow *"Withdrawals to agriculture"*. This is based on the agricultural demand calculated in the "*Agricultural Demand"* sector. This demand is partially offset by the variable *"New Water",* representing reclaimed water aimed at reducing farmer's reliance on the groundwater body.

- The other anthropogenic outflow is WSC's groundwater abstraction for meeting the demand of the non-agricultural sectors, represented by "*withdrawals from groundwater*". This total demand was calculated in the *"Non-Agricultural Sector"* however WSC does not rely solely on groundwater to provide water to customers, in fact only around 35% of the non-agricultural demand is met by groundwater, the rest coming from desalination.
- The final outflow is natural discharge to the sea, which was calculated by establishing a fractional discharge using discharge estimates by ERA (2014).

The model also introduces a time delay between the groundwater's depletion and the corresponding capacity reduction, meaning the groundwater will deplete faster than the capacity will decrease. The ratio between these two is used to generate an effect simulating increasing water scarcity and is used in other parts of the model to reduce consumption. Additionally, this also has the effect wherein if the groundwater is completely used up the corresponding consumption from it would also cease - this is important as it is not possible to abstract water from an empty aquifer.

The groundwater capacity's behaviour is based on the net flow change, which is used to calculate both the yearly balance change of water in the aquifer as well as the cumulative effects, as can be seen in figure 10 below.

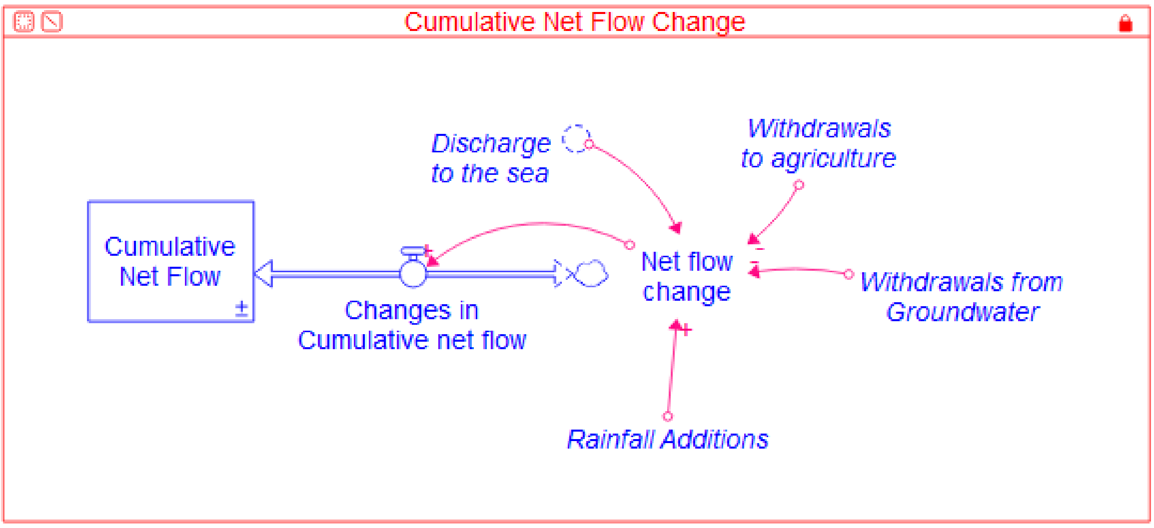

Figure 10: Net Flow Change for groundwater as modelled

4.1.6 Desalination Sector

This sector of the model simulates the desalination of water in order to meet non-agricultural demand. WSC accomplishes this by blending groundwater with desalinated water and distributing the blend through a pipe network. There are two stocks in the model, as can be seen in figure 11 below. The first, *WSC Fresh Water Storage,* represents the 24 reservoirs used by WSC to temporarily store the blend before distribution with a combined maximum capacity of 400,000 m^3 (WSC 2023). The other is a stock representing the total amount of desalinated water produced by the desalination plants.

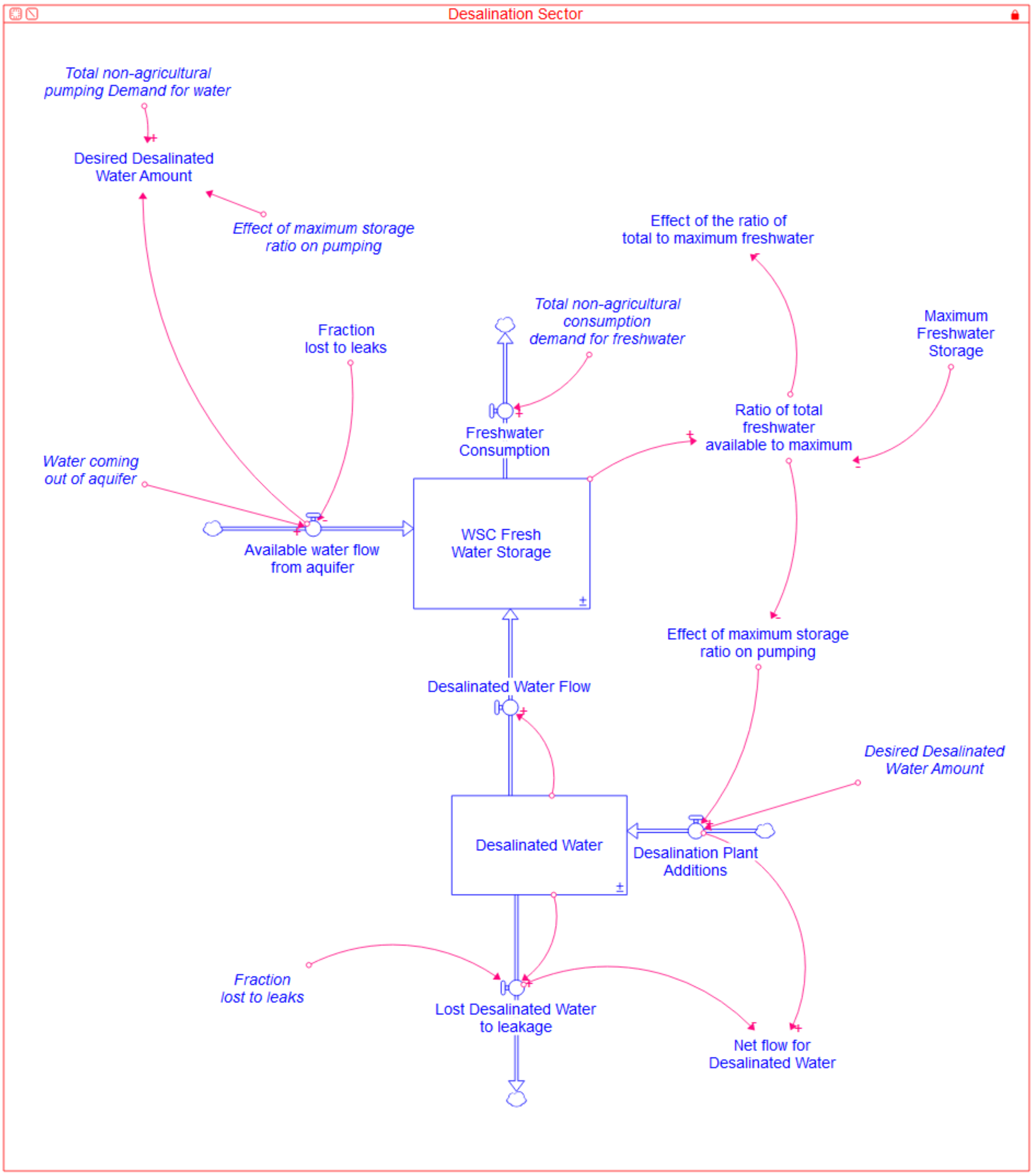

Figure 11: Desalination simulation as modelled

The first step of the model is to calculate the *Desired Desalinated Water Amount* which is done by measuring how much groundwater is being abstracted and making up the shortfall through desalination. Since the groundwater abstraction in the *Groundwater Sector* is calculated as a fraction of the total demand, this ensures that the remainder is taken up by desalination. Since distribution is done through complex piping infrastructure, a portion is lost to leaks the value of which was obtained from WSC's own published data (WSC 2023).

Functionally, water in this system is always flowing. WSC storage capacity can only hold an amount of water that can meet the demand for a few days at best. The storage in fact acts as a buffer, a means of monitoring water quality and gauging whether they need to ramp up production to meet fluctuating demand. Therefore, the model uses the ratio of how full these storage containers are in order to influence production. If the water level in the buffer starts to decrease, it means production is dropping below demand and vice versa. This structure allows the system some stability in the face of fluctuations in demand.

4.2 Model Assumptions

In this section the main model assumptions can be found.

- The model assumes that the population in Malta will continue to grow. An absolute maximum carrying capacity was chosen at 1.6 million people and structure exists in the model to reduce birth rates as this number is approached.
- The model assumes water consumption for the non-agricultural sectors (public, commercial and domestic) to scale with population. The model also assumes that the base per capita consumption for each of these remains constant.
- The model assumes an unchanging rainfall recharge coefficient, in other words the fraction of rainfall that serves as natural recharge for the aquifer. In the case that more and more of Malta's natural surface is lost to urban crawl, this factor coefficient may go down as more of the surface may be impermeable concrete. As such the rainfall coefficient is accurate up to the most recent available data on the subject (ERA 2024) however its remaining constant is an assumption going into the future.
- The model assumes an effect whereby consumption is somewhat affected by water scarcity and increased reliance on desalination.
- The model assumes 100% of "new water" generated through water reclamation facilities is used in agriculture.
- The model assumes the fraction of water lost to leaks in the piping infrastructure to remain constant as per the data published by water services and not to change into the future.
- When modelling a reduction in Malta's agricultural sector, the model assumes that the same average rate of loss as the historical data shows (NSO 2016) is maintained over time.
- The model assumes that the amount of water required by desalination can be met. As such it does not impose a water limit from desalination and assumes additional infrastructure will be built as needed over the 100 years.
- ERA (2018) estimates that the mean sea level aquifers, which are the largest, add up to 1.5 billion cubic metres; however, there was no figure estimating the capacity of the perched and coastal aquifers and thus an overall estimation of 2 billion cubic metres was assumed for the purposes of the model.
- The fraction of agricultural hectares which require irrigation (0.29) was taken to be constant throughout the years.

4.3 Sensitivity Analysis

As part of the validation process for the model structure, sensitivity analysis was conducted on key model parameters whereby assumptions were challenged in order to study their effects on simulation. For example, the model assumes that the *recharge coefficient* for groundwater recharge (in other words, what portion of rainfall recharges the groundwater and what is lost to evapotranspiration and runoff) remains constant throughout the run time, namely 0.27 meaning 27% of rainwater becomes aquifer recharge. By using sensitivity analysis, the software allows the testing of this variable at a range of values and the model can be studied to see whether this change fundamentally changes the behaviour of parts of the model. For the *recharge coefficient* for example, a range of 0.1 to 0.5 was provided (meaning anywhere from 10% to 50% of the rainwater could recharge the aquifer) and the results can be observed in figure 12 below.

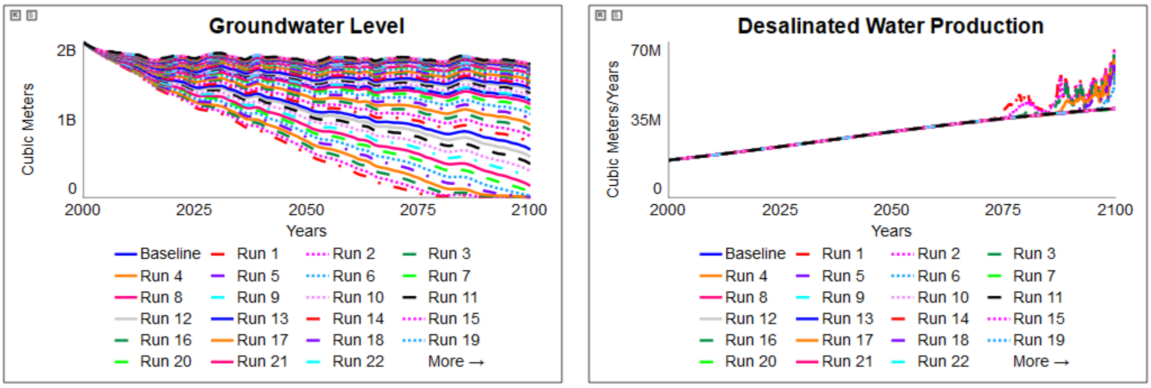

Figure 12: Recharge Coefficient Sensitivity Analysis

The pattern of behaviour remains unchanged, groundwater decreases and when it empties out, desalination spikes in order to compensate. The variance in the possible values for this coefficient do not affect the behaviour of the system in a fundamental manner, therefore even if the model's assumption is incorrect and this *rainfall coefficient* were to change slightly in the future, it does not dramatically affect the outcome.

In a similar manner, all suitable variables listed under the *4.2 Model Assumptions* section were run through a sensitivity analysis simulation. These runs allowed for around at least a ± 50% change in the value of the variable. For example, the groundwater was simulated 50 times to start at a different value within the range of 1 billion to 3 billion cubic metres. These tests were performed under both the *baseline scenario* as well as the *RCP 8.5 Scenario,* the "worst case" climate projection used in the model. The following total of 10 variables were analysed in this manner:

- Recharge Coefficient
- Baseline population birth rate
- Population Carrying Capacity
- Fraction lost to leaks

- The rate of loss of agricultural hectares
- The fraction of agricultural hectares needing irrigation
- The groundwater level starting amount
- The per person consumption for each of the three non-agricultural sectors

Finally, combination sensitivity analysis was conducted where variables were grouped and analysed together. For example, the birth rate, carrying capacity and the per capita consumption for all 3 non-agricultural sectors were tested together. Both the singular and combination sensitivity analysis runs can all be found in section *8.2 Sensitivity Analysis* in the *Supplementary Materials* section.

Ultimately, variation in these parameters did not affect a fundamental behavioural change in the model. While outcomes such as the rates of groundwater decline or amount of desalination changed, they did so along the same pattern of behaviour observed in normal simulations of the model. Thus while these parameters are subject to certain assumptions with regards to their exact value, it does not appear that the overall behaviour of the model is fundamentally changed even if they were to be changed.

5. Results and Discussion

This section of the paper will discuss the results of various scenarios tested out as part of this project. The first is a description of the base scenario, highlighting the key dynamics at play within the system and demonstrating how the current trajectory appears in the model. Afterwards, several different scenarios will be compared and analysed. These will include both environmental scenarios beyond human control as well as possible policy solutions.

Each scenario will focus on six parameters which will be used to highlight the most important aspects of the system's behaviour and resources. These will be the following:

- Groundwater level
- Groundwater withdrawals to aquifer
- Groundwater's cumulative net flow
- Desalinated water production
- Projected Rainfall Average
- Agricultural Freshwater Consumption per Hectare

Some particular policy or scenario may necessitate the inclusion of additional parameters for proper analysis, however scenarios all will at least include these six.

5.1 Baseline Scenario

In this scenario, variables continue existing trends with neither any climate scenario testing nor policy changes. In this scenario, the agricultural sector continues to decrease over time as per the trend found in the historic average. Rainfall, while fluctuating year to year, maintains its overall average of the last 20 years. "New Water" production ramps up to 2028 as per current government planning, but stays there into the future. Figure 13 below shows the behaviour of the key parameters under this scenario.

As can be seen, while the yearly freshwater consumption fluctuates due to varied rainfall, as the average remains constant so too does the per hectare freshwater consumption. However, since the agricultural sector continues to decline, over time the withdrawals from agriculture decrease. The groundwater level gradually decreases as can be seen by the cumulative net flow - going from an estimated 2 billion cubic metres down to around 1.25 billion cubic metres.

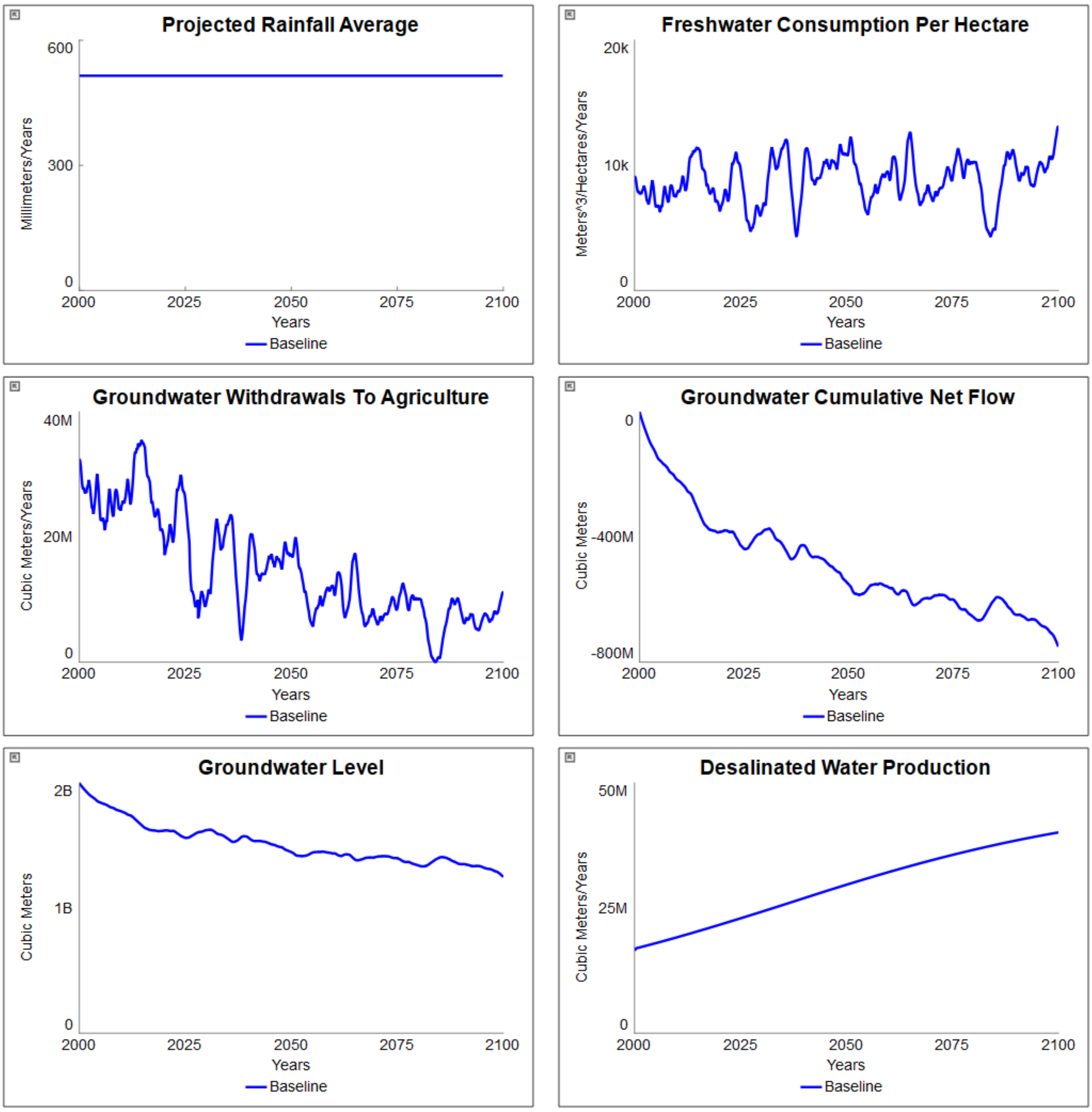

Figure 13: Key Parametres Under Baseline Scenario

5.2 RCP Climate Projection Scenarios

This scenario implements rainfall reductions based on RCP climate projections from Galdies and Vella's (2019) work, with everything else being left as in the baseline. As can be seen in figure 14 below, four additional scenarios were run based on each RCP scenario, each showcasing the cascading effect that reduced rainfall has on the system. As can be seen in the *Groundwater Level* graph, even though agriculture continues its decline along historic averages, a pattern which we can observe through the *Groundwater withdrawals to agriculture,* the groundwater level plummets, dropping to a mere 590 million cubic metres in 100 years under RCP 8.5. This is because reduced rainfall impacts the groundwater level on two fronts: Firstly, as can be seen in the *Freshwater Consumption per Hectare* graph, the amount of water needed per agricultural hectare increases as rainfall decreases. Secondly, reduced rainfall means reduced natural recharge for the groundwater body. Looking at the *Groundwater Cumulative Net Flow,* we can see how this increase in the net flow is draining the groundwater. A final observation is that RCP scenarios 2.6, 4.5 and 6.0 result in similar outcomes for the groundwater level, with all 3 scenarios leading to around 870 million cubic metres.

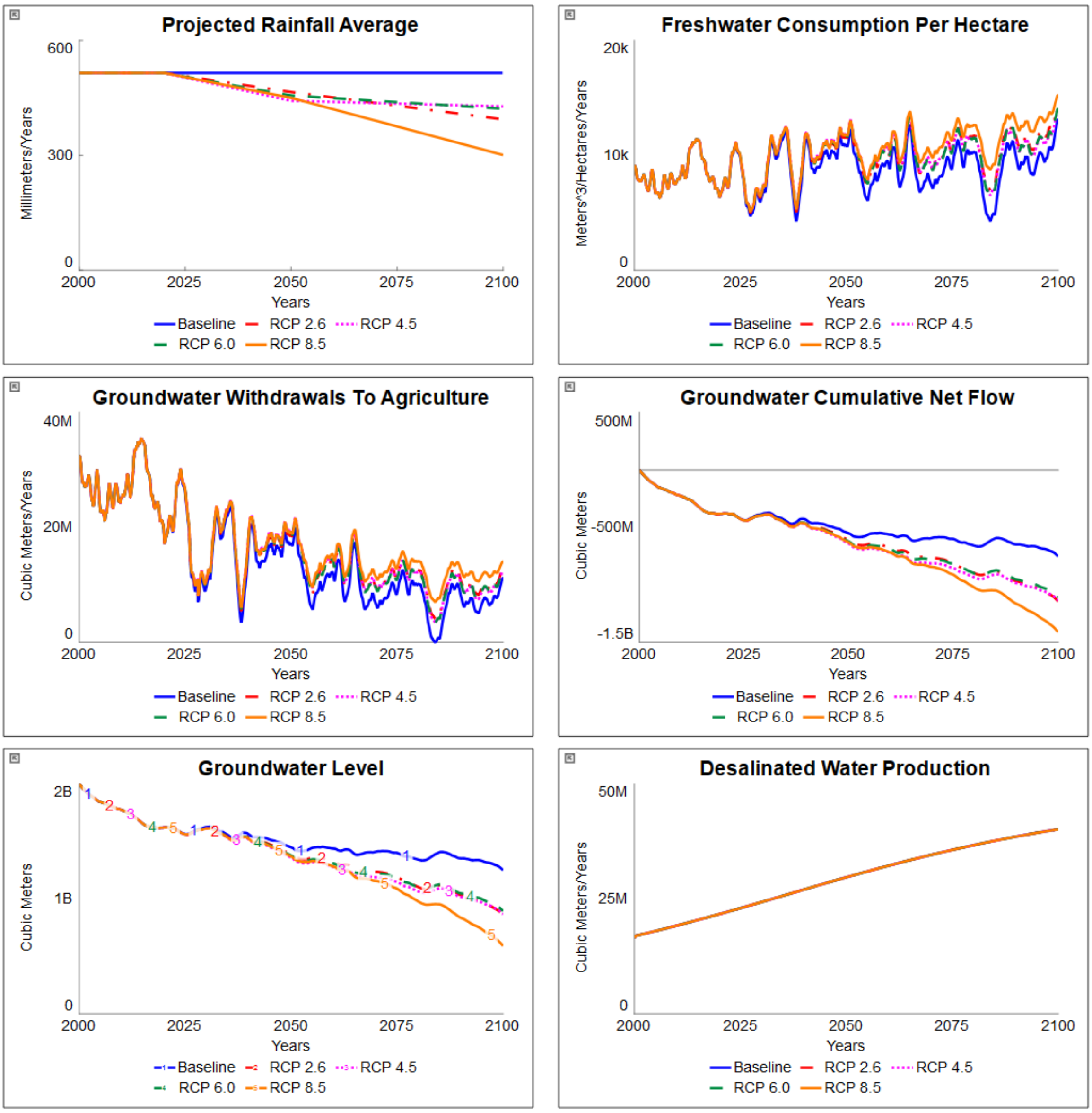

Figure 14: RCP Climate Projection Scenarios

5.3 "Save the Agriculture" Scenario

In previous scenarios, the agricultural sector continued its historic trajectory, starting at 12,300 hectares in the year 2000 and gradually declining to 4,800 hectares by the year 2100. In this scenario, a policy is adopted to conserve the current agricultural hectares and halt this decline, the effects of which can be seen in figure 15 below.

