# New Mexico Regional Social Hydrology System Dynamics Models

February 23, 2021

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# Part I

# The Lower Rio Grand Model

Water scarcity in southern New Mexico is becoming a pressing issue considering the recent prolonged drought and also because socioeconomic development of the state relies on availability of quality water. Of interest is whether the region can sustain its water resources without sacrificing economic prosperity. To answer this question, we need to understand the dynamics of supply and demand of water within a socioeconomic context.

To this end, we developed a system dynamics water demand model for the lower Rio Grande (LRG) region within Doña Ana County, New Mexico. The model acts as an overlay to the NM Water Resources Research Institute's Dynamic Statewide Water Budget (NMDSWB) model (NMWRRI, 2018). While a separate model, it uses the NMDSWB data outputs to define and calibrate the system relationships and behavior. This modeling effort is motivated by the fact that the majority of water demand models in the literature ignore feedback and delay mechanisms that are inherent within and among the social and natural systems. In particular, these models consider crucial variables such as population and economic growth as exogenous variables that do not react to changes in the natural system. To respond to this gap, objectives of the current modeling are defined as:

1. predicting regional water use in the long-term (until 2099);
2. analyzing the impact of water use dynamics on economy, agriculture, and population and their consequent feedback on water use;
3. predicting potential futures of water demand and agriculture in the region under different climate scenarios; and
4. exploring potential leverage points that may lead to improvement in the system's dynamic behavior in the long-run.

As illustrated in Figure 1, the modeling process consists of two cycles of behavior and structure validation. These cycles include data collection, system conceptualization, model formulation, and model analysis.

This model is developed in modules (sub-models), making it easier to follow the logical structure. These modules include hydrology, water use, agriculture, economy, wage, labor allocation, and population. Some of these modules have sub-modules. For example, the water use module includes water use categories in agriculture (irrigation and livestock) and non-agriculture (public, domestic, commercial, industrial, mining, and power) use. There are also some supplementary modules that include future scenario options and data inputs.

The boundary of a model should be defined based on the goals that it is supposed to achieve. For any variable to be added to the model, it must contribute to the model's goals. The main goal of this model is to predict the dynamic behavior of water use under different circumstances. Therefore, water use categories must be included as endogenous variables; that is, they must be calculated within the model boundary. Important drivers of water use include population, economy, agriculture, and energy. Since all of these components react to changes in the natural system, these components should also be inside the boundary as endogenous variables.