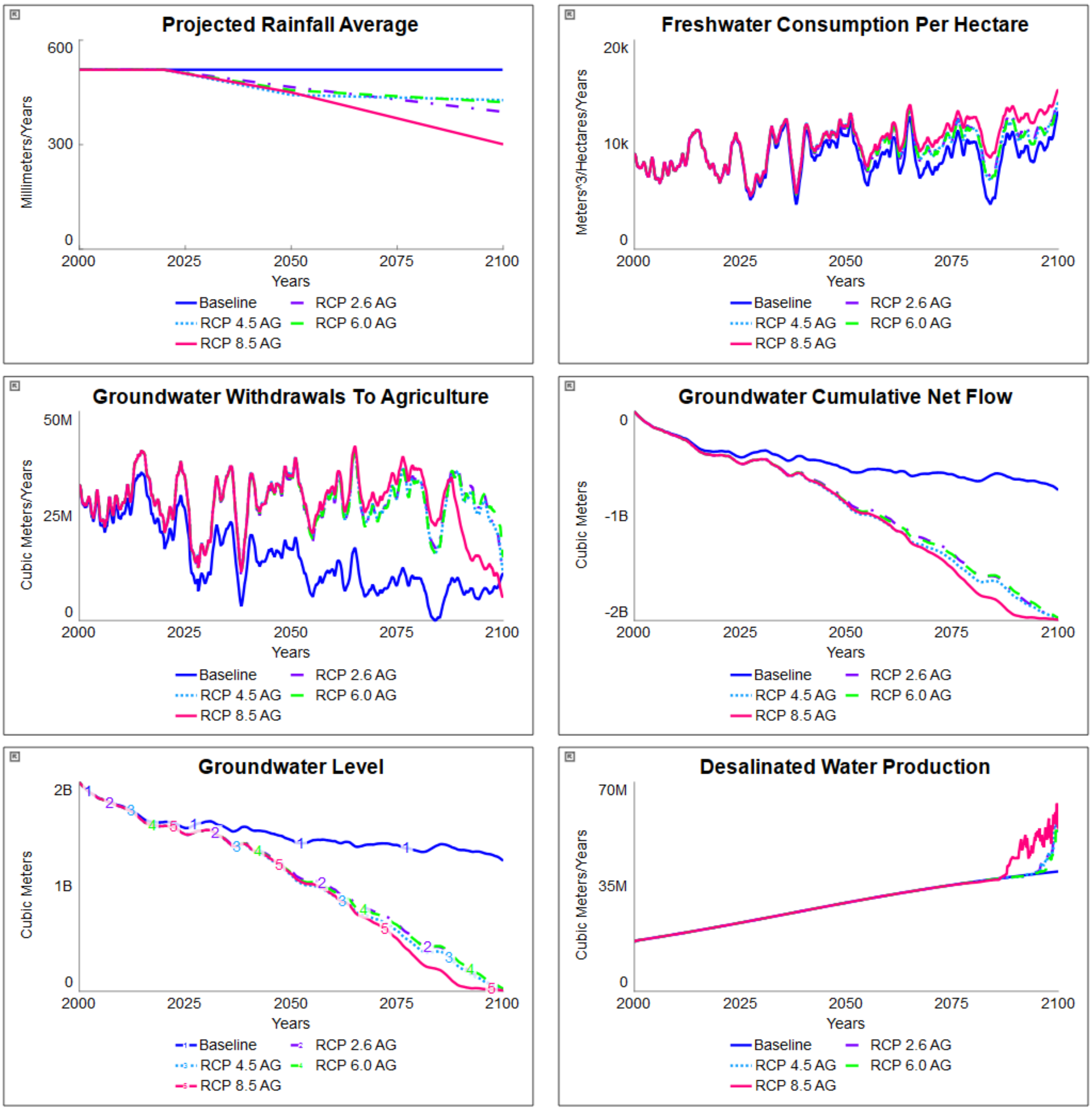

Figure 15: RCP Scenarios if Agriculture in Malta does not decline

What can immediately be observed is that if agriculture remains at its current size, all RCP scenarios point to a catastrophic point of failure for groundwater by 2100, with conditions deteriorating most rapidly under RCP 8.5. Another noteworthy observation is the dramatic spike in desalination production. Since a portion of groundwater is used in the freshwater blend that WSC produces to meet demand, an emptying of the groundwater will require desalination plants to increase their production even further.

5.4 "Save the Agriculture AND the Groundwater" Scenario

As the previous scenario demonstrated, with the current balance of water resources allocation on the island of Malta, maintaining the agricultural sector's current size appears to empty out the groundwater by the year 2100. After testing various approaches in the model, consulting literature on the current trends and identifying good leverage points, a series of promising policies were identified. In this scenario, three policies will be implemented in order to attempt to maintain groundwater levels without sacrificing agriculture, as seen in figure 16 below. These policies include the following:

- *New Water* Production, which currently maxes out at 7.2 million cubic metres per year by 2028, will continue to increase up to 10 million cubic metres of yearly production over the following decade.
- WSC will, over the next 75 years, gradually reduce its groundwater:desalination blend to a ratio of 10:90 by 2100.
- The Agricultural sector is encouraged through incentives and awareness spreading to gradually utilise more water efficient crops and increase water efficiency, such that by 2100, on average, an agricultural hectare will require 70% of the water it required in 2020. A gradual improvement in efficiency, given the right incentives, should be quite realistic, especially given that it is a 30% improvement over the course of many years. It would also be possible to aim for a more ambitious value, but for the purposes of this scenario this was taken to be acceptable.

When these policies were tested independently, the effects were much reduced and in most scenarios the groundwater was still emptied out by 2100. However, when all three policies are combined, as figure 15 shows, there is a marked difference from the previous scenario, with groundwater levels for most RCP scenarios being only slightly worse than the baseline. However, it can also be observed that desalination increases significantly in order to compensate for the reduced groundwater usage. Groundwater withdrawals to agriculture gradually diminished over time as agricultural practices became more water efficient.

When comparing the combined effects of the implemented policies to the simulation of the RCP Scenarios where agriculture was allowed to decline (found in section *5.2 RCP Climate Projection Scenarios)* it can be seen that the policies resulted in a higher level of groundwater even while maintaining the agricultural sector's size, as seen in figure 17 below.

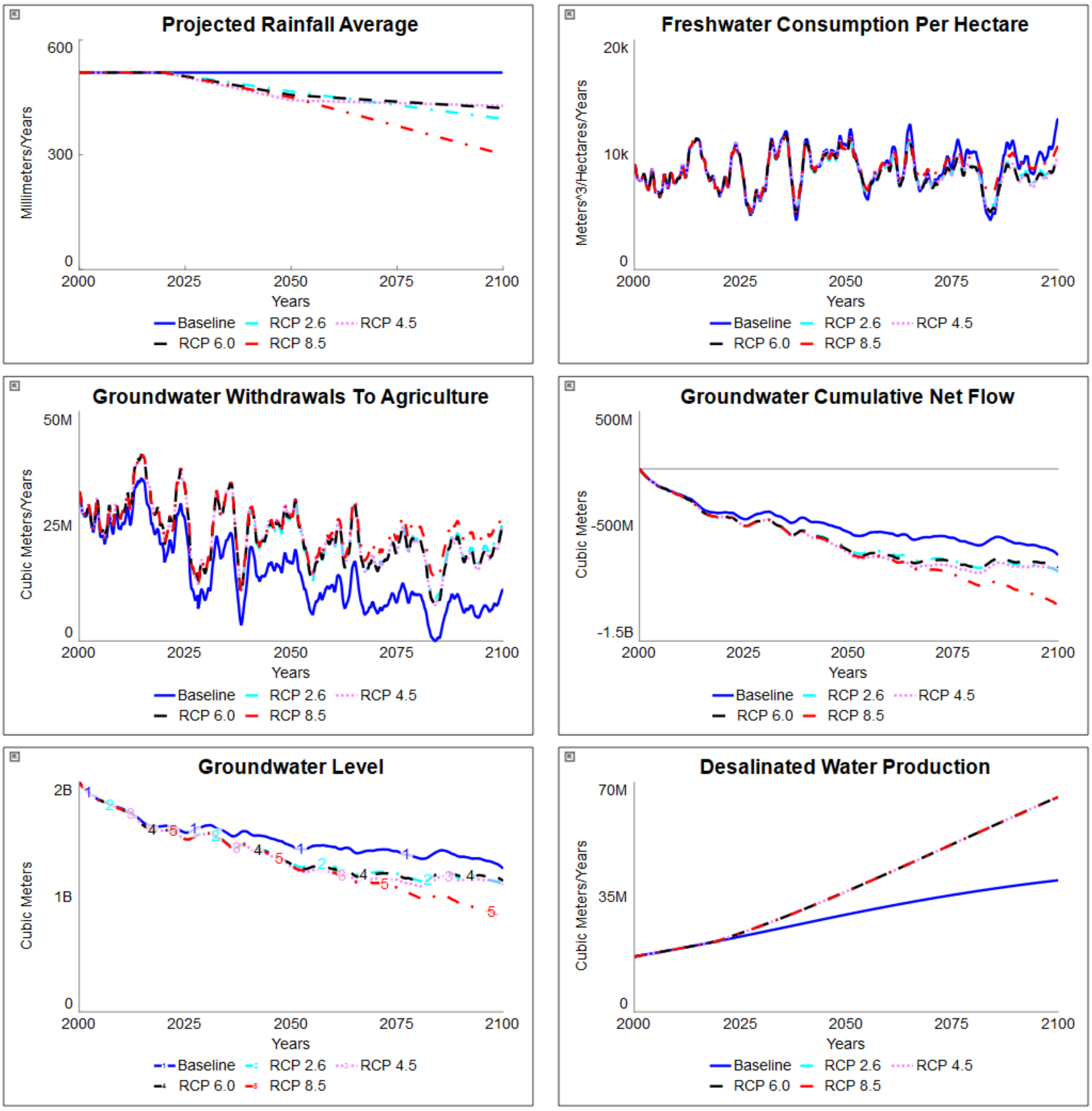

Figure 16: "Save the Agriculture AND the Groundwater" Scenario

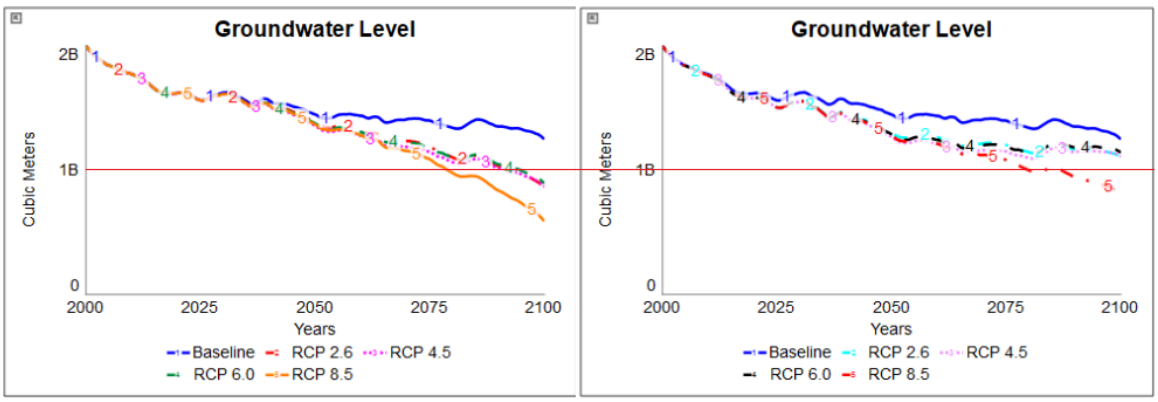

Figure 17: Agricultural Decline vs Policy Implementation

5.5 Allowing Groundwater Levels to Recover Scenario

All scenarios up until this point resulted in the groundwater level being reduced. Certain policies or scenarios accelerated this loss of groundwater such that the groundwater is empty by 2100, others slowed the reduction and left it at around half its starting amount in that same timeframe. This scenario aimed to allow the groundwater to actually eventually recover its water level. This was accomplished by combining the policy solutions discussed in the *5.4 "Save the Agriculture AND the groundwater" Scenario* together with allowing the agricultural sector to continue its historic decline at the same rate. The results, seen in figure 18 below, show the cumulative net flow initially declining along the same trajectory as previous scenarios before curving upwards. This is reflected in the groundwater level itself, where the initial decline levels out and then begins to slowly recover. Comparing the years 2050 to 2100, every single RCP scenario including the worst case scenario, showed an increase in the groundwater level.

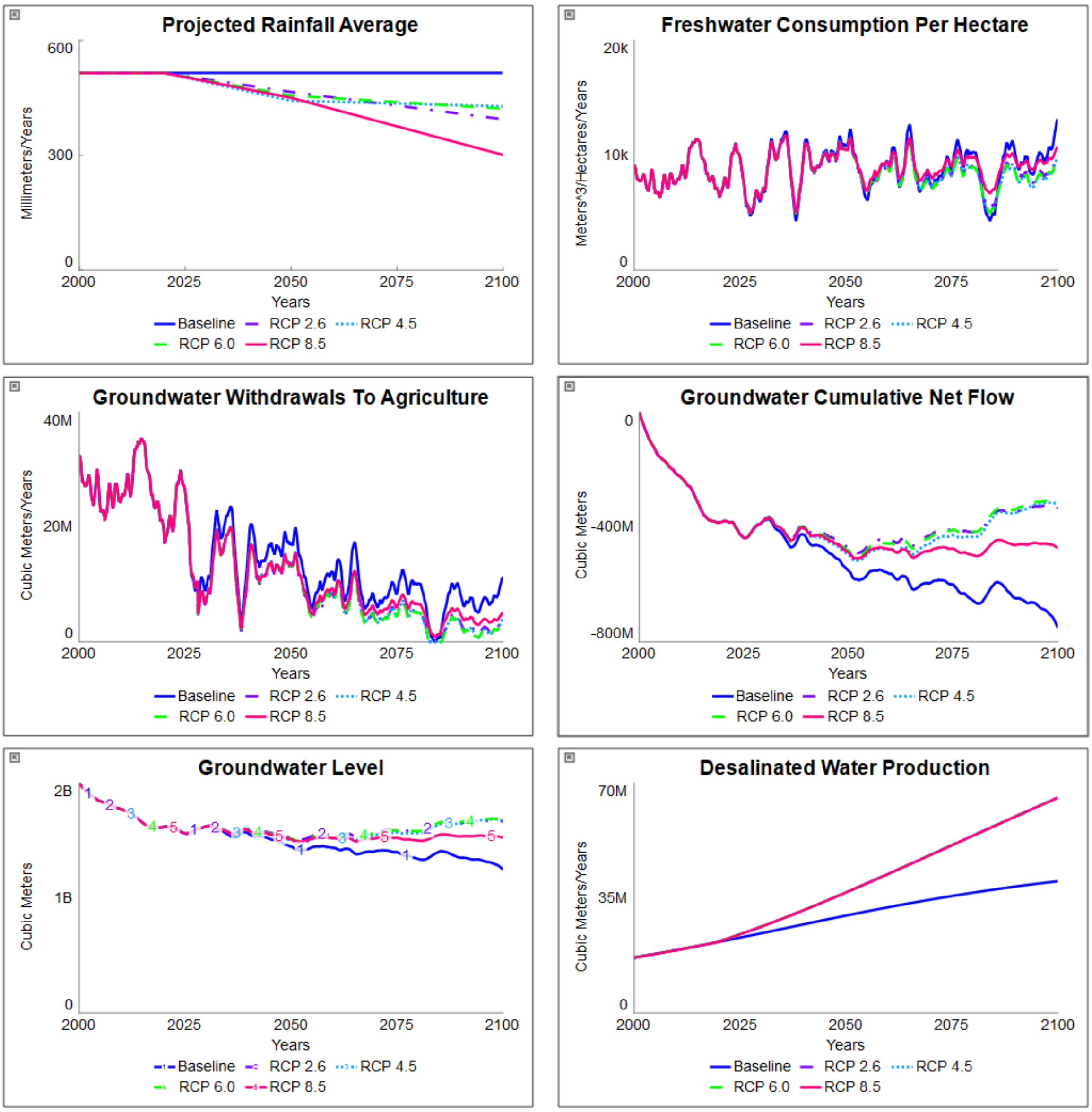

Figure 18: Groundwater is allowed to recover

5.6 Analysis and Recommendations

Based on the scenarios and policies tested as part of this project, there are several things that can be understood to be the case in Malta's context. First, it is evident that the groundwater level could sink to catastrophically low levels in various different scenarios by the year 2100. Groundwater is an important resource, and so it is desirable that this fate is avoided. Secondly, the pressure on the groundwater level comes from several different factors. Agricultural abstraction drains a lot of resources. Even worse, more abstraction is needed in years of drought, yet it is exactly during those years that the groundwater's natural recharge is at its lowest. Groundwater abstraction also worsens with population growth, as WSC abstracts groundwater for its freshwater blend, the primary consumer of which is the domestic sector.

There appear to be two primary considerations to be made with regards to freshwater resource management in Malta. The first is whether the agricultural sector should remain at its current size and the second is what policies should be implemented to conserve Malta's groundwater resources. As the scenario testing revealed, the only scenario where groundwater ceased its decline completely and even began recovery, was one where the agricultural sector shrank and reasonable policies were implemented in order to reduce the pressure on groundwater abstraction.

Thus four key policies have been identified as detailed below. Additional information on their rationale can also be found in section 5.4, where most were first established.

- **The Agricultural Sector To Reduce Its Water Consumption**- This can be accomplished through a combination of reducing the amount of agricultural hectares being irrigated and improving the water efficiency of crops. This is an important target as the agricultural sector is not only the biggest consumer of groundwater but this consumption is liable to increase under climate scenarios where Malta receives reduced rainfall. Critically, it is precisely during periods of low rain where the natural recharge is also taking a hit that the agricultural sector would require the most water. Attempting to attain a balance between abstraction and recharge without somehow reducing agriculture's water consumption appears to be quite challenging in the model.

- **New Water Production To Increase -** This water should then be used to supply farmers with freshwater and reduce their dependance on groundwater. As New Water production has increased in the last few years in Malta and the government currently has plans to continue that growth, this policy is realistic and feasible.

- **Water Services Corporation To More Heavily Use Desalination -** A gradual transition to a lower and lower ratio of groundwater in the freshwater blend will be needed as if population continues to increase, the strain on the aquifers will be too high. This is already the direction in which WSC appears to be heading. The freshwater blend WSC provides was once at a groundwater:desalination ratio of 40:60, was 35:65 in 2022 and is now 30:70. It is therefore considered to be a feasible and realistic policy to attempt.

5.7 Future Research

In the scenario testing where these policies were carried out, the values of the parameters for each were listed. However it should be noted that this solution is not exhaustive and other approaches may also yield successful results. For example if the agricultural sector were to decline more and at a fast rate, WSC's freshwater blend could likely contain more groundwater while maintaining sustainable abstraction rates, and vice versa. Other policy solutions could also be tested, such as decreasing the fraction of agricultural hectares needing irrigation through increasing the amount of forage, or implementing strategies that reduce the per capita domestic consumption of freshwater (as this is the biggest of the non-agricultural sectors).

Additional structures may also be added to the model in order to capture aspects which could affect policy recommendations. The current simulation does not directly account for energy efficiency or what the economic burden born from increasing desalination would be. There is also room for evaluating the agricultural sector's economics and how earnings may be affected by changes in hectares or changes in crops. Such additional solutions are beyond the scope of this paper, however they may yield different policy recommendations if implemented in the future.

A final point of note is that the model assumes policies are met with rational responses and real world implementations should be complemented by stakeholder engagement as farmers, utilities and end users all have their own priorities and constraints.

6. Conclusion

The work carried out in this study shows that Malta’s current trajectory in its freshwater use risks depleting groundwater resources in many climate scenarios. This trajectory is shaped by a mix of population growth, agriculture, changing rainfall patterns and limited natural recharge. Using a System Dynamics approach, the model built for this project demonstrates the interlinked pressures on Malta’s water systems and the likely future outcomes in various scenarios.

The baseline scenario and the climate change projections both suggest a continued decline in groundwater levels unless corrective action is taken and testing revealed that there exists no single silver bullet policy solution to reverse this trend. An integrated strategy however, such as the one proposed which includes increased use of reclaimed “New Water” for agriculture, a shift in Water Services Corporation’s supply away from groundwater towards desalination, and improvements in agricultural water efficiency, can work. When such policies are implemented in combination, decline is either slowed significantly or in some cases even allow for the recovery of groundwater levels. While the policies presented here are not exclusively the only solution that can work, the model offers a practical and flexible framework that can be used to test, explore or refine different water management strategies.

Ultimately the project finds that while Malta’s freshwater resources face the risk of depletion in the future, they can be saved provided that timely and targeted policy interventions are implemented.

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8. Supplementary Materials

8.1 Full Model

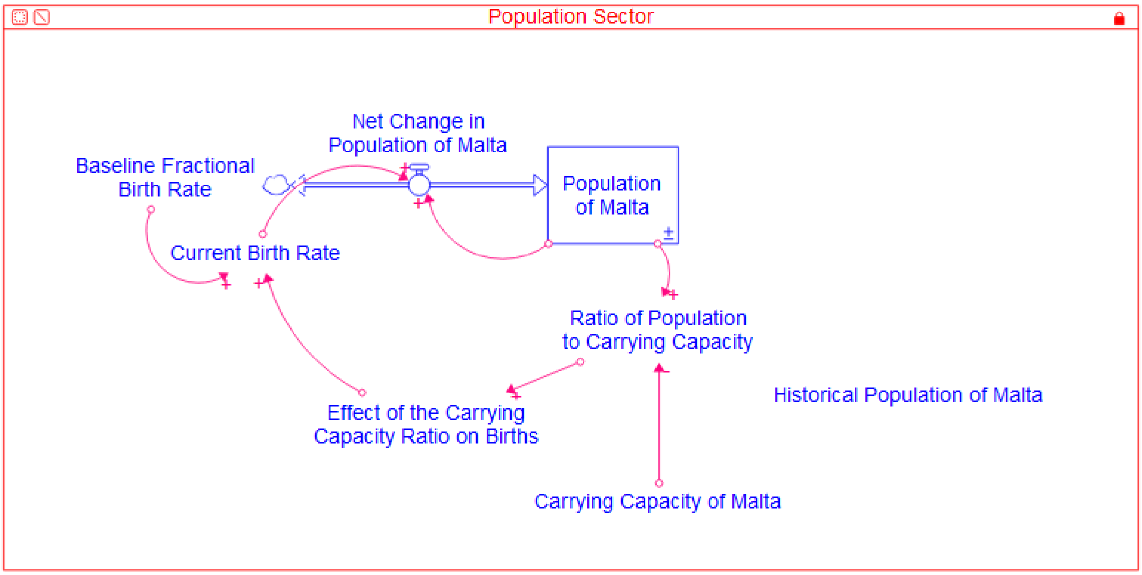


Figure A1: Population Sector

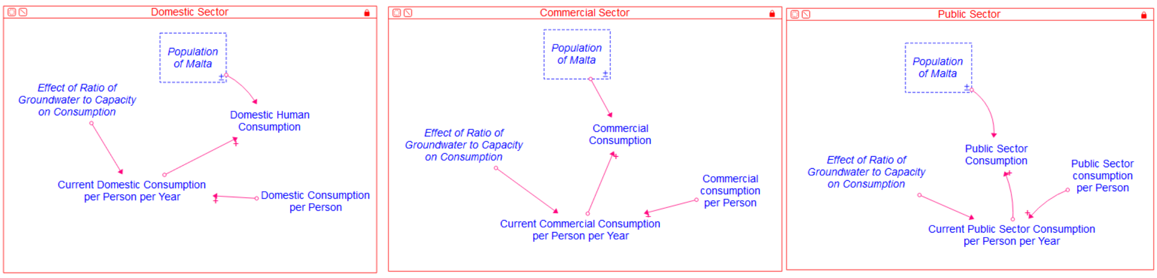


Figure A2: Non-Agricultural Sectors

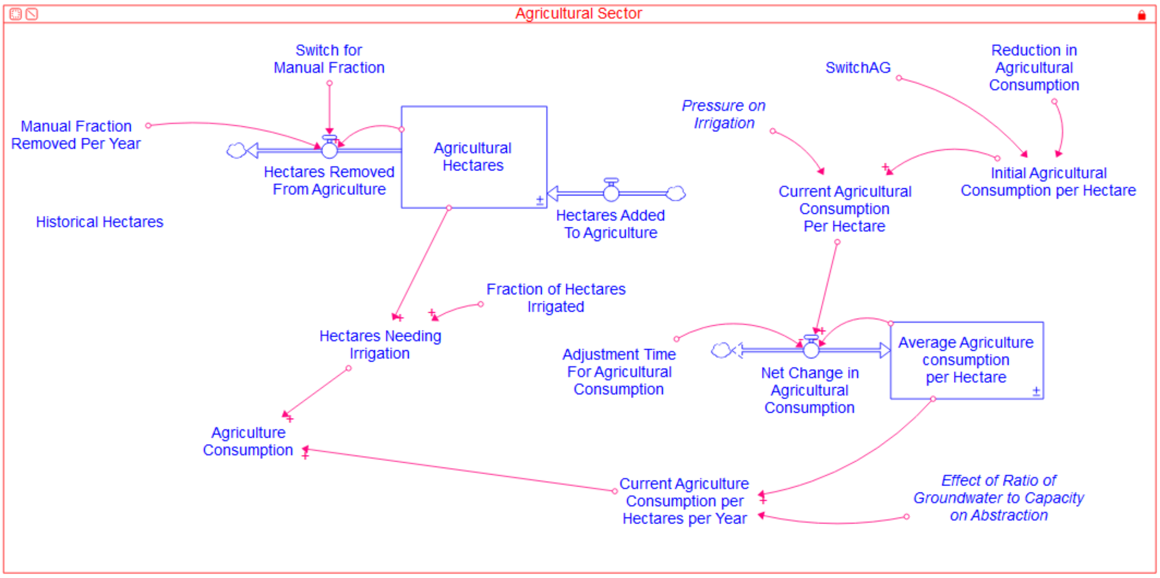


Figure A3: Agricultural Sector

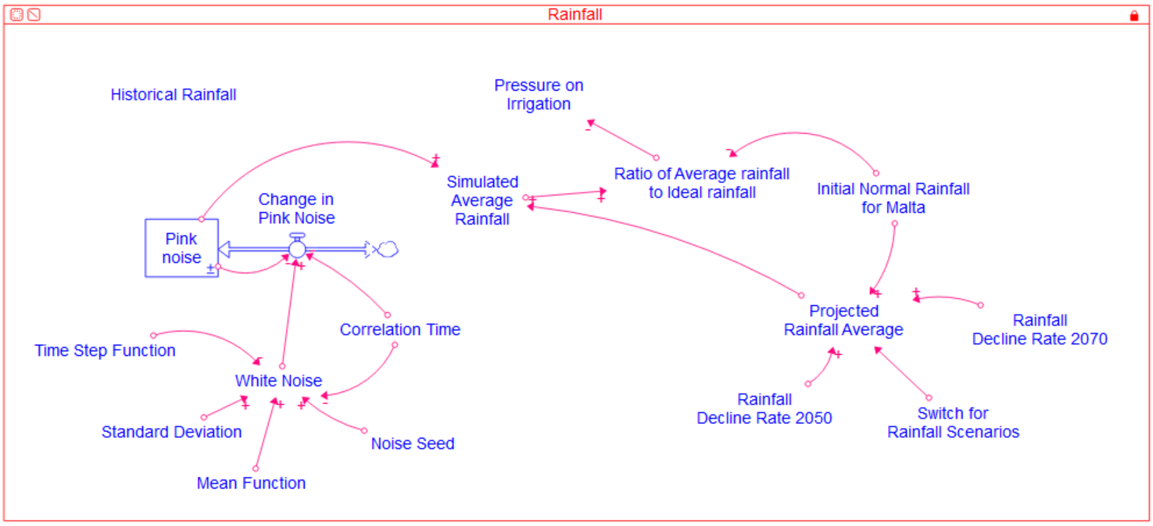


Figure A4: Rainfall Sector

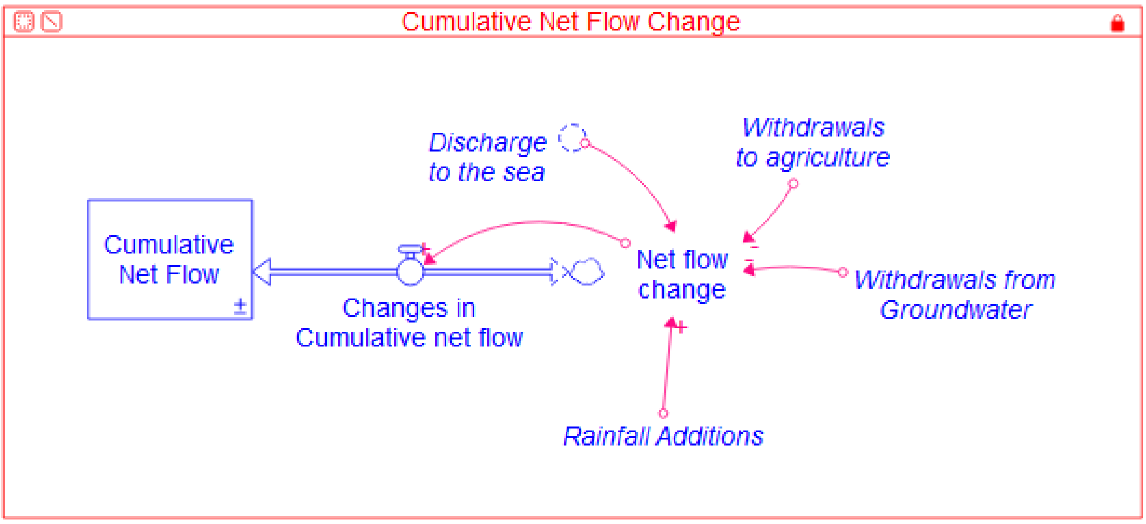


Figure A5: Net Flow Change Sector

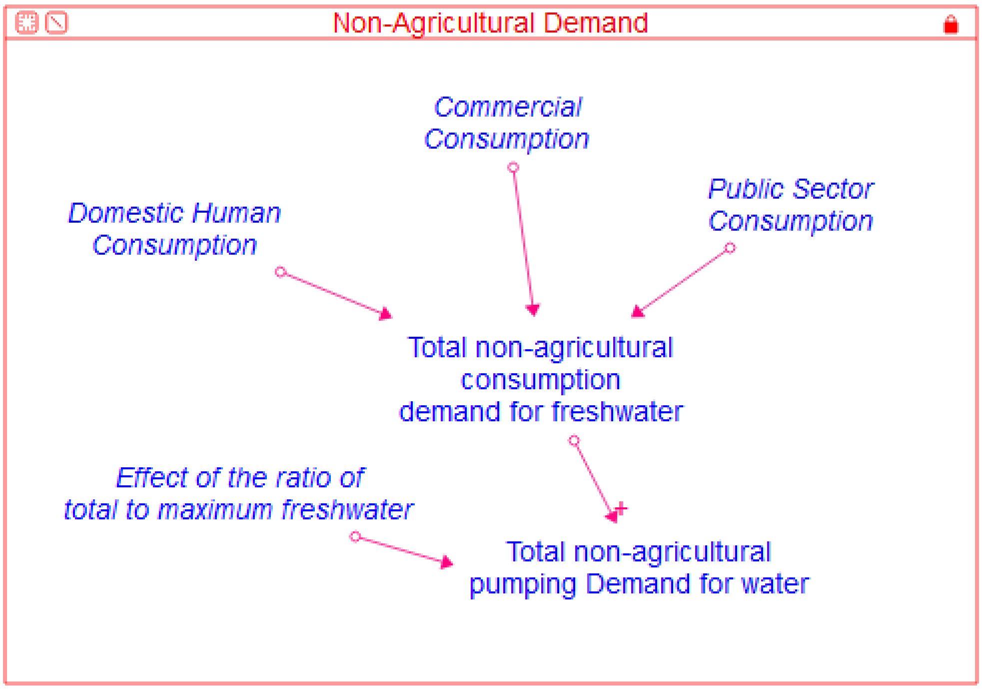


Figure A6: Total Non-Agricultural Demand

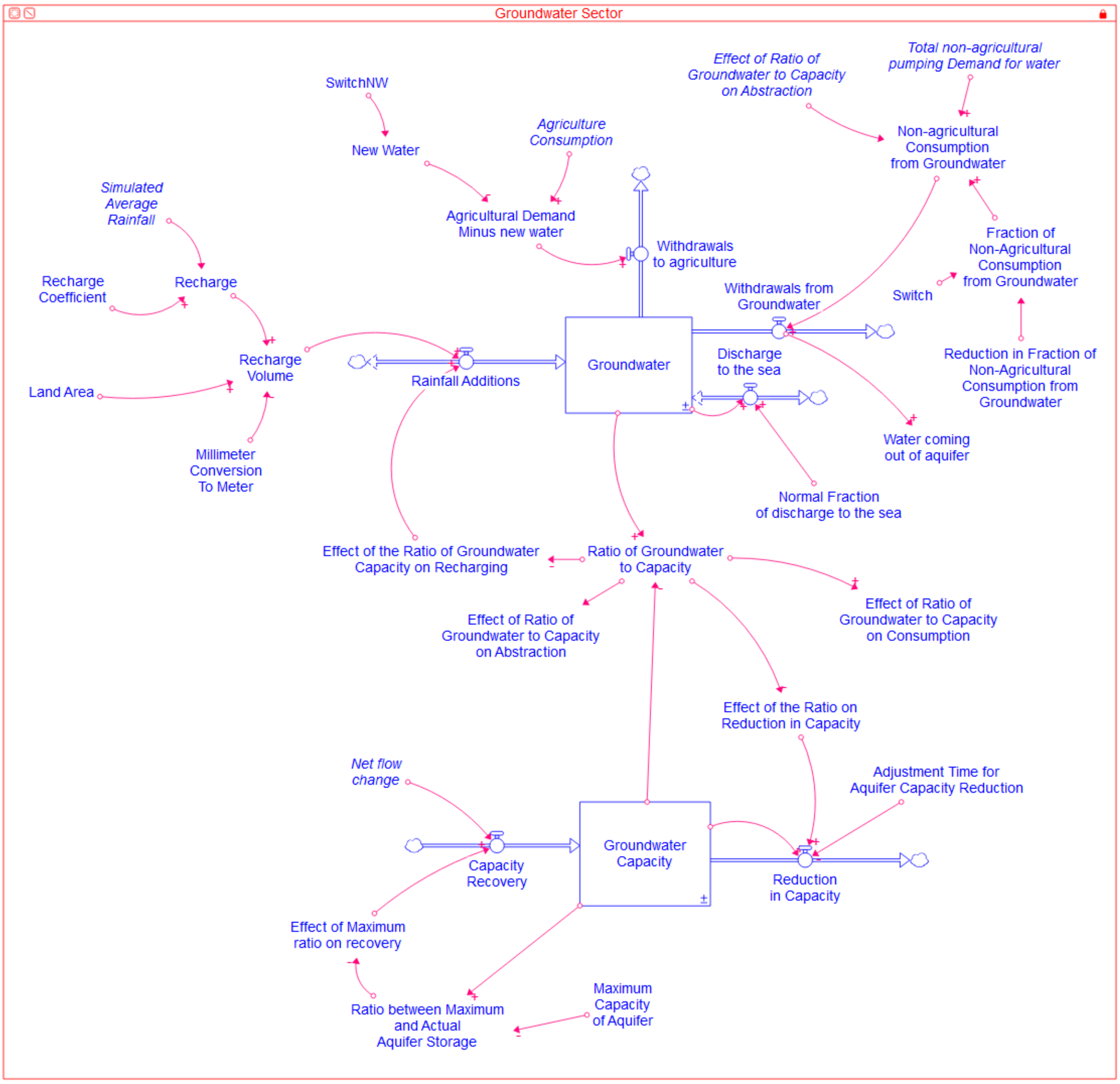


Figure A7: Groundwater Sector

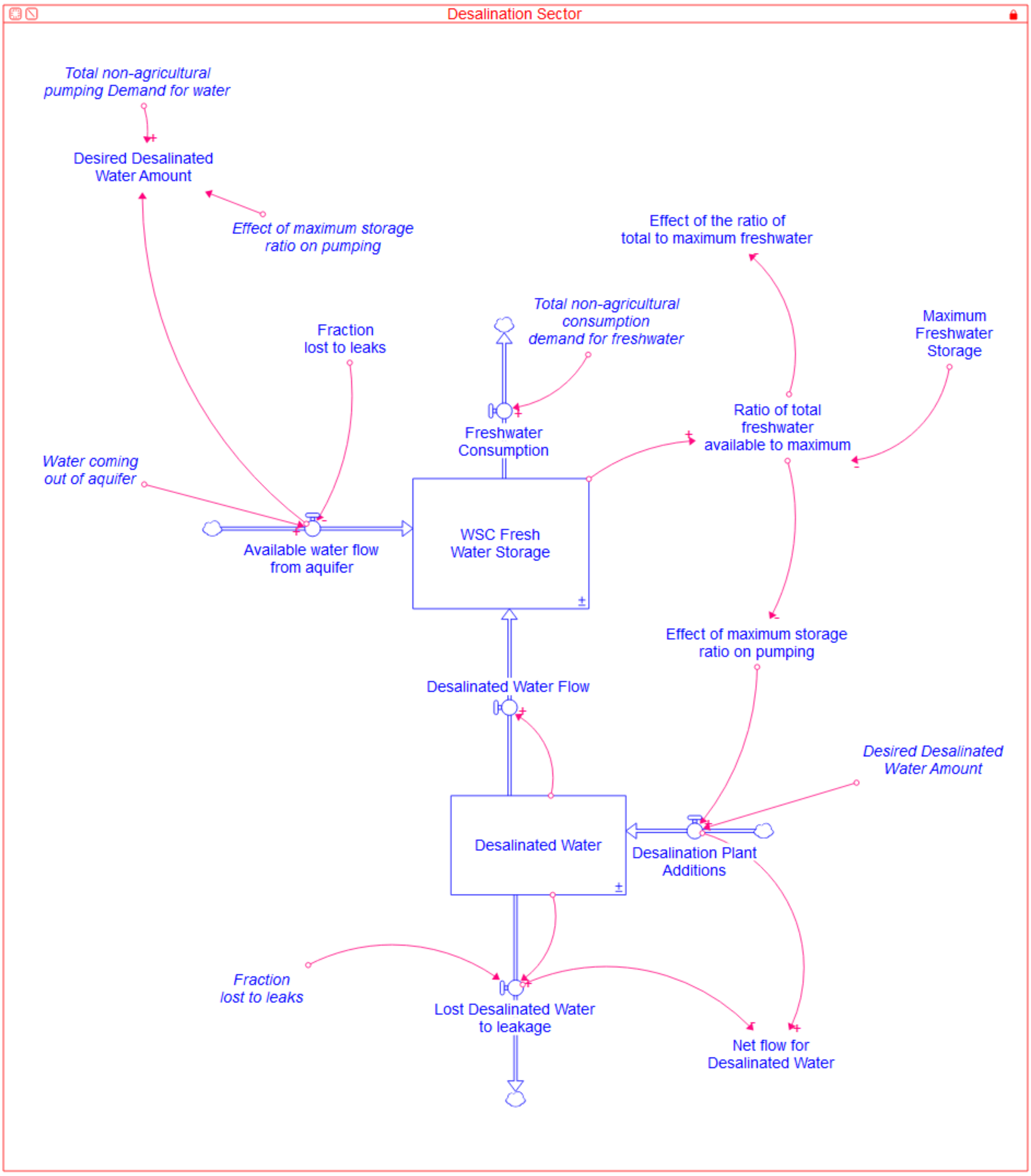


Figure A8: Desalination Sector

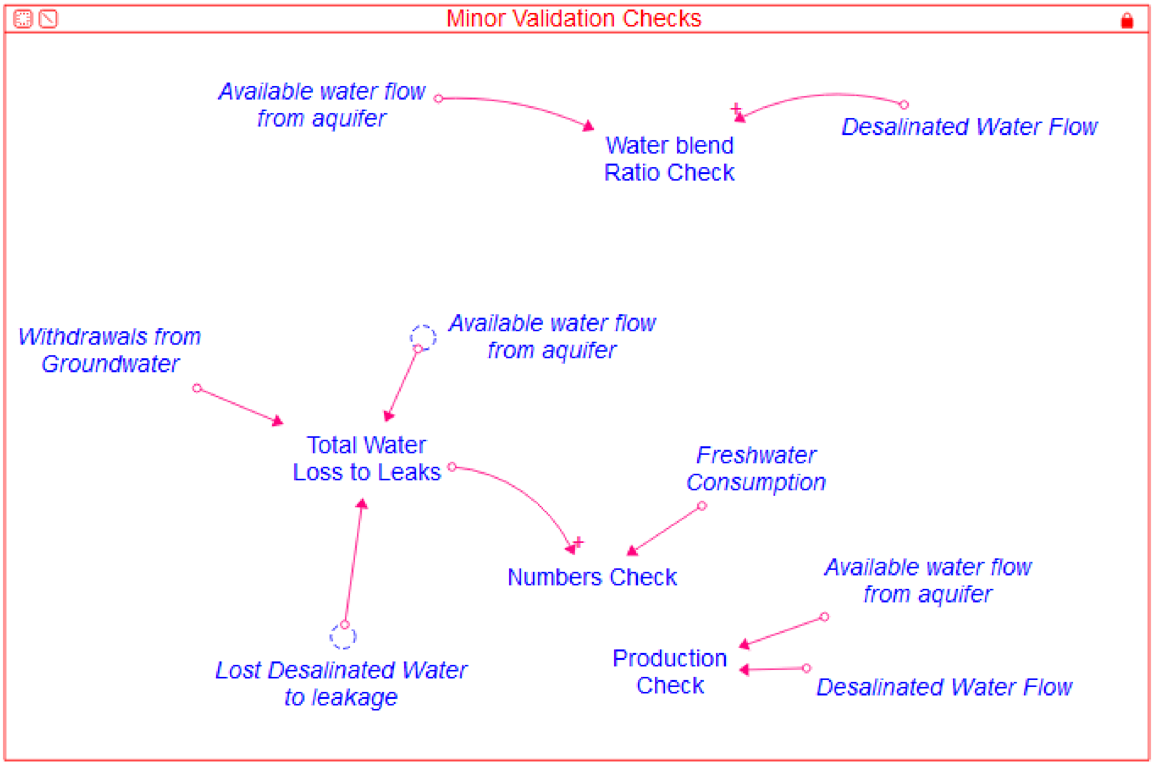


Figure A9: Minor Validation Checks

8.2 Sensitivity Analysis Figures

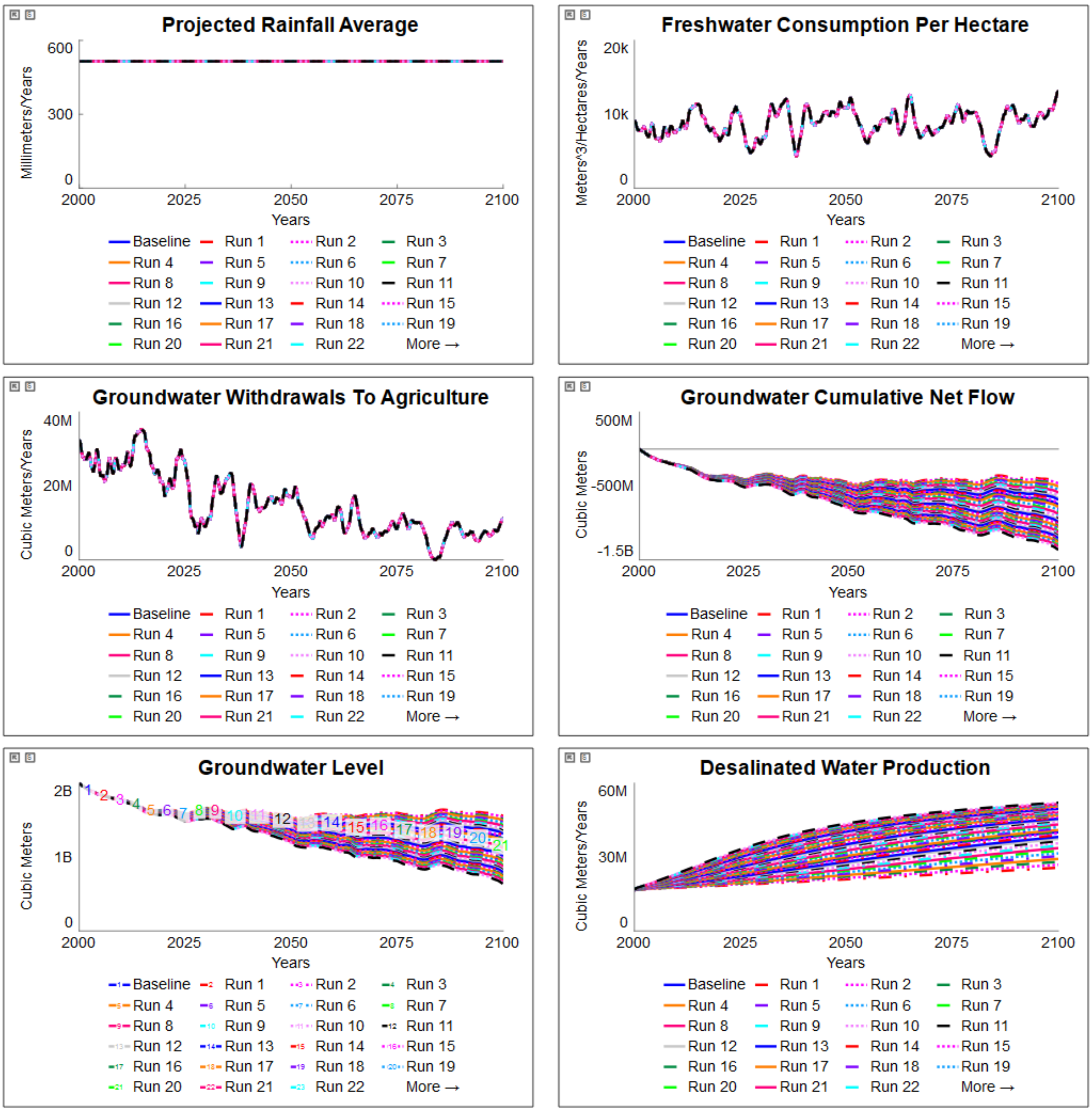