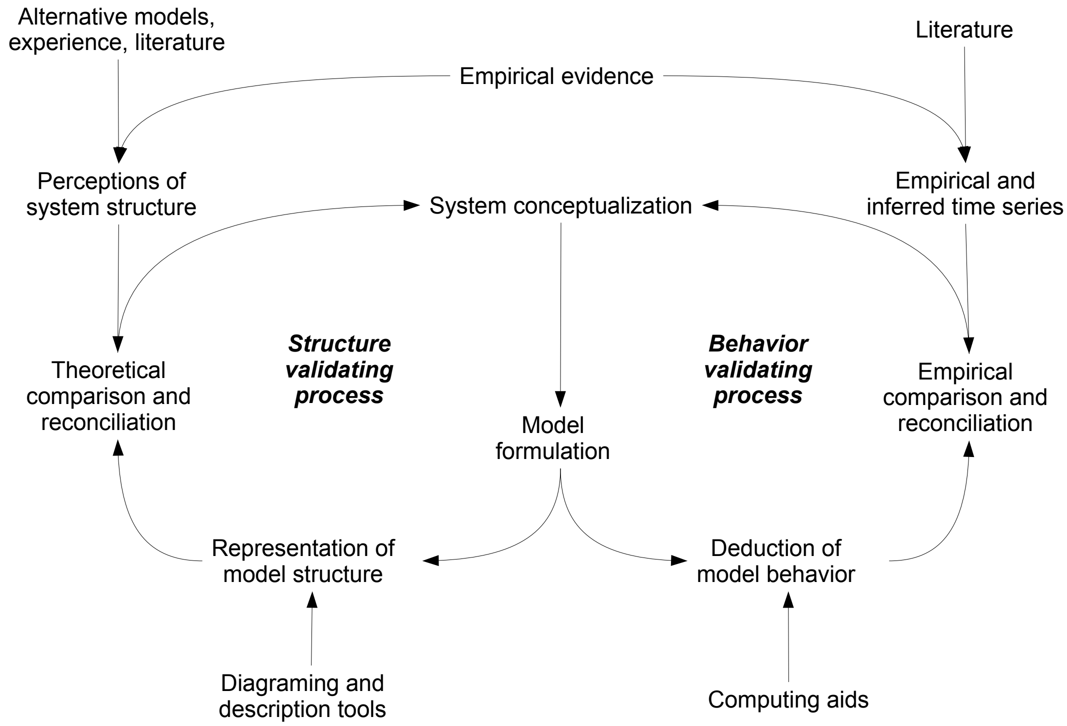


Figure 1: Modeling approach in system dynamics

Additionally, there are some exogenous variables within the model boundary. The dynamic behavior of exogenous variables is not driven by other variables within the model. They are predefined as independent scenarios. Exogenous variables included within the model are surface water inflow, temperature, precipitation, and workforce participation. Details of the model boundary and other modeling choices are explained extensively in the following chapters.

System dynamics models usually have many equations, and this current model has around 250. Therefore, it is always a challenge to present the model in an easy-to-understand fashion. In order to make the model structure easier to follow and understand, several tools and techniques are used.

First, the model is broken down to modules and each module is explained in a separate section. Each module then starts with an overview of the causal structure that is supported by a graphical illustration of the module. Then, the formulation of each variable is described in a story-telling fashion along with explanations about data sources that are used to quantify the relationships.

To make the equations easier to understand, variable names are abbreviated so that mathematical forms of the functions become easier to grasp. The starting letter of a variable name tells us about the variable type. Variable names starting with the letter $C$ represent constants. These are either parameters or initial values that have a constant numerical value throughout the simulation period. All of the parameters used in this model along with their values are listed in Table 8.2. Variable names starting with the letter $A$ represent auxiliaries. These variables contain mathematical formulas that calculate specific concepts. These concepts could be accounting definitions, physical relationships, decision rules, or behavioral functions. Variable names starting with the letter $L$ represent levels (stocks) that accumulate physical or information flows (rates) over time. The latter variables, rates (flows), have their names starting with the letter $R$. Variable names starting with the letter $D$ represent data input that work as exogenous time series. These variables are listed in Table 8.1.

Immediately below each equation, a given variables full name and units of measure are described so that readers can easily relate the formula to the bigger picture illustrated in graphical causal structure. Each equation has a unique numerical label that is clickable if you are reading the electronic version of this document. Clicking the labels will take you to the equation of the corresponding variable. If you are reading the hard copy of the document, it is still very easy to find each equation by their numbered label as the labels are sorted numerically.

# Chapter 1

# Hydrology

The hydrology module is reported in this chapter. Overview of the module is shown in Figure 1.1. Due to the size of the module, not every detail is visible from this figure. Thus, the structure is broken down into four key sub-modules:

1. reservoir-surface water;
2. irrigated land;
3. non-irrigated land; and
4. groundwater.

Each segment is explained in further details in the following sections.

## 1.1 Reservoir & Surface Water

This sub-module includes the reservoir and surface water stocks, which represents the volume of water stored in reservoirs and river channels, respectively, at each time increment. Although there is not a reservoir in the LRG region, the reservoir structure is kept inside the boundary of the model to maintain generalizability of the model (for applying to other regions in the future). Elephant Butte and Caballo are the most proximally located reservoirs to the LRG region, which are located upstream in Sierra County, New Mexico. Consequently, all inflows and outflows of the reservoir stock are zero.