Figure A10: Baseline Scenario Sensitivity Analysis Fractional Birth Rate

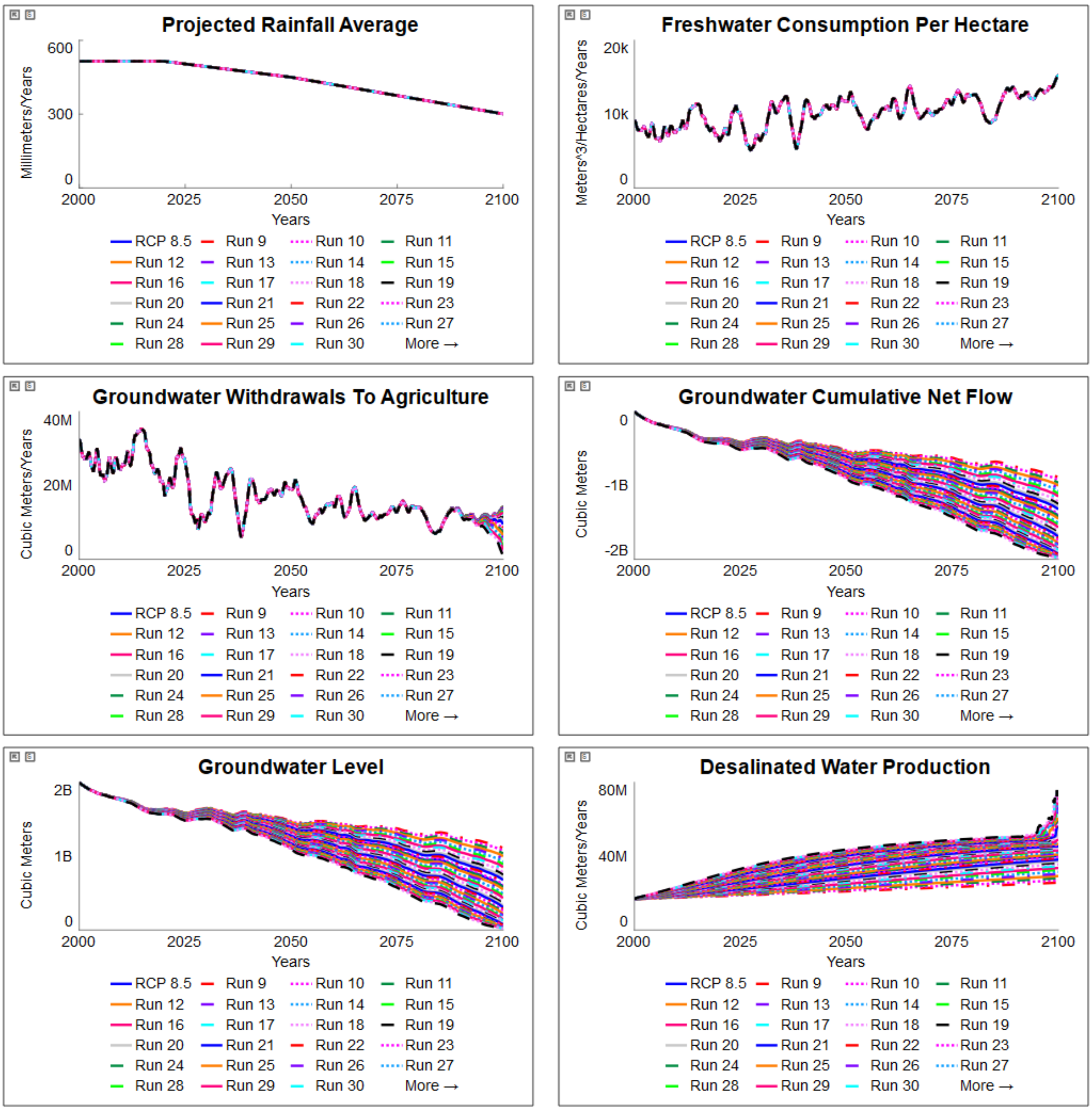


Figure A11: RCP 8.5 Scenario Sensitivity Analysis Fractional Birth Rate

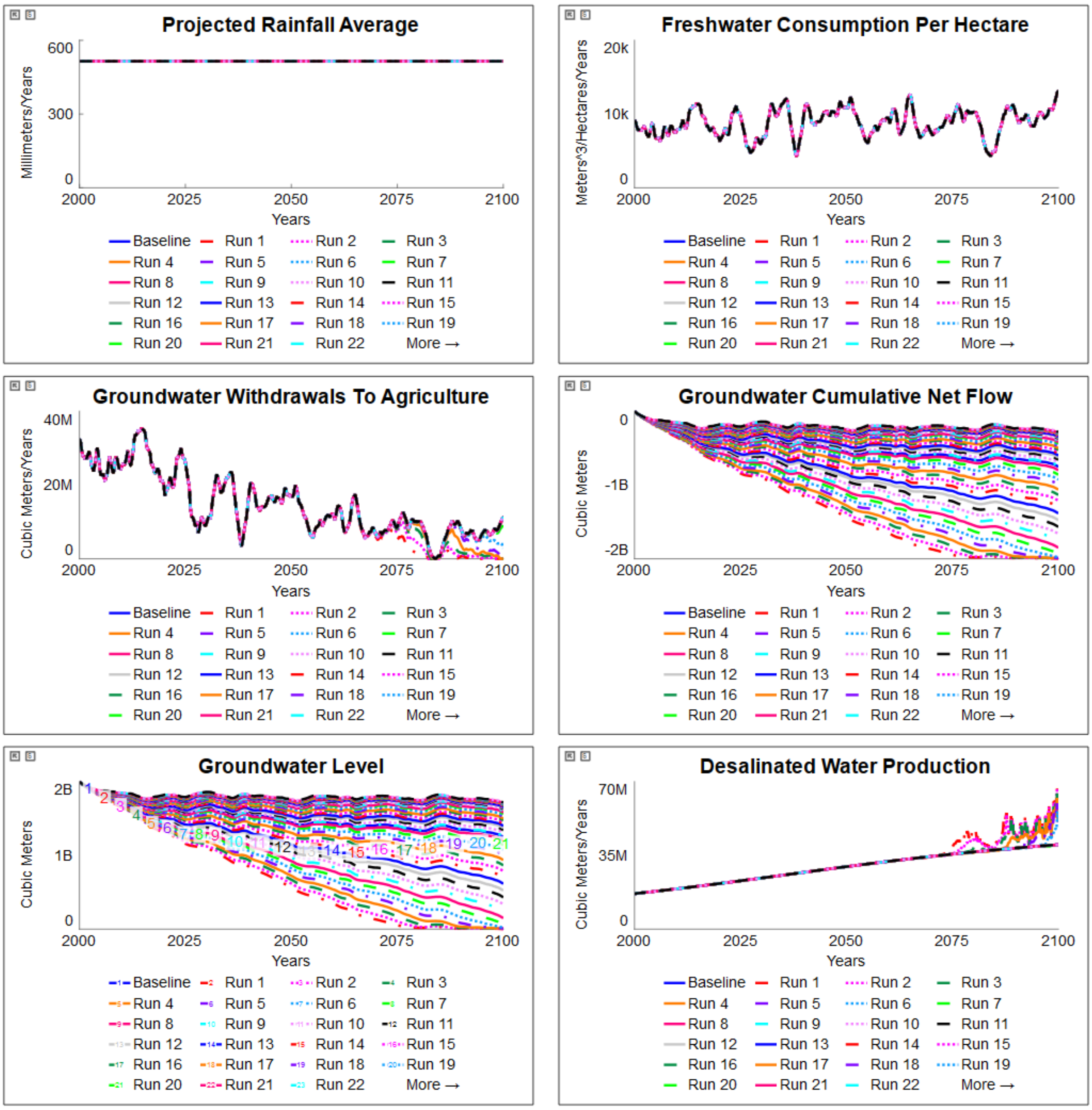


Figure A12: Baseline Scenario Sensitivity Analysis Recharge Coefficient

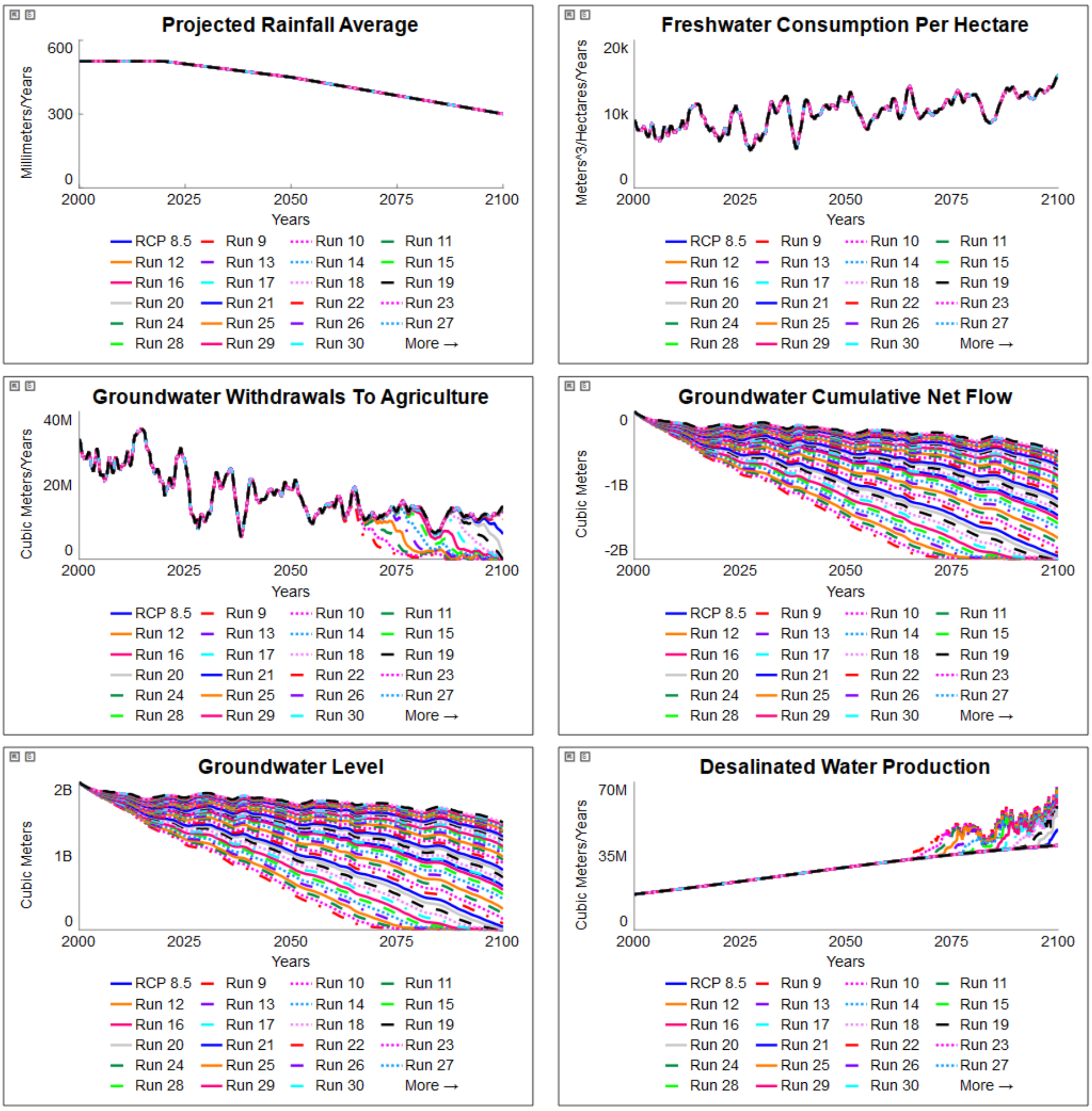


Figure A13: RCP 8.5 Scenario Sensitivity Analysis Recharge Coefficient

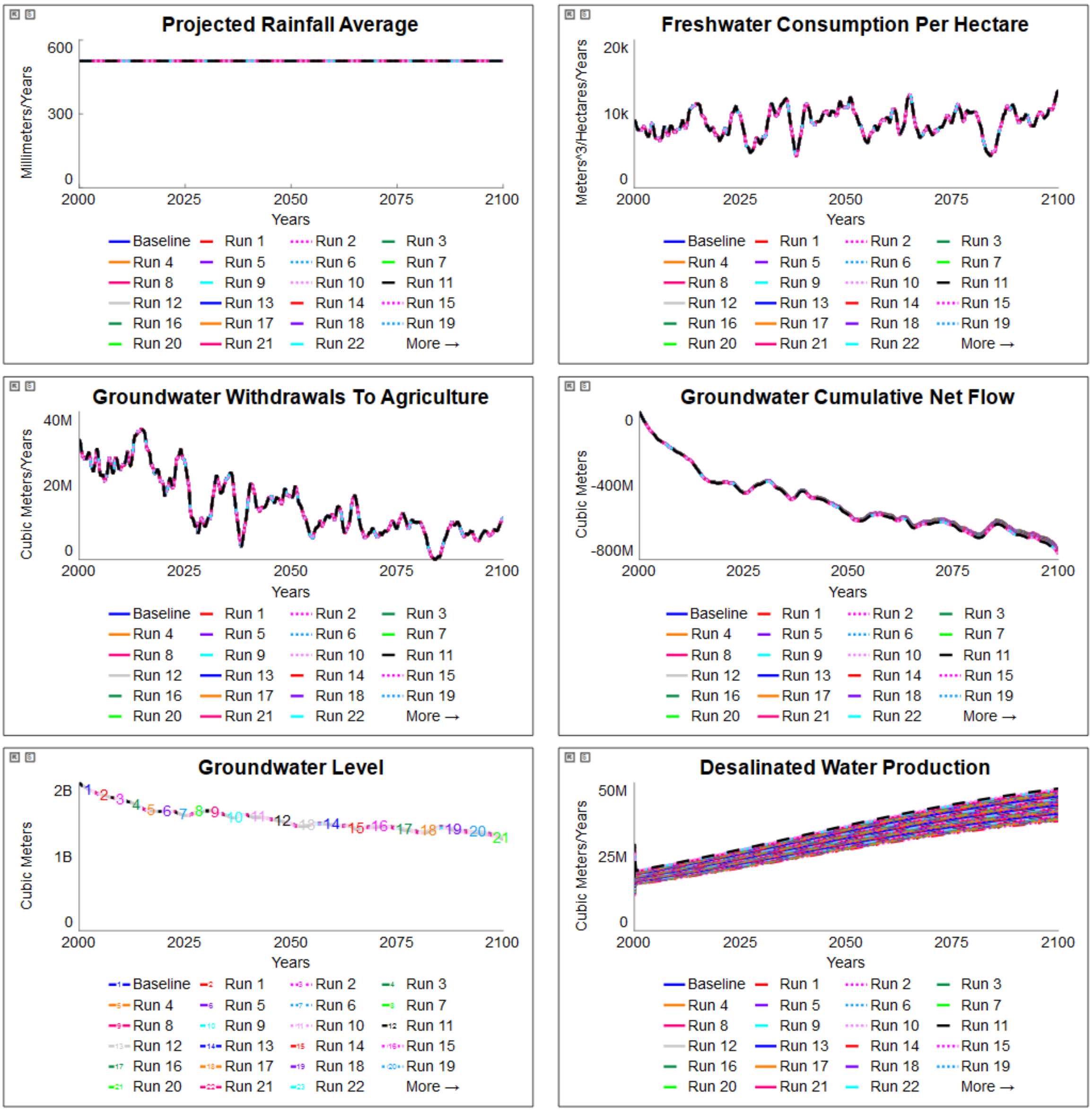


Figure A14: Baseline Scenario Sensitivity Analysis Fraction Lost to Leaks

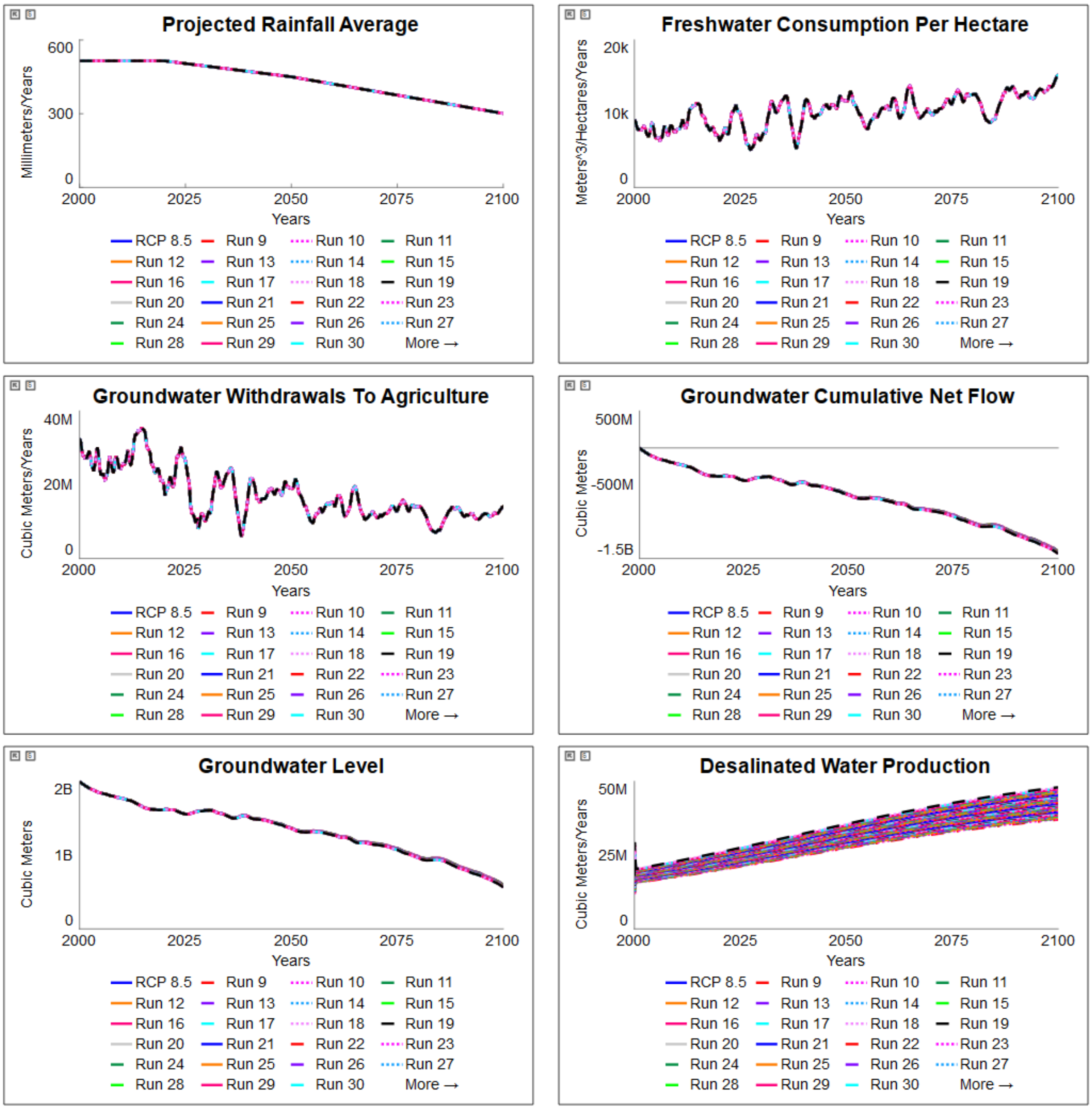


Figure A15: RCP 8.5 Scenario Sensitivity Analysis Fraction Lost to Leaks

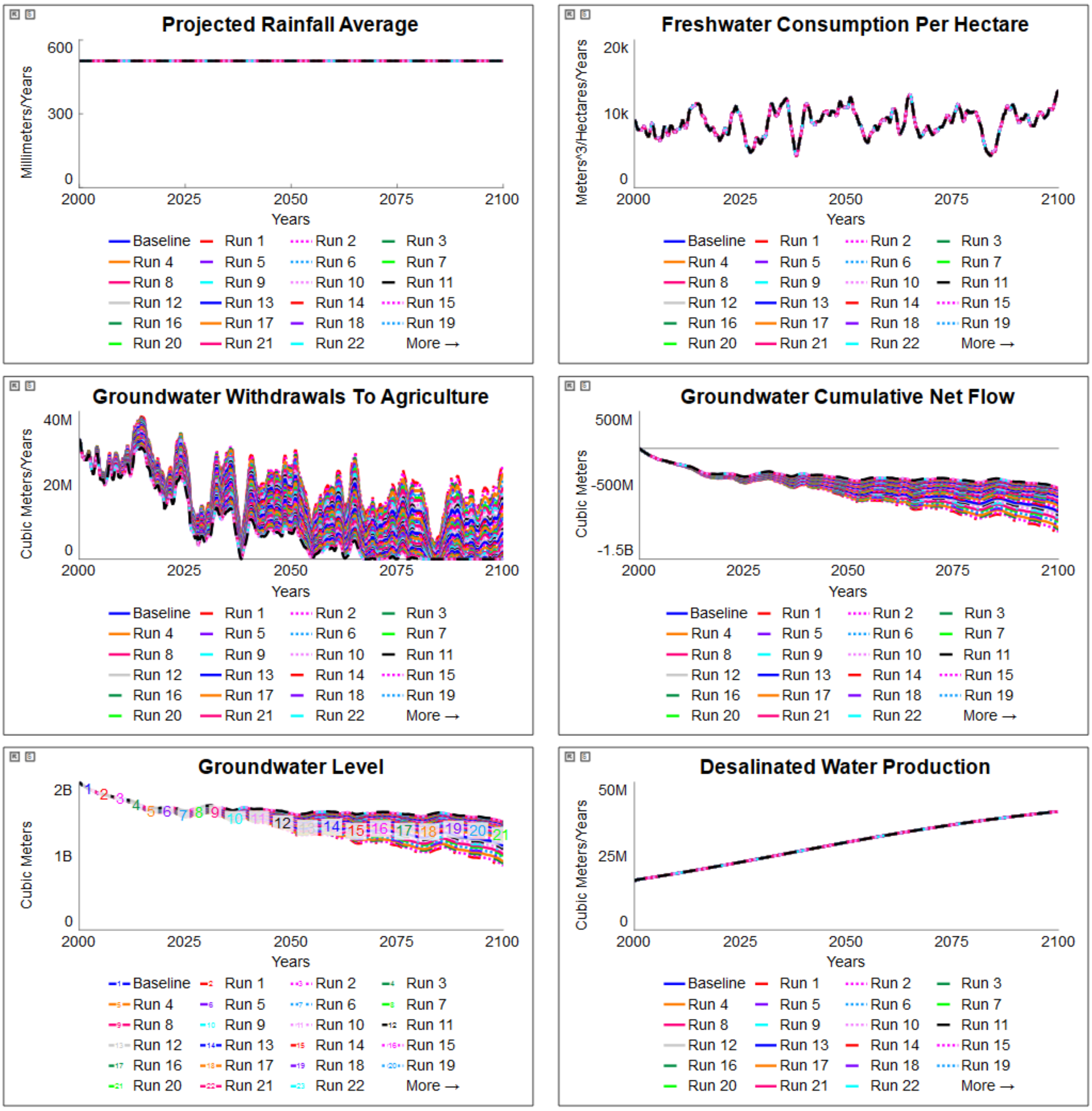


Figure A16: Baseline Scenario Sensitivity Analysis Agricultural Rate of Loss

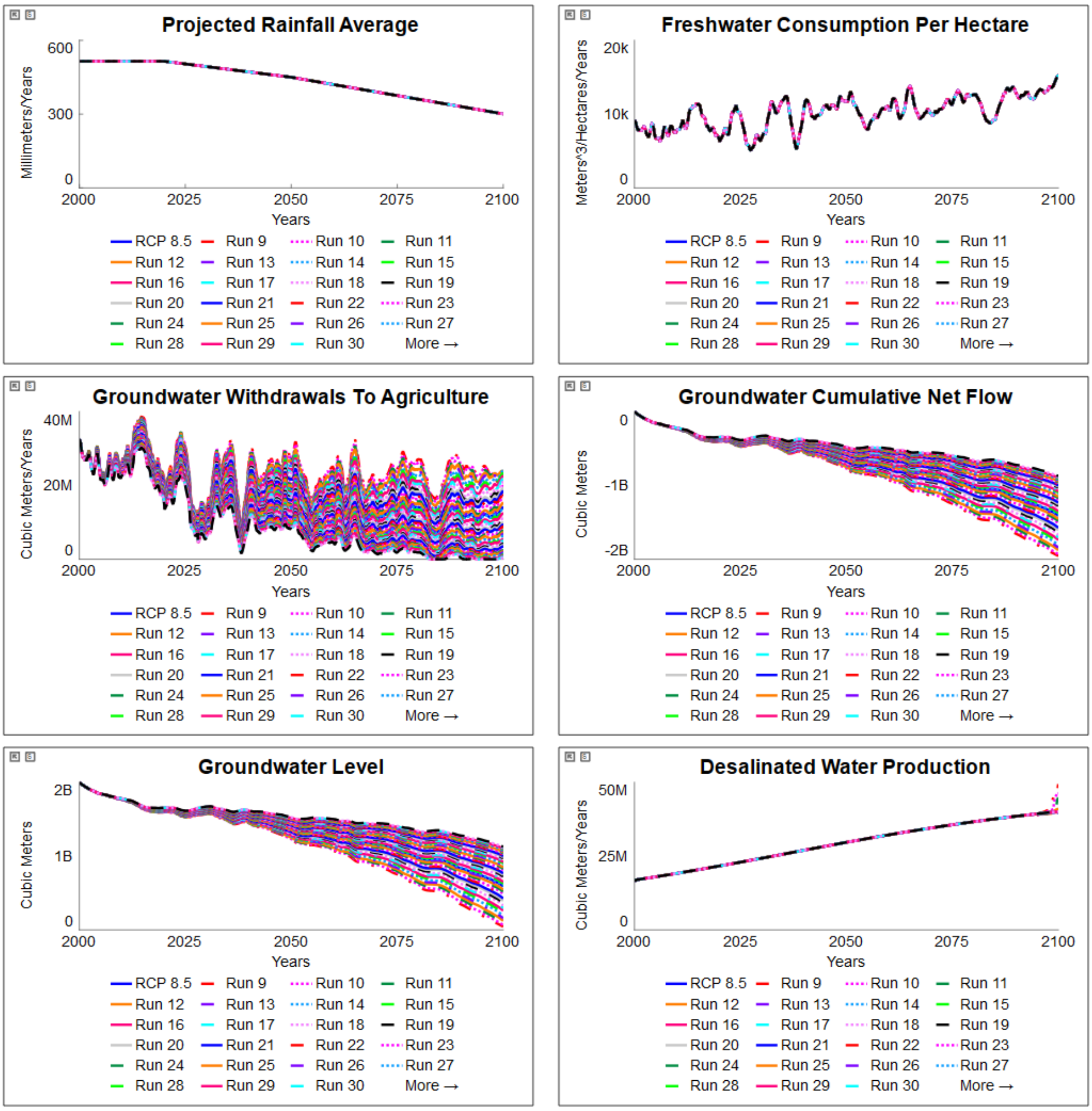


Figure A17: RCP 8.5 Scenario Sensitivity Analysis Agricultural Rate of Loss

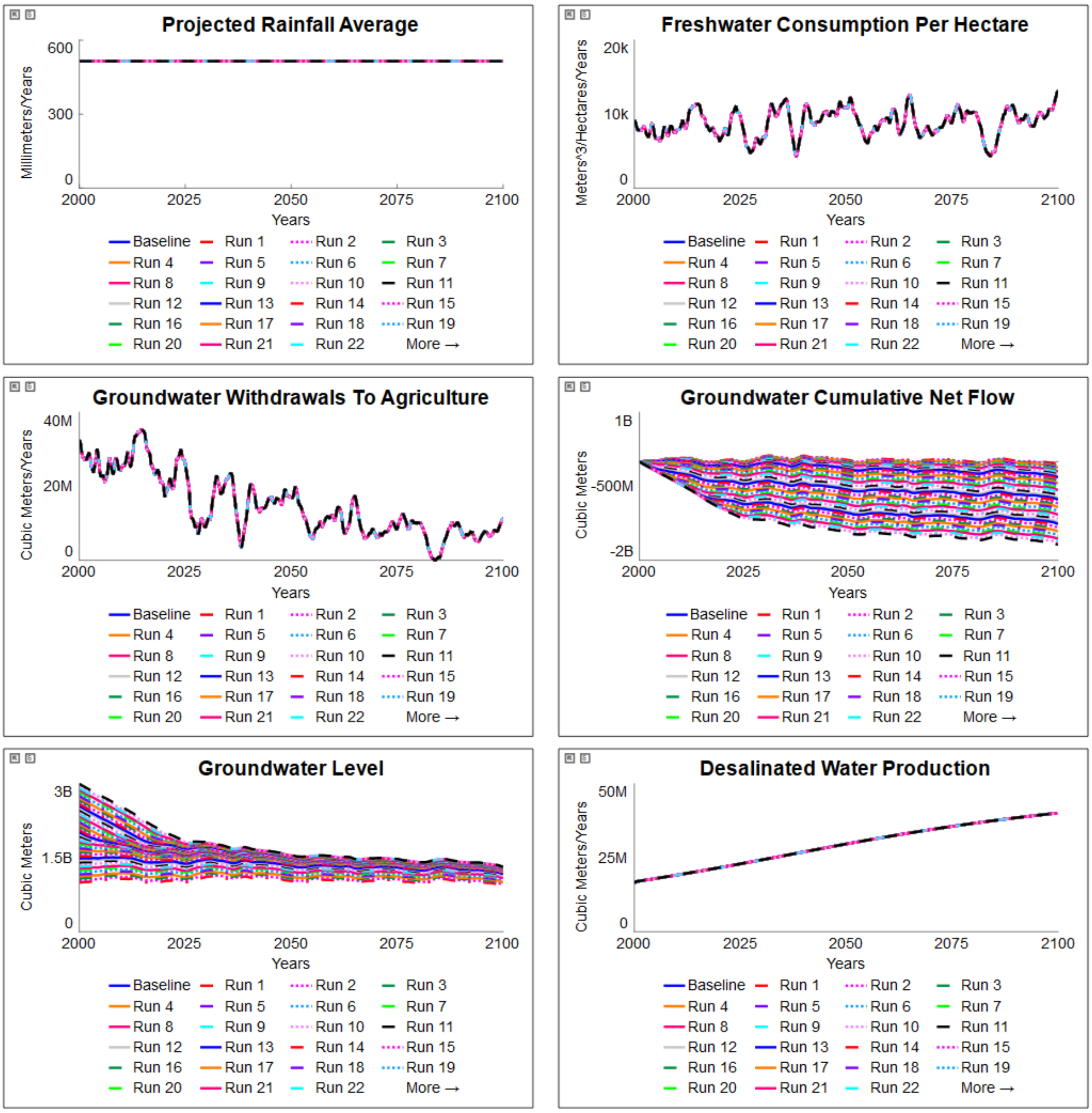


Figure A18: Baseline Scenario Sensitivity Analysis Groundwater Level Starting Amount

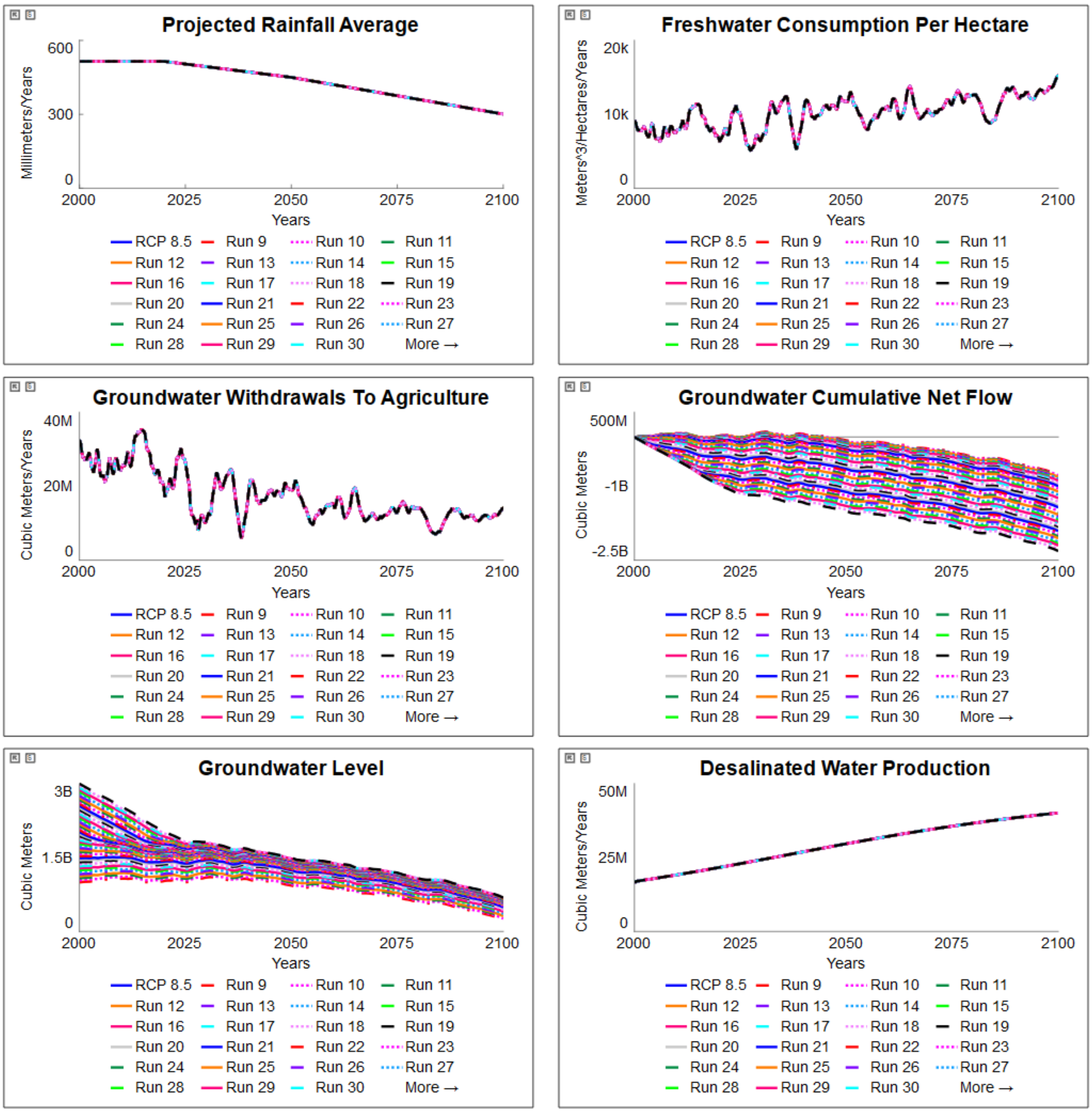


Figure A19: RCP 8.5 Scenario Sensitivity Analysis Groundwater Level Starting Amount

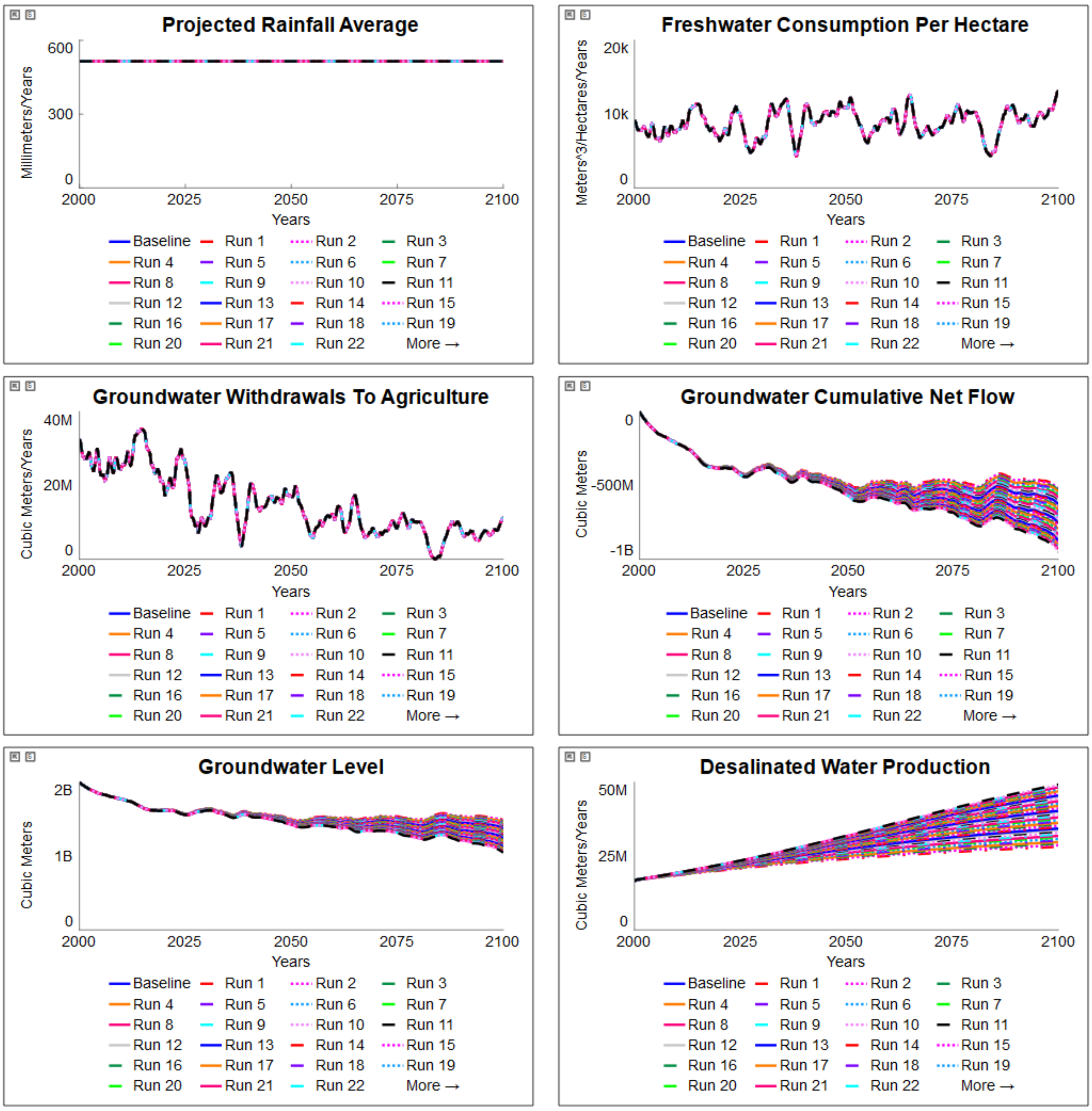


Figure A20: Baseline Scenario Sensitivity Analysis Population Carrying Capacity

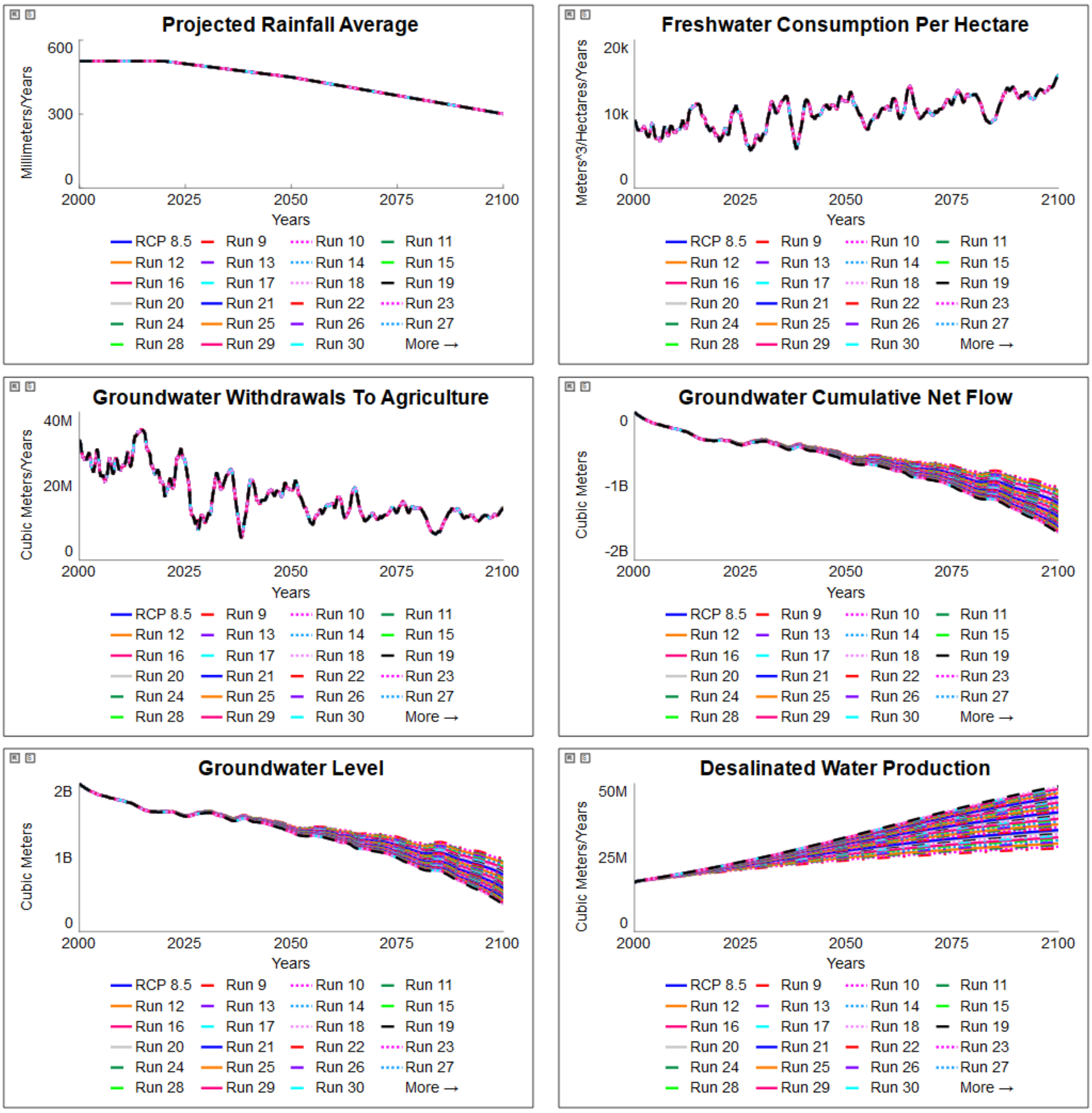


Figure A21: RCP 8.5 Scenario Sensitivity Analysis Population Carrying Capacity

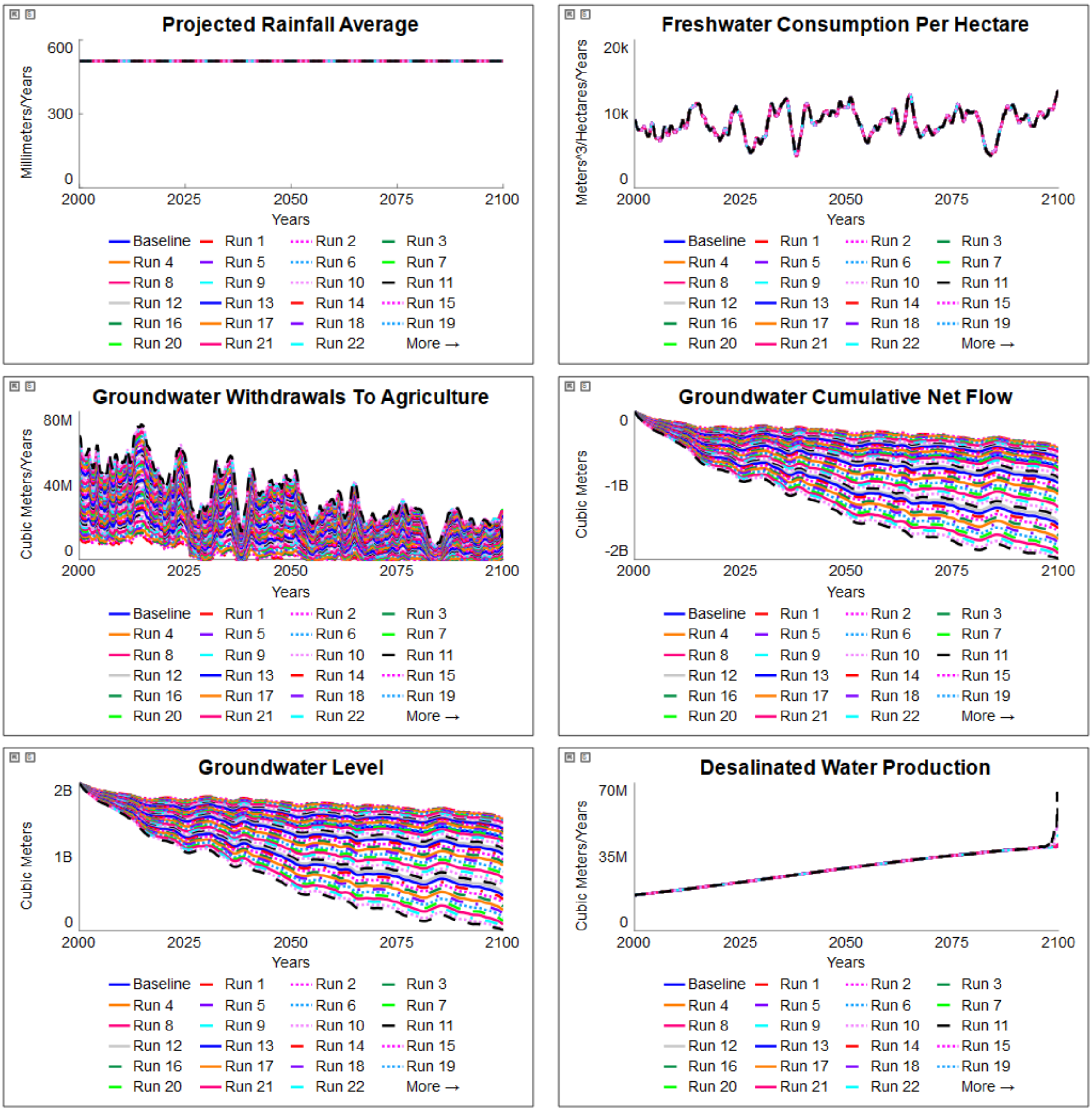


Figure A22:Baseline Scenario Sensitivity Analysis Fraction of Hectares Needing Irrigation

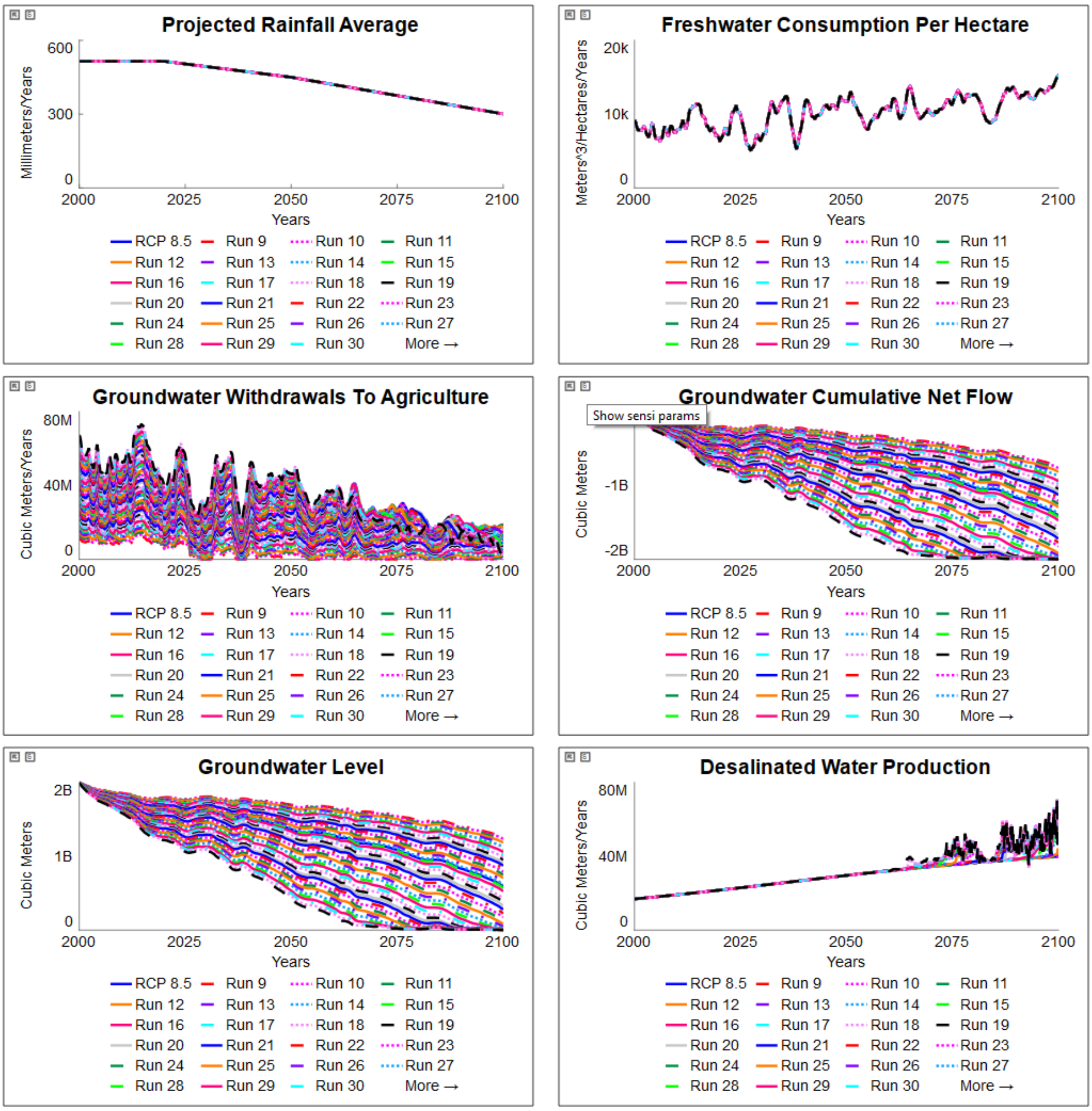


Figure A23: RCP 8.5 Scenario Sensitivity Analysis Fraction of Hectares Needing Irrigation