$$LRES_t = LRES_{t-dt} + (RRIN_{t-dt} - RREV_{t-dt} - RRLK_{t-dt} - RRWR_{t-dt}) \cdot dt \quad (1.1)$$

$$LRES_0 = 0 \quad (1.2)$$

$$RRIN_t = RREV_t = RRLK_t = RRWR_t = 0 \quad (1.3)$$

```
LRES - RESERVOIR STORAGE (KAF)
RRIN - INCOMING WATER TO RESEVOIR (KAF PER YEAR)
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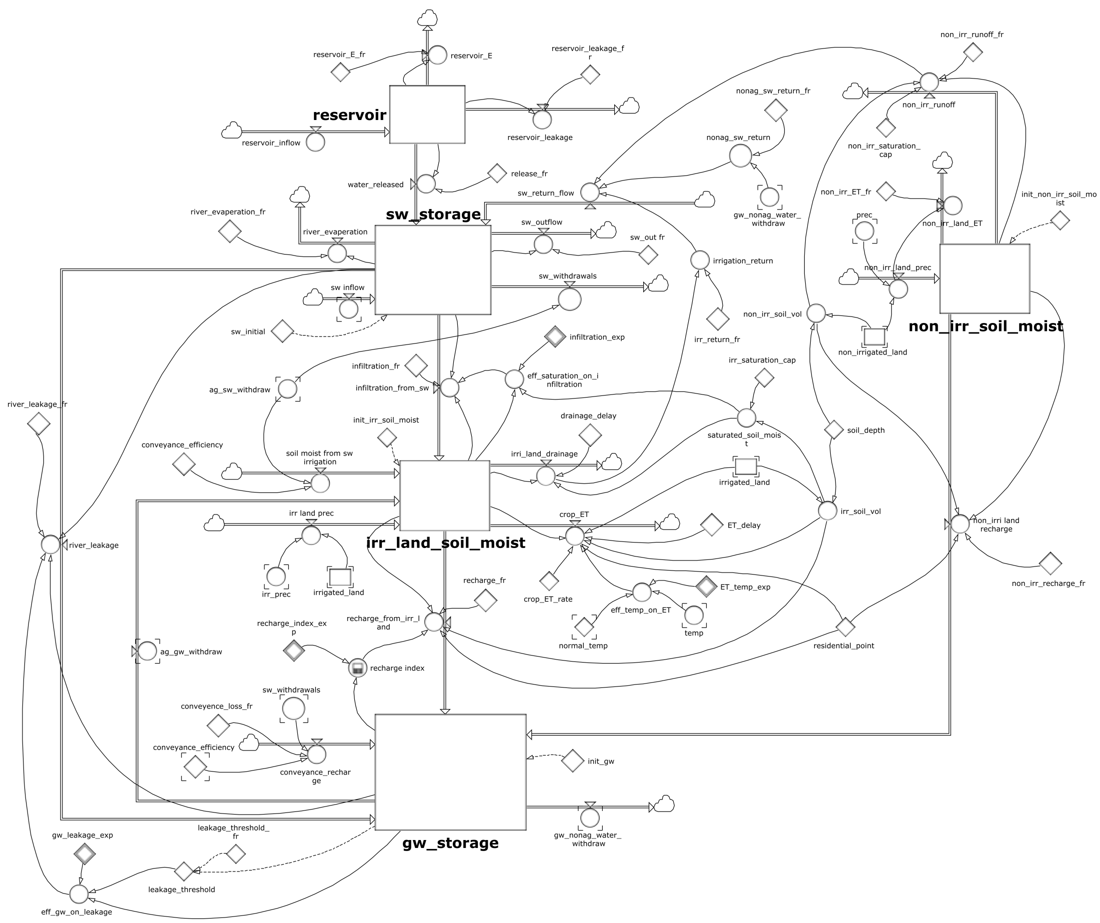


Figure 1.1: Causal structure of the hydrology module

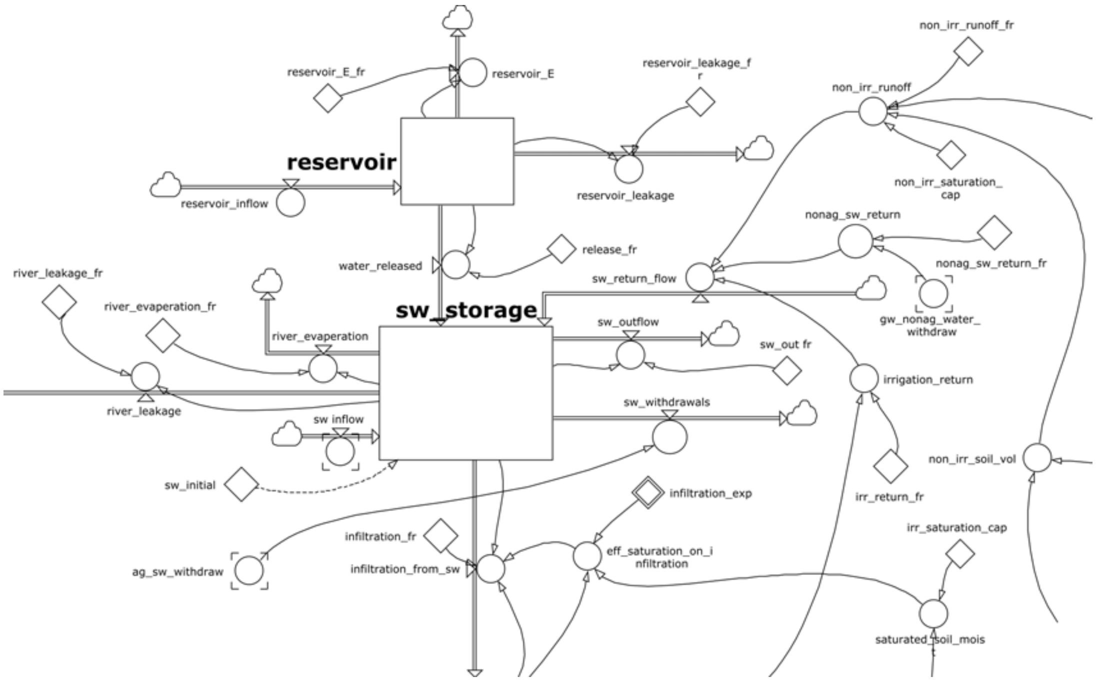


Figure 1.2: Causal structure of the hydrology module – surface water

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RREV - RESEVOIR EVAPORATION (KAF PER YEAR)
RRLK - LEAKAGE FROM RESEVOIR (KAF PER YEAR)
RRWR - FLOW RELEASED FROM RESERVOIR TO RIVER CHANNEL (KAF PER YEAR)
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The Rio Grande River, which flows across the whole LRG region from northwest to southeast is the physical representation of the surface water stock for this model (Foscue, 1931). Additions to the surface water stock include surface water inflow from the top (i.e., upstream) of the system, irrigation drainage, and runoff generation. Losses to the surface water stock include surface water evaporation, surface water outflow from the bottom (i.e., downstream) of the system, withdrawal for irrigation, river leakage, and infiltration.

Annual stream analysis has been conducted over the years. The newest lower Rio Grande Regional Water Planning report shows that the annual inflow of the Rio Grande River (i.e., surface water stock) below Elephant Butte Dam ranges from 169,757 acre-feet to 1,818,605 acre-feet (OSE, 2017). Gage records from USGS below Caballo roughly agree and show discharge ranges from 168,924.7 acre-feet to 1,929,637 acre-feet from 1917 to 2017. Since