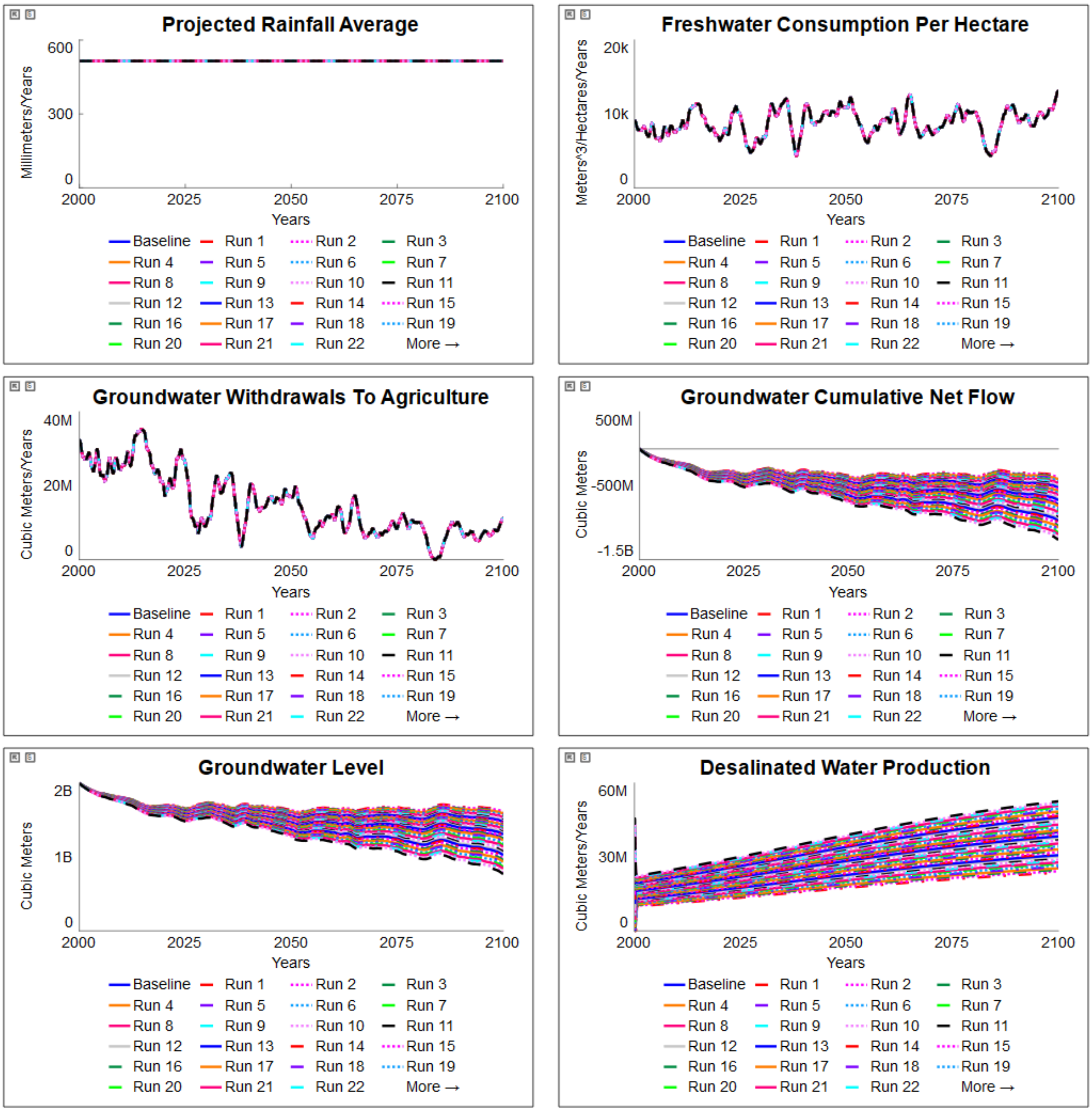


Figure A24: Baseline Scenario Sensitivity Analysis Domestic Consumption per Person

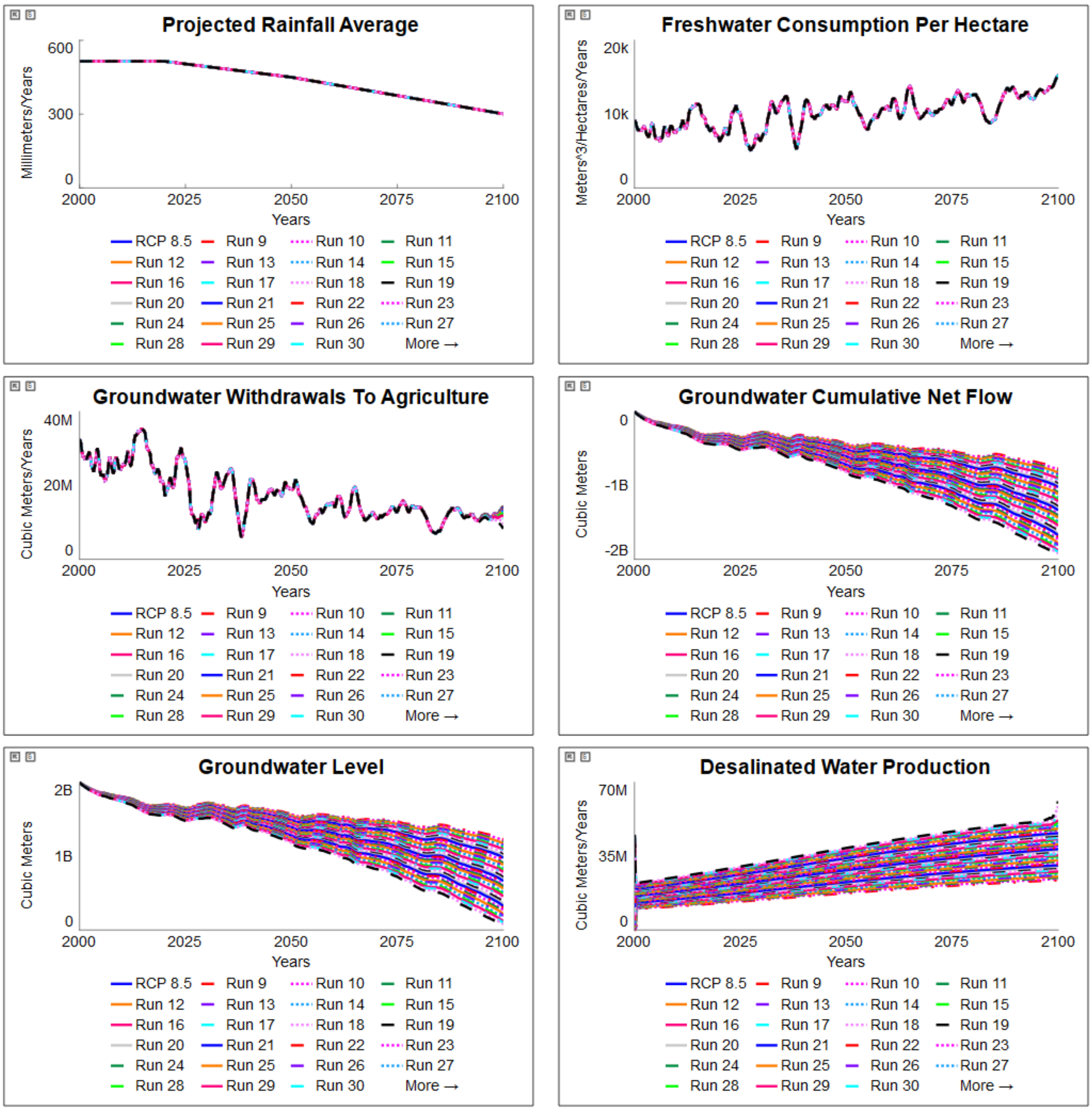


Figure A25: RCP 8.5 Scenario Sensitivity Analysis Domestic Consumption per Person

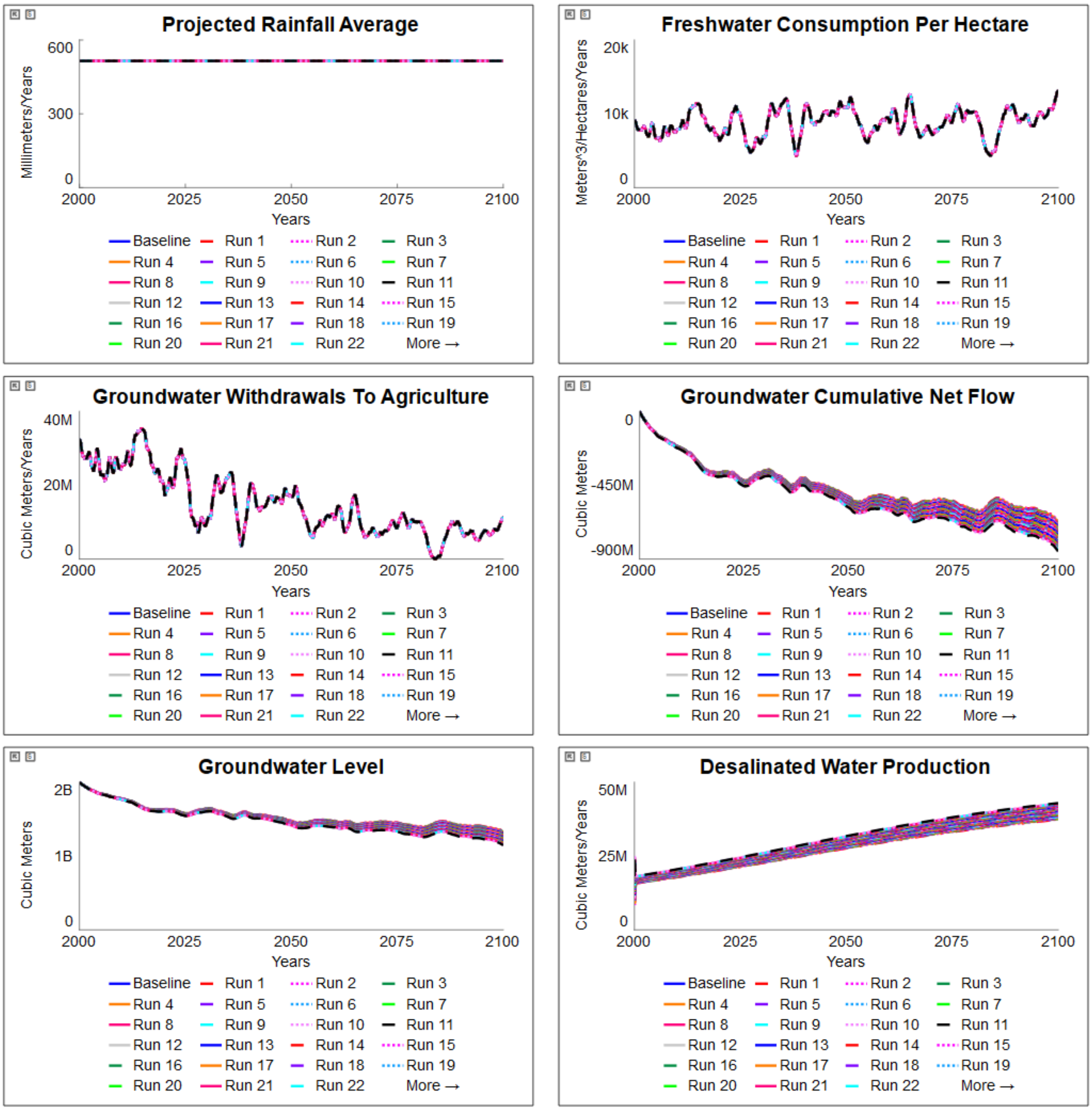


Figure A26: Baseline Scenario Sensitivity Analysis Commercial Consumption per Person

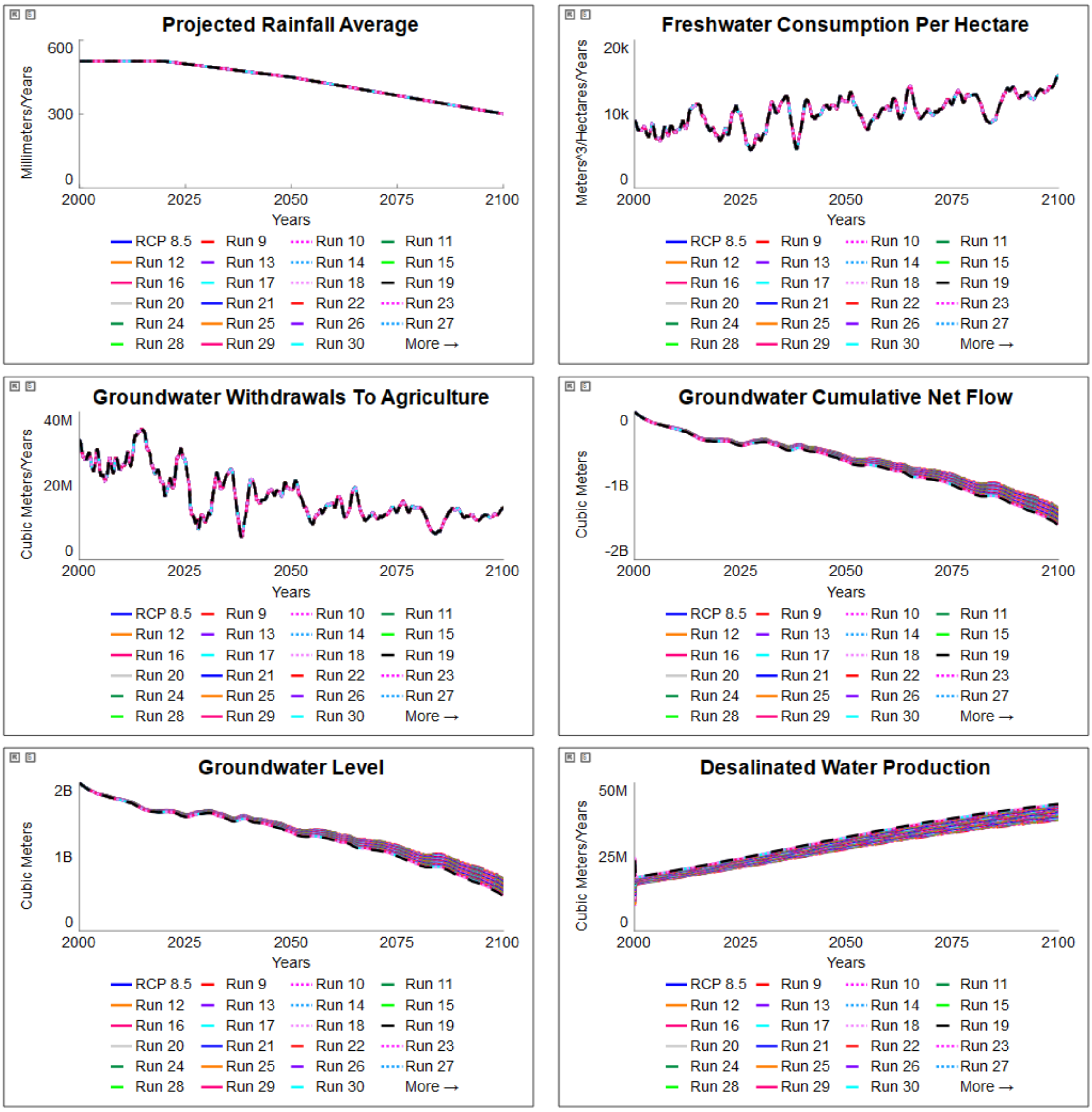


Figure A27: RCP 8.5 Scenario Sensitivity Analysis Commercial Consumption per Person

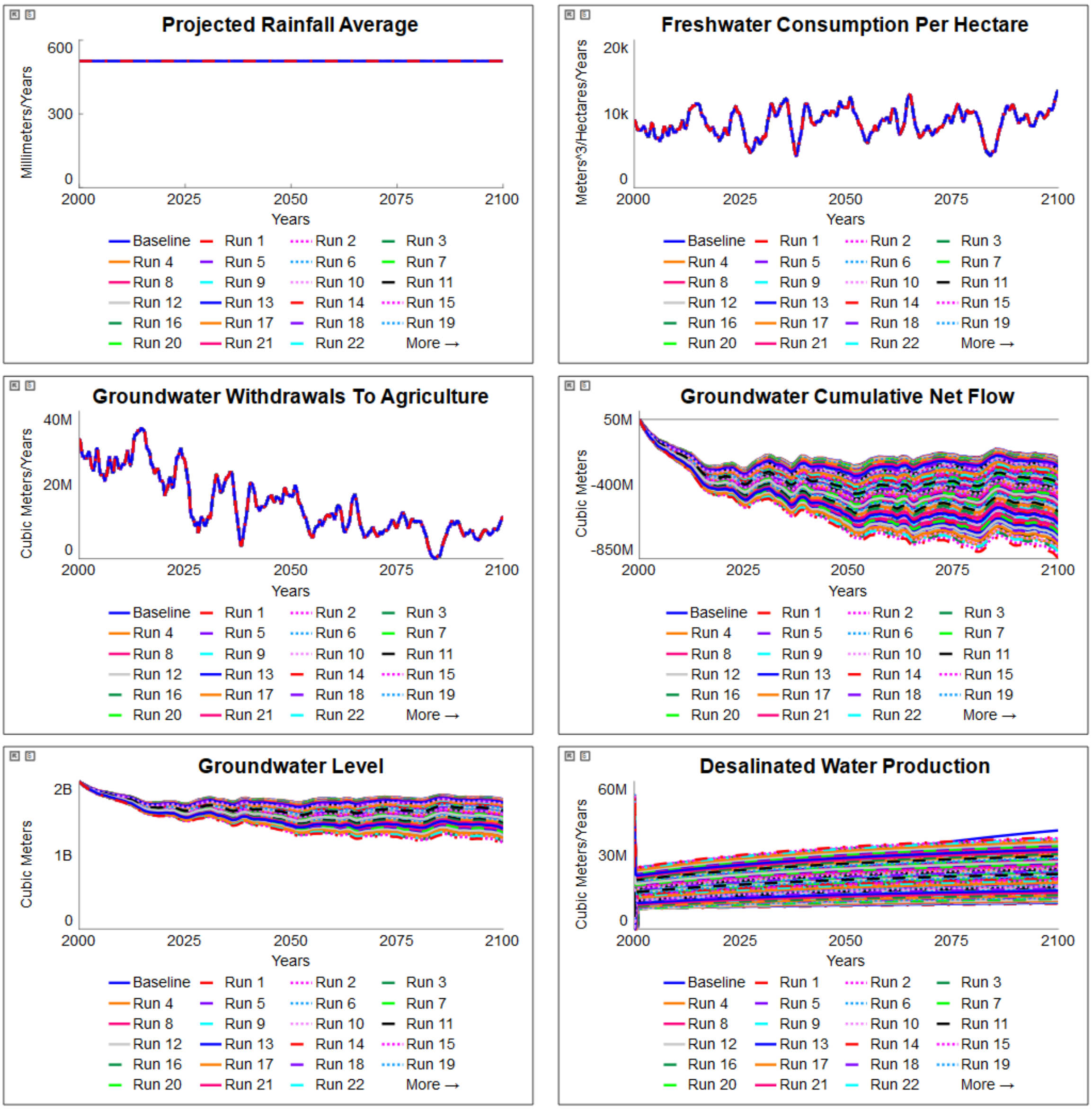


Figure A28: Baseline Scenario Sensitivity Analysis Combined - Birth Rate, Carrying Capacity and non-agricultural sector per capita consumption rates

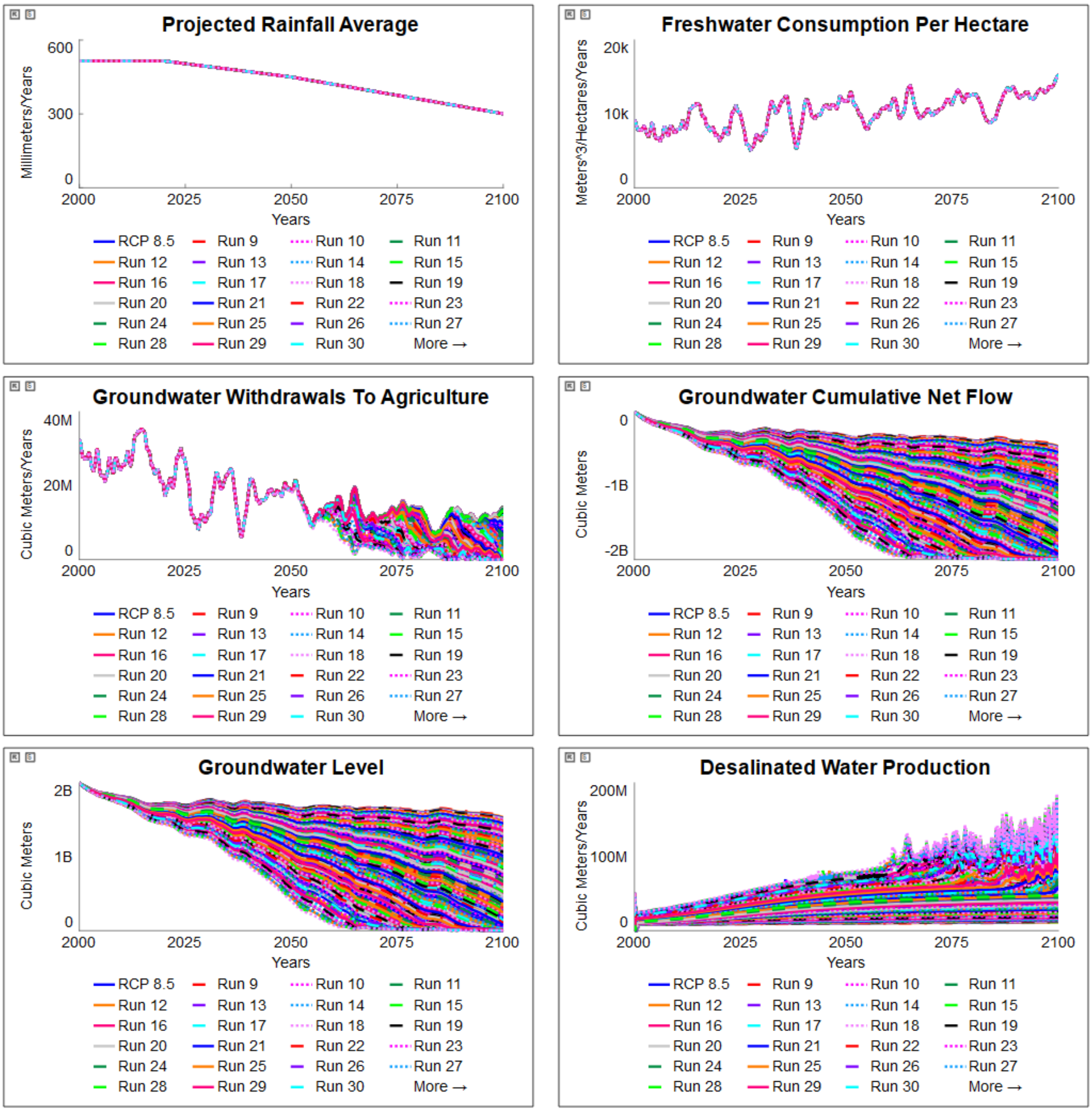


Figure A29: RCP 8.5 Scenario Sensitivity Analysis Combined - Birth Rate, Carrying Capacity and non-agricultural sector per capita consumption rates