the surface water stock is also sensitive to evapotranspiration (ET) and precipitation (Duan, 2003), we made the assumption that the initial value of surface water storage should be a number that is large enough to supply surface water ET and is within the reported ranges of annual releases from the Caballo gage. In perspective of mathematics, the initial value is larger than the minimum volume capacity of the river channel.

Capacity of the surface water stock could be determined as a volume estimate of the Rio Grande River channel, which is calculated as length of the main river channel (115 km) multiplied by the average width (100 m) and depth (3 m). It is worth noting that the natural channel of Rio Grande River has continually shifted and changed over time. The main incoming water source is inflow from upstream, which is monitored by the USGS. Irrigation drainage and stream generation (i.e., runoff) are also additions to the surface water stock.

$$LSWS_t = LSWS_{t-dt} + (RRWR_{t-dt} + RSWR_{t-dt} + DSWI_{t-dt} - RRIL_{t-dt} - RSAU_{t-dt} - RRIE_{t-dt} - RISW_{t-dt} - RSWO_{t-dt}) \cdot dt \tag{1.4}$$

$$168 < LSWS_0 < 700 \tag{1.5}$$

LSWS - SURFACE STREAM SYSTEM STORAGE (KAF)
RRWR - FLOW RELEASED FROM RESERVOIR TO RIVER CHANNEL (KAF PER YEAR) [1.3]
RSWR - RETURN FLOW TO SURFACE STREAM SYSTEM (KAF PER YEAR) [1.6]
DSWI - SURFACE WATER FLOW THROUGH INLET (KAF PER YEAR) [Table 8.1]
RRIL - LEAKAGE FROM RIVER CHANNEL TO GROUNDWATER (KAF PER YEAR) [1.11]
RSAU - SURFACE WATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR) [2.30]
RRIE - EVAPORATION FROM STREAM SURFACE (KAF PER YEAR) [1.17]
RISW - INFILTRATION FROM RIVER CHANNEL TO IRRIGATED LAND (KAF PER YEAR) [1.19]
RSWO - FLOW THROUGH OUTLET (KAF PER YEAR) [1.9]