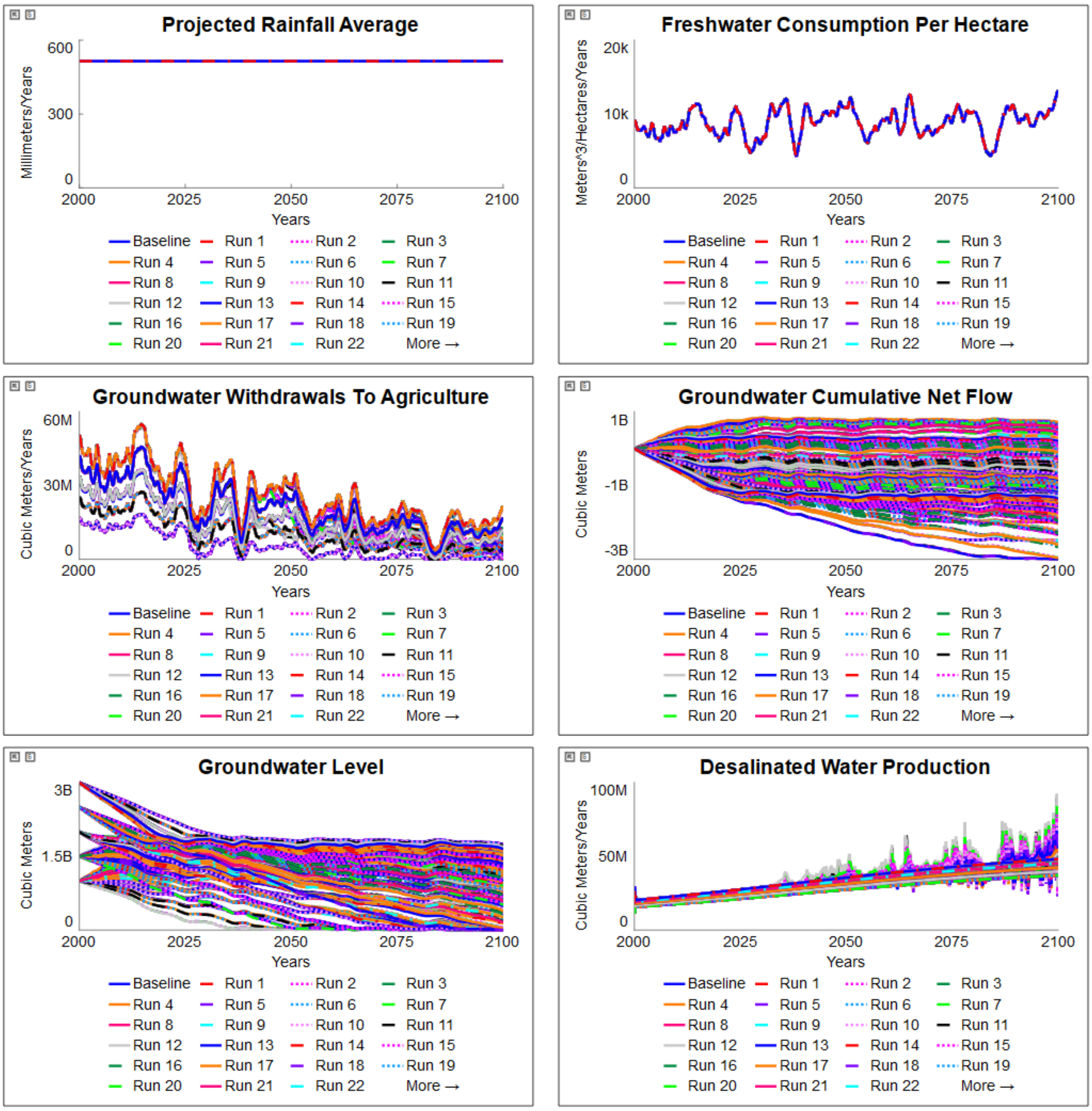


Figure A30: Baseline Scenario Sensitivity Analysis Combined - Groundwater level, recharge coefficient, fraction lost to leaks and fraction of hectares irrigated

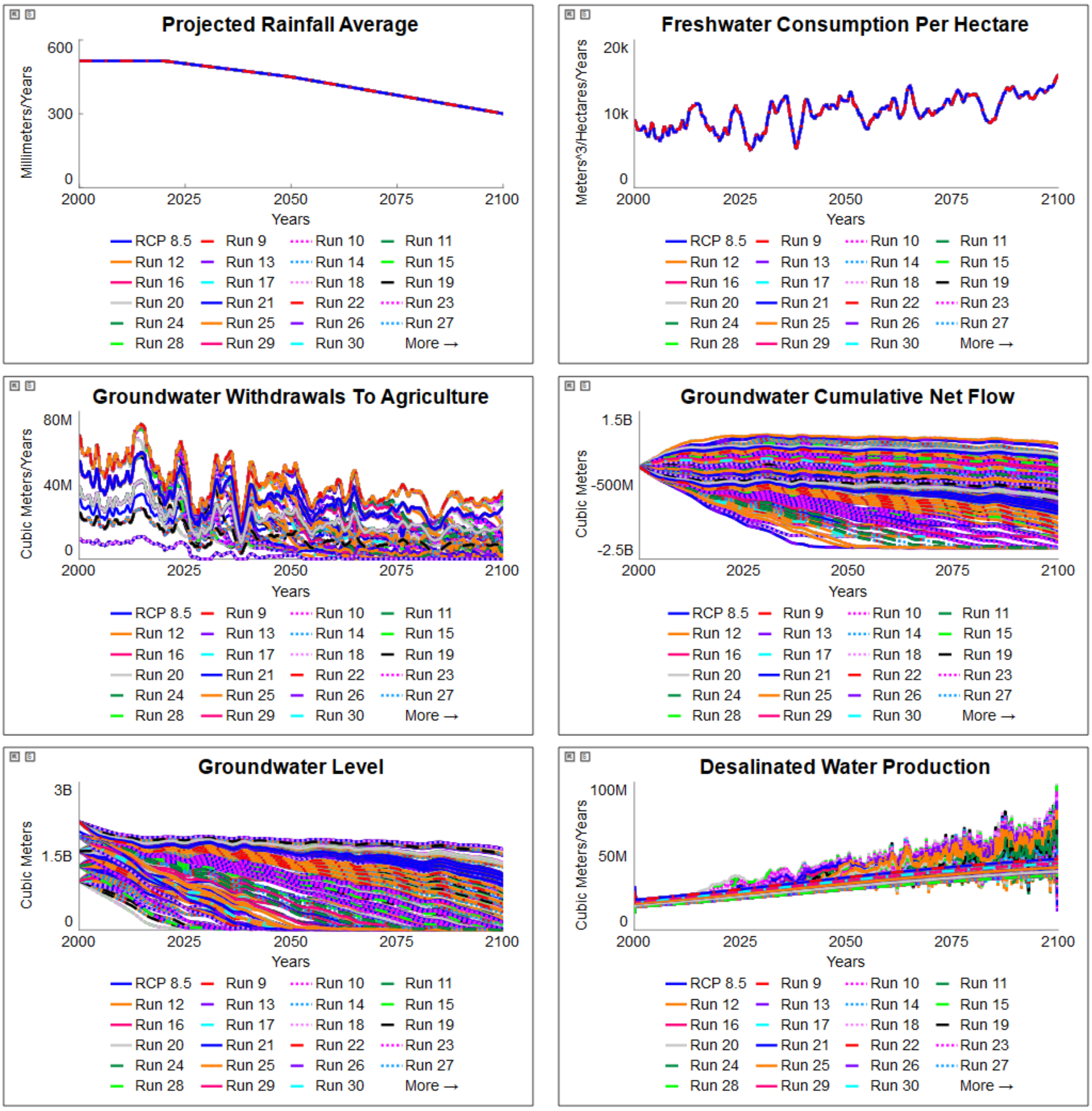


Figure A31: RCP 8.5 Sensitivity Analysis Combined - Groundwater level, recharge coefficient, fraction lost to leaks and fraction of hectares irrigated

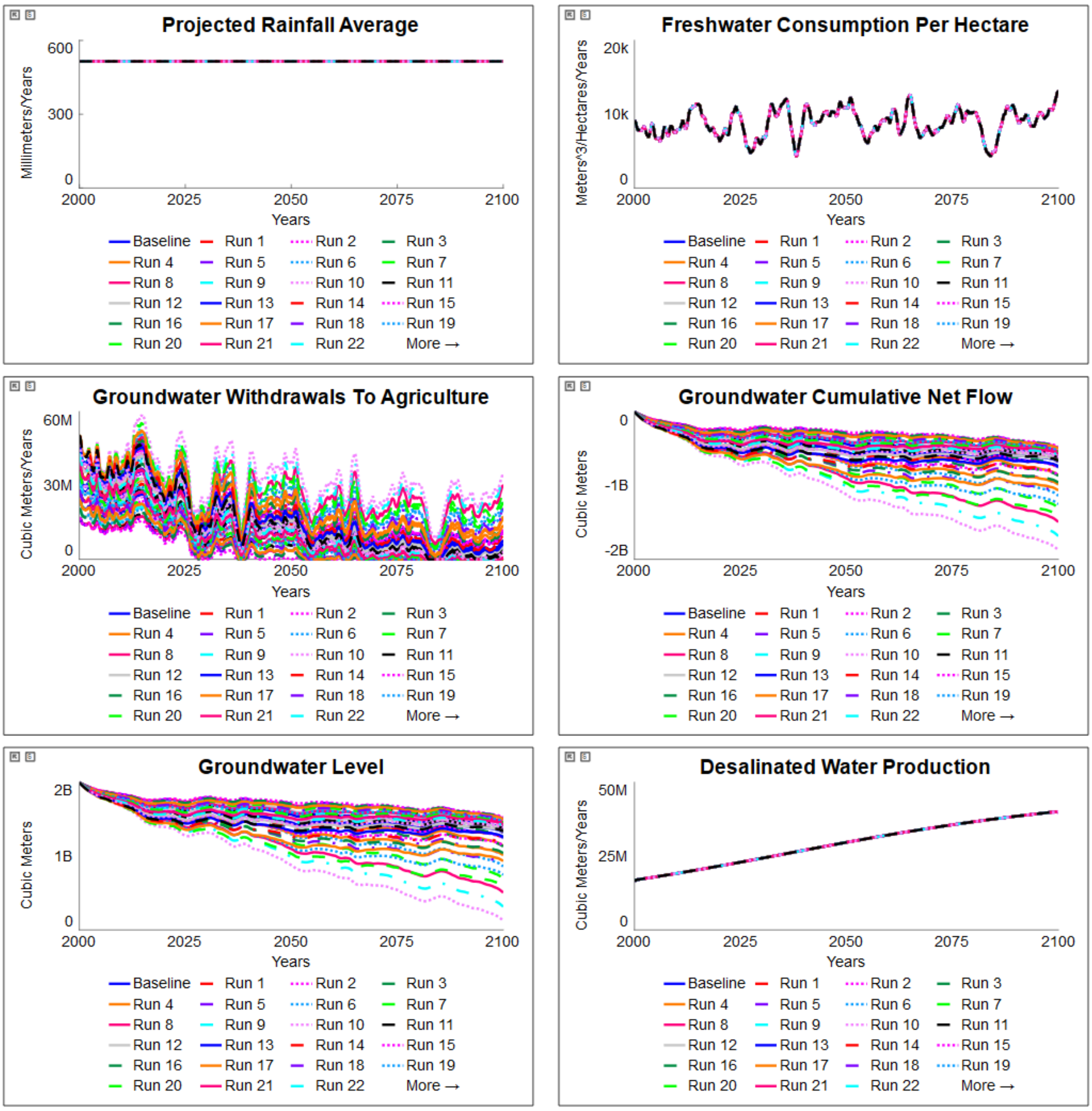


Figure A32: Baseline Scenario Sensitivity Analysis Combined - Yearly Agricultural decline and fraction of hectares irrigated

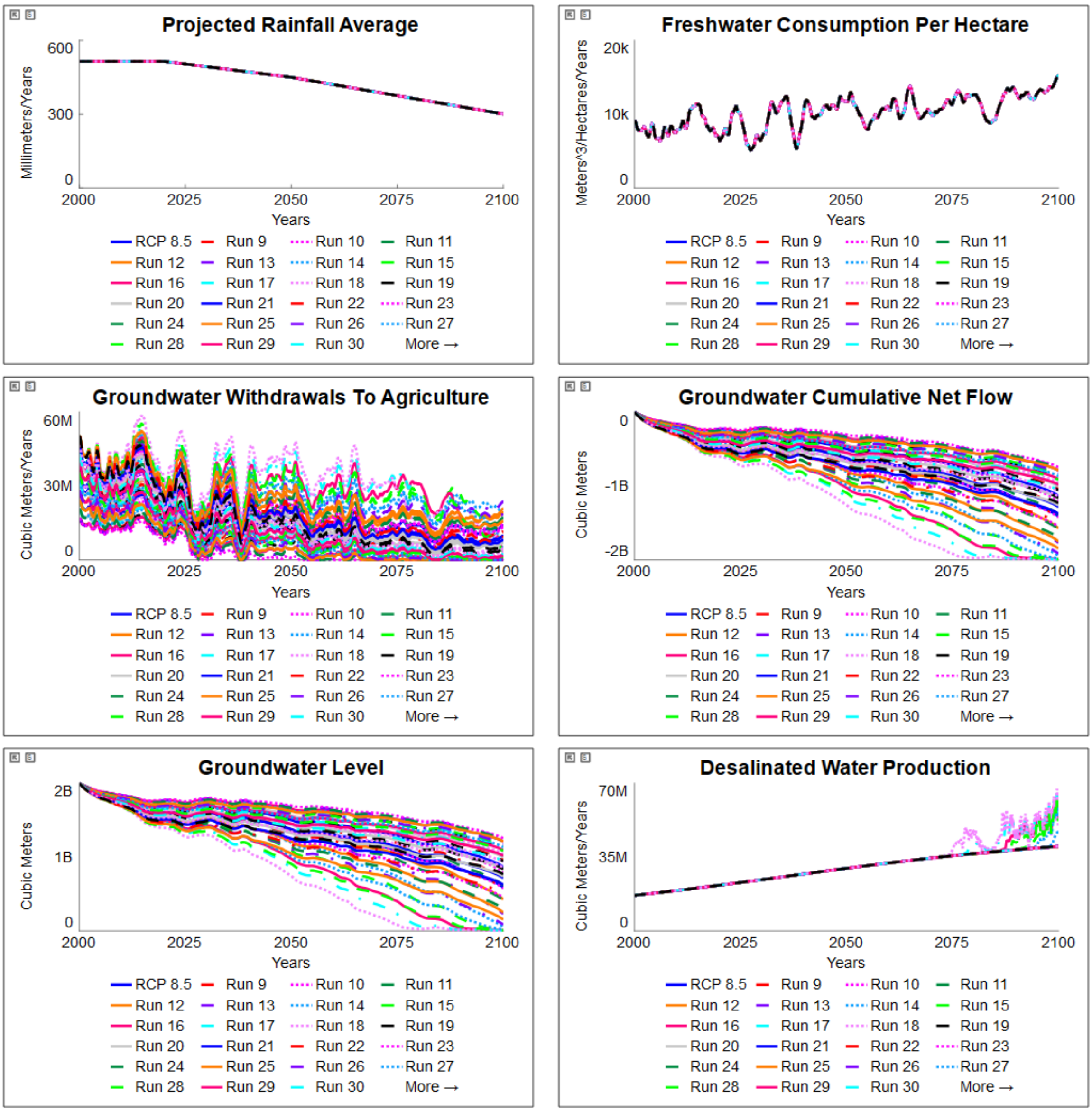


Figure A33: RCP 8.5 Scenario Sensitivity Analysis Combined - Yearly Agricultural decline and fraction of hectares irrigated

Figure A34: Baseline Scenario Sensitivity Analysis Public Sector Consumption per Person

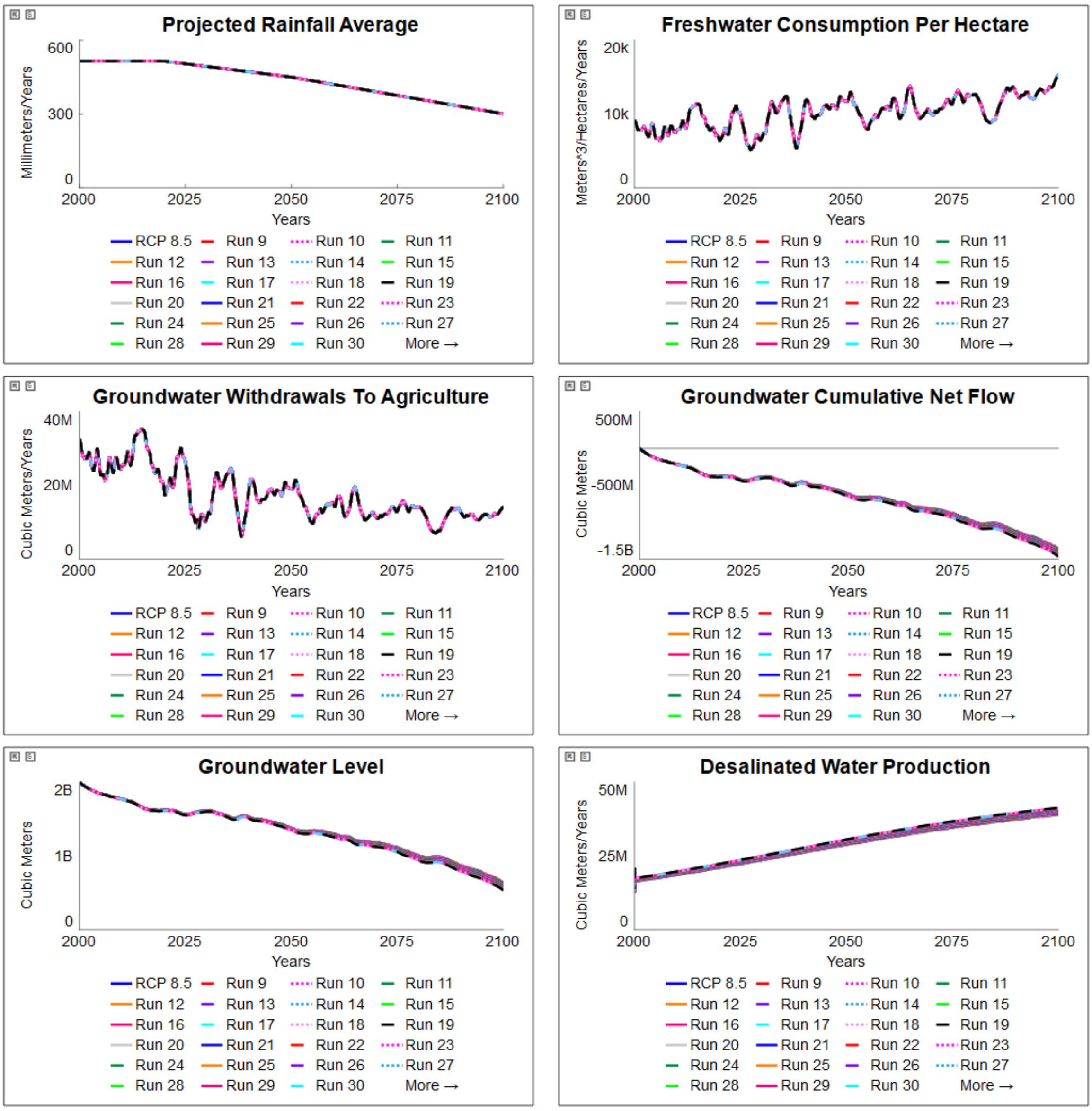


Figure A35: RCP 8.5 Scenario Sensitivity Analysis Public Sector Consumption per Person

8.3 Model Equation Viewer - Parameter Breakdown

Malta Water Model v20 sensitivity analysis.stmx

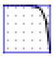
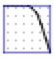
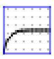
		Equation	Properties	Units	Documentation
	Top-Level Model:				
	Agricultural_Hectares(t)	Agricultural_Hectares(t - dt) + (Hectares_Added_To_Agriculture - Hectares_Removed_From_Agriculture) * dt	INIT Agricultural_Hectares = 12254	Hectares	The total area of land used for agriculture. It decreases due to hectares being removed. Initial value is 12254 hectares.
	Average_Agriculture_consumption_per_Hectare(t)	Average_Agriculture_consumption_per_Hectare(t - dt) + (Net_Change_in_Agricultural_Consumption) * dt	INIT Average_Agriculture_consumption_per_Hectare = 9145	Meters^3/Hectares/Years	The average agricultural water consumption per hectare. It adjusts over time based on the difference between current and initial consumption. Initial value is 9145 cubic metres per hectare per year.
	Cumulative_Net_Flow(t)	Cumulative_Net_Flow(t - dt) + (Changes_in_Cumulative_net_flow) * dt	INIT Cumulative_Net_Flow = 0	Cubic metres	The cumulative net flow of groundwater over time. Initial value is 0 cubic metres.
	Desalinated_Water(t)	Desalinated_Water(t - dt) + (Desalination_Plant_Additions - Lost_Desalinated_Water_to_leakage - Desalinated_Water_Flow) * dt	INIT Desalinated_Water = 15.3e6	Cubic metres	The accumulated volume of desalinated water. It increases due to desalination plant additions and decreases due to leakage and flow for consumption. Initial value is 15.3e6 cubic metres.
	Groundwater(t)	Groundwater(t - dt) + (Rainfall_Additions - Withdrawals_from_Groundwater - Discharge_to_the_sea - Withdrawals_to_agriculture) * dt	INIT Groundwater = 2e+9	Cubic metres	The accumulated volume of groundwater in the aquifer. It changes due to rainfall additions and various withdrawals and discharges. Initial value is set to 2e+9 cubic metres.
	Groundwater_Capacity(t)	Groundwater_Capacity(t - dt) + (Capacity_Recovery - Reduction_in_Capacity) * dt	INIT Groundwater_Capacity = 2e+9	Cubic metres	The maximum storage capacity of the groundwater aquifer. It can be reduced due to over-extraction and recover under favorable conditions. Initial value is set to 2e+9 cubic metres.
	Pink_noise(t)	Pink_noise(t - dt) + (Change_in_Pink_Noise) * dt	INIT Pink_noise =	Dimensionless	A stock variable representing pink noise, which introduces correlated randomness to the

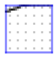
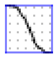
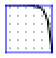
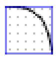
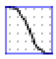
			Mean_Function		system. It changes based on the difference between white noise and its current value, smoothed by a correlation time. Initial value is equal to Mean Function.
	Population_of_Malta(t)	Population_of_Malta(t - dt) + (Net_Change_in_Population_of_Malta) * dt	INIT Population_of_Malta = 399895.0	People	The simulated population of Malta. It changes due to the net change in population (births minus deaths, though only births are explicitly modeled here). Initial value is 399895 people.
	WSC_Fresh_Water_Storage(t)	WSC_Fresh_Water_Storage(t - dt) + (Available_water_flow_from_aquifer + Desalinated_Water_Flow - Freshwater_Consumption) * dt	INIT WSC_Fresh_Water_Storage = 347000	Cubic metres	The total volume of fresh water available from both groundwater and desalinated sources. Initial value is 347,000 cubic metres.
	Available_water_flow_from_aquifer	Water_coming_out_of_aquifer*(1-Fraction_lost_to_leaks)		Cubic metres/Years	The flow of usable water available from the aquifer after accounting for losses.
	Capacity_Recovery	(MAX(0, Net_flow_change))*Effect_of_Maximum_ratio_on_recovery		Meters^3/Years	The rate at which the aquifer capacity recovers, influenced by the net flow change in groundwater and the effect of the maximum storage ratio on recovery.
	Change_in_Pink_Noise	(White_Noise-Pink_noise)/Correlation_Time		Dimensionless/Year	The rate of change in pink noise, driven by the difference between white noise and pink noise, and smoothed by the correlation time.
	Changes_in_Cumulative_net_flow	Net_flow_change		Cubic metres/Years	The rate of change in the cumulative net flow, directly equal to the net flow change in groundwater.
	Desalinated_Water_Flow	Desalinated_Water		Cubic metres/Years	The flow rate of desalinated water, calculated from the stock of desalinated water and its transportation time.
	Desalination_Plant_Additions	Desired_Desalinated_Water_Amount*Effect_of_maximum_storage_ratio_on_pumping		Cubic metres/Years	The volume of water added from desalination plants, influenced by the desired desalinated water amount and the effect of maximum storage ratio on pumping.

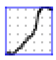
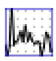
	Discharge_to_the_sea	Groundwater*Normal_Fraction_of_discharge_to_the_sea		Cubic metres/Years	The volume of groundwater discharged to the sea, calculated as a fraction of the current groundwater volume.
	Freshwater_Consumption	"Total_non-agricultural_consumption_demand_for_freshwater"		Cubic metres/Years	The total freshwater consumption, which is equal to the total consumption demand for water.
	Hectares_Added_To_Agriculture	0		Hectares/Years	The rate at which new hectares are added to agriculture. Currently set to 0, implying no new agricultural land is being added.
	Hectares_Removed_From_Agriculture	Agricultural_Hectares*Manual_Fraction_Removed_Per_Year*Switch_for_Manual_Fraction		Hectares/Years	The rate at which agricultural hectares are removed from production, calculated as a fraction of the total agricultural hectares. You can use either a manual switch or allow a feedback loop to control the reduction in the number of hectares farmed.
	Lost_Desalinated_Water_to_leakage	Desalinated_Water*Fraction_lost_to_leaks		Cubic metres/Years	The volume of desalinated water lost due to leakage during transportation, calculated from the desalinated water stock, transportation time, and fraction lost to leaks.
	Net_Change_in_Agricultural_Consumption	(Current_Agricultural_Consumption_Per_Hectare-Average_Agriculture_consumption_per_Hectare)/Adjustment_Time_For_Agricultural_Consumption		Meters^3/Hectares/Years/Years	The net change in average agricultural consumption per hectare, driven by the difference between current and average consumption, adjusted by an adjustment time.
	Net_Change_in_Population_of_Malta	Current_Birth_Rate*Population_of_Malta		People/Years	The net change in the population of Malta, primarily driven by the current birth rate and the existing population. This represents the inflow to the population stock.
	Rainfall_Additions	Recharge_Volume*Effect_of_the_Ratio_of_Groundwater_Capacity_on_Recharging		Meters^3/Year	The total volume of water added to the groundwater stock from rainfall, adjusted by the effect of the groundwater ratio on

					recharging.
	Reduction_in_Capacity	Groundwater_Capacity*Effect_of_the_Ratio_on_Reduction_in_Capacity/Adjustment_Time_for_Aquifer_Capacity_Reduction		Meters^3/Years	The rate at which the groundwater capacity is reduced due to factors like over-extraction or salinization. It is influenced by the current groundwater capacity, the effect of the groundwater ratio on reduction, and an adjustment time.
	Withdrawals_from_Groundwater	"Non-agricultural_Consumption_from_Groundwater"		Cubic metres/Years	The volume of water withdrawn from groundwater for human consumption.
	Withdrawals_to_agriculture	Agricultural_Demand_Minus_new_water		Cubic metres/Years	The volume of water withdrawn for agriculture, which is the agricultural demand not met by new water sources.
	Adjustment_Time_For_Agricultural_Consumption	1		Years	The time it takes for agricultural consumption per hectare to adjust to changes in irrigation pressure. Set to 1 year.
	Adjustment_Time_for_Aquifer_Capacity_Reduction	3		Years	The time it takes for the aquifer capacity to adjust to changes in groundwater levels. Set to 3 years.
	Agricultural_Demand_Minus_new_water	MAX(0, (Agriculture_Consumption-New_Water))		Cubic metres/Year	The portion of agricultural water demand that needs to be met by existing sources (like groundwater), after accounting for new water sources. It cannot be negative.
	Agriculture_Consumption	Hectares_Needing_Irrigation*Current_Agriculture_Consumption_per_Hectares_per_Year		Cubic metres/Years	The total water consumption for agriculture, calculated from the hectares needing irrigation and the current consumption per hectare.
	Baseline_Fractional_Birth_Rate	.014		Per Year	The baseline fractional birth rate for Malta, representing the inherent birth rate per person per year.
	Carrying_Capacity_of_Malta	1600000		People	An assumed carrying capacity for Malta's population. This is a placeholder and would

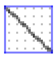
					ideally be dynamically linked to resource availability in a more detailed model. Set to 600,000 people.
	Commercial_Consumption	Population_of_Malta*Current_Commercial_Consumption_per_Person_per_Year		Cubic metres/Years	The total commercial water consumption, calculated by multiplying the population by the current commercial consumption per person.
	Commercial_consumption_per_Person	10		Meters^3/People/Year	The baseline commercial water consumption per person per year. Set to 10 cubic metresper person per year.
	Correlation_Time	1		Years	The correlation time for the pink noise, determining how quickly pink noise adjusts to white noise. Set to 1 year.
	Current_Agricultural_Consumption_Per_Hectare	Pressure_on_Irrigation*Initial_Agricultural_Consumption_per_Hectare		Cubic metres/Hectares/Years	The current agricultural water consumption per hectare, influenced by the pressure on irrigation and the initial consumption per hectare.
	Current_Agriculture_Consumption_per_Hectares_per_Year	Effect_of_Ratio_of_Groundwater_to_Capacity_on_Abstraction*Average_Agriculture_consumption_per_Hectare		Meters^3/Hectares/Years	The current agricultural water consumption per hectare per year, adjusted by the effect of the groundwater ratio on consumption.
	Current_Birth_Rate	Effect_of_the_Carrying_Capacity_Ratio_on_Births*Baseline_Fractional_Birth_Rate		Per Year	The current birth rate, calculated by multiplying the baseline fractional birth rate by the effect of the carrying capacity ratio on births.
	Current_Commercial_Consumption_per_Person_per_Year	Effect_of_Ratio_of_Groundwater_to_Capacity_on_Consumption*Commercial_consumption_per_Person		Meters^3/People/Year	The current commercial water consumption per person per year, adjusted by the effect of the groundwater ratio on consumption. https://era.org.mt/wp-content/uploads/2019/05/2nd_Water_Catchment_Management_Plan-Malta_Water_in_Maltese_Islands-3.pdf
	Current_Domestic_Consumption_per_Person_per_Year	Domestic_Consumption_per_Person*Effect_of_Ratio_of_Groundwater_to_Capacity_on_Consumption		Cubic metres/People/Year	The current domestic water consumption per person per year, adjusted by the effect of the groundwater ratio on consumption.

	Current_Public_Sector_Consumption_per_Person_per_Year	Effect_of_Ratio_of_Groundwater_to_Capacity_on_Consumption*Public_Sector_consumption_per_Person		Meters^3/People/Year	The current public sector water consumption per person per year, adjusted by the effect of the groundwater ratio on consumption.
	Desired_Desalinated_Water_Amount	("Total_non-agricultural_pumping_Demand_for_water"-Available_water_flow_from_aquifer)*Effect_of_maximum_storage_ratio_on_pumping		Meters^3/Years	The desired amount of desalinated water needed to meet demand, calculated based on total pumping demand, water from the aquifer, and the effect of maximum storage ratio on pumping.
	Domestic_Consumption_per_Person	57.6		Meters^3/People/Year	The baseline domestic water consumption per person per year. Set to 57.6 cubic metresper person per year.
	Domestic_Human_Consumption	Population_of_Malta*Current_Domestic_Consumption_per_Person_per_Year		Cubic metres/Years	The total domestic water consumption by the human population, calculated by multiplying the population by the current domestic consumption per person.
	Effect_of_Maximum_ratio_on_recovery	GRAPH(Ratio_between_Maximum_and_Actual_Aquifer_Storage) Points: (0.000, 1.000), (0.100, 0.9999), (0.200, 0.9997), (0.300, 0.9991), (0.400, 0.9976), (0.500, 0.9933), (0.600, 0.9817), (0.700, 0.9503), (0.800, 0.8647), (0.900, 0.6321), (1.000, 0.000)		Dimensionless	A graphical function that determines how the ratio between maximum and actual aquifer storage affects the recovery rate. As the ratio increases (more capacity available), the effect on recovery decreases, implying less need for recovery when capacity is high.
	Effect_of_maximum_storage_ratio_on_pumping	GRAPH(Ratio_of_total_freshwater_available_to_maximum) Points: (0.5000, 1.000), (0.5500, 1.000), (0.6000, 1.000), (0.6500, 1.000), (0.7000, 1.000), (0.7600, 1.000), (0.8000, 0.950), (0.8500, 0.850), (0.9000, 0.600), (0.9500, 0.300), (1.0000, 0.000)		Dimensionless	A graphical function that determines how the ratio of total freshwater available to maximum affects pumping. As the ratio increases (more freshwater available), the effect decreases, implying less need for pumping.
	Effect_of_Ratio_of_Groundwater_to_Capacity_on_Abstraction	GRAPH(Ratio_of_Groundwater_to_Capacity) Points: (0.000, 0.000), (0.100, 0.6321), (0.200, 0.8647), (0.300, 0.9503), (0.400, 0.9817), (0.500, 0.9933), (0.600, 0.9976), (0.700, 0.9991), (0.800,		Dimensionless	A graphical function that determines how the ratio of groundwater to capacity affects water abstraction. As the ratio increases (more groundwater), the effect on abstraction increases, implying higher consumption

		0.9997), (0.900, 0.9999), (1.000, 1.000)			when groundwater is abundant.
	Effect_of_Ratio_of_Groundwater_to_Capacity_on_Consumption	GRAPH(Ratio_of_Groundwater_to_Capacity) Points: (0.000, 0.850), (0.100, 0.870), (0.200, 0.910), (0.300, 0.9503), (0.400, 0.9817), (0.500, 0.9933), (0.600, 0.9976), (0.700, 0.9991), (0.800, 0.9997), (0.900, 0.9999), (1.000, 1.000)		Dimensionless	A graphical function that determines how the ratio of groundwater to capacity affects water consumption. As the ratio increases (more groundwater), the effect on consumption increases, implying higher consumption when groundwater is abundant.
	Effect_of_the_Carrying_Capacity_Ratio_on_Births	GRAPH(Ratio_of_Population_to_Carrying_Capacity) Points: (0.000, 1.000), (0.100, 0.9874), (0.200, 0.9566), (0.300, 0.8835), (0.400, 0.7324), (0.500, 0.500), (0.600, 0.2676), (0.700, 0.1165), (0.800, 0.04341), (0.900, 0.01263), (1.000, 0.000)		Dimensionless	A graphical function that determines how the ratio of population to carrying capacity affects the birth rate. As the population approaches carrying capacity (ratio increases), the effect on births increases, implying a positive feedback on population growth based on the current graph.
	Effect_of_the_Ratio_of_Groundwater_Capacity_on_Recharging	GRAPH(Ratio_of_Groundwater_to_Capacity) Points: (0.000, 1.000), (0.100, 0.9999), (0.200, 0.9997), (0.300, 0.9991), (0.400, 0.9976), (0.500, 0.9933), (0.600, 0.9817), (0.700, 0.9503), (0.800, 0.8647), (0.900, 0.6321), (1.000, 0.000)		Dimensionless	A graphical function that determines how the ratio of groundwater to capacity affects the recharging rate. As the ratio increases (more groundwater), the effect on recharging decreases, implying less recharge when the aquifer is fuller.
	Effect_of_the_ratio_of_total_to_maximum_freshwater	GRAPH(Ratio_of_total_freshwater_available_to_maximum) Points: (0.000, 2.000), (0.100, 1.996), (0.200, 1.989), (0.300, 1.978), (0.400, 1.960), (0.500, 1.929), (0.600, 1.878), (0.700, 1.791), (0.800, 1.647), (0.900, 1.405), (1.000, 1.000)		Dimensionless	A graphical function that determines how the ratio of total to maximum freshwater affects the total pumping demand. As the ratio increases (more freshwater available), the effect decreases, implying less need for additional pumping.
	Effect_of_the_Ratio_on_Reduction_in_Capacity	GRAPH(Ratio_of_Groundwater_to_Capacity) Points: (0.000, 0.2000), (0.100, 0.1975), (0.200, 0.1913), (0.300, 0.1767), (0.400, 0.1465), (0.500, 0.1000), (0.600, 0.05352), (0.700, 0.02331), (0.800, 0.008682), (0.900, 0.002526), (1.000, 0.0000)		Dimensionless	A graphical function that determines how the ratio of groundwater to capacity affects the reduction in aquifer capacity. As the ratio increases (more groundwater), the effect on reduction decreases, implying less capacity loss when the aquifer is fuller.

◯	Fraction_lost_to_leaks	0.09376901408		Dimensionless	The fraction of water lost due to leaks in the distribution system. Based on WSC data, set to 0.09376901408. https://www.wsc.com.mt/about-us/water-production-distribution/
◯	Fraction_of_Hectares_Irrigated	0.29		Dimensionless	The fraction of agricultural hectares that are irrigated. Set to 0.29.
◯	"Fraction_of_Non-Agricultural_Consumption_from_Groundwater"	0.35+(RAMP("Reduction_in_Fraction_of_Non-Agricultural_Consumption_from_Groundwater", 2020)*Switch)		Dimensionless	The fraction of total human water consumption that is drawn from groundwater. Set to 0.35.
◯	Hectares_Needing_Irrigation	Agricultural_Hectares*Fraction_of_Hectares_Irrigated		Hectares	The total number of agricultural hectares that require irrigation, calculated from total agricultural hectares and the fraction irrigated.
◯	Historical_Hectares	GRAPH(TIME) Points: (2000.00, 12254), (2005.00, 10254), (2007.00, 10326), (2010.00, 11453), (2013.00, 11689), (2020.00, 10730), (2023.00, 8880), (2024.00, 8880), (2025.00, NaN)		Hectares	Historical data for agricultural hectares in Malta, used as a reference or for initialization. This is represented as a graphical function of time.
◯	Historical_Population_of_Malta	GRAPH(TIME) Points: (1955.00, 318139), (1960.00, 330820), (1965.00, 327398), (1970.00, 326011), (1975.00, 333450), (1980.00, 342877), (1985.00, 352566), (1990.00, 367908), (1995.00, 384550), (2000.00, 399895), (2005.00, 413320), (2010.00, 422651), (2015.00, 444981), (2020.00, 518207), (2022.00, 528192), (2023.00, 532956), (2024.00, 537753), (2025.00, 545405), (2030.00, 555231), (2035.00, 556508), (2040.00, 551735), (2045.00, 544634), (2050.00, 535721)		People	Historical population data for Malta, used as a reference or for initialization. This is represented as a graphical function of time.
◯	Historical_Rainfall	GRAPH(TIME) Points: (2000.00, 460.0), (2001.00, 340.0), (2002.00, 450.0), (2003.00, 900.0), (2004.00,		Millimeters/Year	Historical rainfall data for Malta, used as a reference or for initialization. This is represented as a graphical

		460.0), (2005.00, 505.0), (2006.00, 530.0), (2007.00, 610.0), (2008.00, 500.0), (2009.00, 680.0), (2010.00, 510.0), (2011.00, 590.0), (2012.00, 515.0), (2013.00, 480.0), (2014.00, 505.0), (2015.00, 490.0), (2016.00, 320.0), (2017.00, 430.0), (2018.00, 600.0), (2019.00, 550.0), (2020.00, 390.0), (2021.00, 390.0)			function of time. https://nso.gov.mt/wp-content/uploads/Climate-publication-2022.pdf
○	Initial_Agricultural_Consumption_per_Hectare	9145+(RAMP(Reduction_in_Agricultural_Consumption,2020)*SwitchAG)		Meters^3/Hectares/Years	The initial agricultural water consumption per hectare. Set to 9145 cubic metresper hectare per year.
○	Initial_Normal_Rainfall_for_Malta	515		Millimeters/Years	The initial normal rainfall for Malta, used as a reference. Based on historical data, set to 515 mm/year. It is the average rainfall between 2000-2020 https://nso.gov.mt/wp-content/uploads/Climate-publication-2022.pdf
○	Land_Area	316000000		Meters^2	The total land area of Malta, used in calculating recharge volume. Set to 316,000,000 square metres.
○	Manual_Fraction_Removed_Per_Year	.0093		Dimensionless/Year	The rate of decrease experienced by the agricultural sector in Malta. Has been calculated based on historical data obtained from https://nso.gov.mt/wp-content/uploads/Agriculture-and-Fisheries-2014.pdf
○	Maximum_Capacity_of_Aquifer	2e+9		Meters^3	The absolute maximum capacity of the aquifer. Set to 2e+9 cubic metres.
○	Maximum_Freshwater_Storage	400000		Cubic metres	The maximum possible volume of freshwater available. Set to 400,000 cubic metres.
○	Mean_Function	1		Dimensionless	The mean value for the white noise. Set to 1.
○	Millimeter_Conversion_To_Meter	1000		Millimeters/Meters	A conversion factor to convert millimetresto metres. Set to 1000 mm/meter.

	Net_flow_change	Rainfall_Additions-(Discharge_to_the_sea+Withdrawals_from_Groundwater+Withdrawals_to_agriculture)		Meters^3/Years	The net change in groundwater volume, calculated as rainfall additions minus all outflows (discharge to sea, human withdrawals, and agricultural withdrawals).
	Net_flow_for_Desalinated_Water	Desalination_Plant_Additions-Lost_Desalinated_Water_to_leakage		Cubic metres/Years	The net flow into the desalinated water stock, calculated as additions minus leakage.
	New_Water	0+STEP(1.5e+6, 2020)+STEP(2.7e+6, 2026)+STEP(3e+6, 2028)+(STEP(2.8e+6, 2028)*SwitchNW)		Meters^3/Years	The volume of new water sources available, such as reclaimed water, added at specific times. This is a step function with additions in 2020, 2026, and 2028. https://www.wsc.com.mt/wsc-annual-report-2023/
	Noise_Seed	7		Dimensionless	The seed for the random number generator used in white noise. Set to 7.
	"Non-agricultural_Consumption_from_Groundwater"	"Total_non-agricultural_pumping_Demand_for_water"*"Fraction_of_Non-Agricultural_Consumption_from_Groundwater"*Effect_of_Ratio_of_Groundwater_to_Capacity_on_Abstraction		Cubic metres/Years	The total volume of water consumed by humans that is drawn directly from groundwater.
	Normal_Fraction_of_discharge_to_the_sea	0.00175		Dimensionless/Year	The normal fraction of groundwater that discharges to the sea annually. Set to 0.00175.
	Numbers_Check	(Freshwater_Consumption+Total_Water_Loss_to_Leaks)		Cubic metres/Years	A check variable to sum freshwater consumption and total water loss, ensuring mass balance in the model.
	Pressure_on_Irrigation	GRAPH(Ratio_of_Average_rainfall_to_Ideal_rainfall) Points: (0.000, 2.000), (0.200, 1.800), (0.400, 1.600), (0.600, 1.400), (0.800, 1.200), (1.000, 1.000), (1.200, 0.800), (1.400, 0.600), (1.600, 0.400), (1.800, 0.200), (2.000, 0.000)		Dimensionless	A graphical function that determines the pressure on irrigation based on the ratio of average rainfall to ideal rainfall. As the ratio increases (more rainfall), the pressure on irrigation decreases.
	Production_Check	Available_water_flow_from_aquifer+Desalinated_Water_Flow		Cubic metres/Year	A variable used to check the total freshwater produced for non-agricultural use. Can be checked against total non-agricultural demand to

					ensure that demand is being met in the system.
	Projected_Rainfall_Average	Initial_Normal_Rainfall_for_Malta+(STEP(RAMP(Rainfall_Decline_Rate_2050, 2020, 2050)+ RAMP(Rainfall_Decline_Rate_2070, 2050), 2020))*Switch_for_Rainfall_Scenarios		Millimeters/Years	The current and projected rainfall, starting from the initial normal rainfall and declining over time based on specified decline rates for 2050 and 2070. https://www.um.edu.mt/library/oar/bitstream/123456789/44841/1/Galdies%20%26%20Vella%202019%20%282%29.pdf
	Public_Sector_Consumption	Population_of_Malta*Current_Public_Sector_Consumption_per_Person_per_Year		Cubic metres/Years	The total public sector water consumption, calculated by multiplying the population by the current public sector consumption per person. This was matched to historical data based on the 2nd WCMP.
	Public_Sector_consumption_per_Person	4.4		Meters^3/People/Year	The baseline public sector water consumption per person per year. Set to 4.4 cubic metresper person per year.
	Rainfall_Decline_Rate_2050	-2.163333333		Millimeters/Years	The projected annual decline rate of rainfall by 2050, in millimetresper year. Set to -2.163333333 mm/year.
	Rainfall_Decline_Rate_2070	-2.982		Millimeters/Years	The projected annual decline rate of rainfall by 2070, in millimetresper year. Set to -2.982 mm/year.
	Ratio_between_Maximum_and_Actual_Aquifer_Storage	Groundwater_Capacity/Maximum_Capacity_of_Aquifer		Dimensionless	The ratio of the current groundwater capacity to the maximum possible aquifer capacity. This indicates how much of the aquifer's potential storage is currently available.
	Ratio_of_Average_rainfall_to_Ideal_rainfall	Simulated_Average_Rainfall/Initial_Normal_Rainfall_for_Malta		Dimensionless	The ratio of the average rainfall to the ideal (initial normal) rainfall. This indicates how current rainfall compares to a historical norm.

	Ratio_of_Groundwater_to_Capacity	Groundwater/Groundwater_Capacity		Dimensionless	The ratio of current groundwater volume to the groundwater capacity. This indicates how full the aquifer is.
	Ratio_of_Population_to_Carrying_Capacity	Population_of_Malta/Carrying_Capacity_of_Malta		Dimensionless	The ratio of the current population to the carrying capacity. This indicates how close the population is to its environmental limits.
	Ratio_of_total_freshwater_available_to_maximum	WSC_Fresh_Water_Storage/Maximum_Freshwater_Storage		Dimensionless	The ratio of the total fresh water available to the maximum possible freshwater available.
	Recharge	Simulated_Average_Rainfall*Recharge_Coefficient		Millimeters/Year	The rate of groundwater recharge, calculated by multiplying the average rainfall by the recharge coefficient.
	Recharge_Coefficient	0.27		Dimensionless	The coefficient that determines how much of the average rainfall contributes to groundwater recharge. Set to 0.27.
	Recharge_Volume	(Recharge*Land_Area)/Millimeter_Conversion_To_Meter		Cubic metres/Year	The volume of water recharged into the aquifer, calculated from the recharge rate, land area, and a conversion factor. https://era.org.mt/wp-content/uploads/2019/05/2nd_Water_Catchment_Management_Plan-Malta_Water_in_Maltese_Islands-3.pdf
	Reduction_in_Agricultural_Consumption	-34.29375		Hectares/Years	The rate at which the water consumption per hectare decreases. The variable is meant to simulate the adoption of more water efficient crops by the agricultural sector. Can be activated with "SwitchAG"
	"Reduction_in_Fraction_of_Non-Agricultural_Consumption_from_Groundwater"	-0.003125		Dimensionless	Is used to reduce the fraction of WSC's water which comes from groundwater. This gradually changes the final water blend to contain more desalinated water and less groundwater. Can be activated with "Switch"

◯	Simulated_Average_Rainfall	Projected_Rainfall_Average*Pink_noise		Millimeters/Year	The average rainfall, influenced by the current and projected rainfall and modulated by pink noise to introduce variability.
◯	Standard_Deviation	.3		Dimensionless	The standard deviation for the white noise, determining the amplitude of random fluctuations. Set to 0.4.
◯	Switch	0		Dimensionless	Used to activate "Reduction in Fraction of Non-Agricultural Consumption from Groundwater" when set to 1. When set to 0, the fraction remains the default amount, 0.35
◯	Switch_for_Manual_Fraction	1		Dimensionless	When the switch is zero, the feedback loop is active that reduces the number of hectares farmed and when it set to one the Manual Fraction Removed Per Year is active.
◯	Switch_for_Rainfall_Scenarios	0		Dimensionless	Is used to activate rainfall scenarios "Rainfall Decline Rate 2050" and "Rainfall Decline Rate 2070" when set to 1. When set to 0, projected rainfall remains constant.
◯	SwitchAG	0		Dimensionless	Used to Activate "Reduction in Agricultural Consumption" when 1. When 0, the agricultural consumption per hectare remains constant.
◯	SwitchNW	0		Dimensionless	Is used to activate the increased amount of new water generated by the "new water" converter when set to 1. When 0, the amount of "new water" generated is only the amount currently planned.
◯	Time_Step_Function	DT		Year	The time step of the model, used in the calculation of white noise. Equal to DT.
◯	"Total_non-agricultural_consumption_de	(Public_Sector_Consumption+Commercial_Consumption+Domestic_Human_Consumption)		Cubic metres/Years	The sum of domestic, commercial, and public sector water consumption, representing the total human

	mand_for_freshwater"				demand for water.
	"Total_non-agricultural_pumping_Demand_for_water"	"Total_non-agricultural_consumption_demand_for_freshwater"*Effect_of_the_ratio_of_total_to_maximum_freshwater		Cubic metres/Years	The total pumping demand for water, influenced by the total consumption demand and the effect of the ratio of total to maximum freshwater.
	Total_Water_Loss_to_Leaks	(Withdrawals_from_Groundwater-Available_water_flow_from_aquifer)+Lost_Desalinated_Water_to_leakage		Cubic metres/Years	The total volume of water lost from both groundwater withdrawals and desalinated water leakage.
	Water_blend_Ratio_Check	Available_water_flow_from_aquifer/(Available_water_flow_from_aquifer+Desalinated_Water_Flow)		Dimensionless	A check variable to calculate the ratio of desalinated water flow to the total available water flow (aquifer + desalinated).
	Water_coming_out_of_aquifer	Withdrawals_from_Groundwater		Cubic metres/Years	The volume of water extracted from the aquifer, adjusted for the fraction lost to leaks.
	White_Noise	Mean_Function+Standard_Deviation*((24*Correlation_Time/Time_Step_Function)^0.5*(RANDOM(-0.5, 0.5, Noise_Seed)))		Dimensionless	A variable representing white noise, which is uncorrelated random fluctuations. It is calculated using a random function, standard deviation, mean, and time step.

Run Specs	
Start Time	2000
Stop Time	2100
DT	1/64
Fractional DT	True
Save Interval	0.015625
Sim Duration	1.5
Time Units	Years
Pause Interval	0
Integration Method	RK4

Track flow quantities	True
Keep all variable results	True
Run By	Run
Calculate loop dominance information	True
Exhaustive Search Threshold	1000

Custom Unit	Aliases	Equation
Dimensionless	dmnl unitless	1
kilowatt hours per day		kWh/day
kilowatts	kilowatt	kW