The return flow represents the sum of water drainage from irrigated and non-irrigated land, and runoff generation. In this region, the return flow is an important replenishment to the surface water withdrawal.

$$RSWR_t = CNAF \cdot RGNA_t + RNIS_t + CIRF \cdot RILD_t \tag{1.6}$$

$$0.1 < CNAF < 0.4 \tag{1.7}$$

$$0.7 < CIRF < 0.9 \tag{1.8}$$

RSWR - RETURN FLOW TO SURFACE STREAM SYSTEM (KAF PER YEAR)
CNAF - NON-AGRICULTURE WATER RETURN FRACTION (UNITLESS)
RGNA - GROUNDWATER NON-AGRICULTURE WATER WITHDRAWAL (KAF PER YEAR) [2.38]
RNIS - RUNOFF GENERATION OF NON IRRIGATED (KAF PER YEAR) [1.49]
CIRF - IRRIGATION RETURN FRACTION (UNITLESS)
RILD - DRAINAGE OF IRRIGATED LAND (KAF PER YEAR) [1.32]

Stream inflow is a data input of actual measurements from stream gages that are monitored by the USGS. For future simulations, we consider the common relation between outflow and total volume of the surface water stock, and set outflow as a proportion of the surface water storage.

$$RSWO_t = CSOF \cdot LSWS_t \tag{1.9}$$
$$0.80 < CSOF < 0.95 \tag{1.10}$$

RSWO - SURFACE WATER OUTFLOW (KAF PER YEAR)
CSOF - SURFACE OUTFLOW FRACTION (PER YEAR)
LSWS - SURFACE STREAM SYSTEM STORAGE (KAF) [1.4]

River leakage is a gross recharge and discharge between surface water storage and groundwater. Although currently a losing stream in the LRG region, historically, the Rio Grande River was a gaining stream. Conover (1954) has a detailed discussion on river seepage in Mesilla valley, which is supported by groundwater contour maps that show the Rio Grande River behavior altering from a gaining to a losing stream.

$$RRIL_t = CRLF \cdot (LSWS_t \cdot \max(AEGL_t, 0) + LGWV_t \cdot \min(AEGL_t, 0)) \tag{1.11}$$
$$0 < CRLF < 0.10 \tag{1.12}$$

RRIL - LEAKAGE FROM RIVER CHANNEL TO GROUNDWATER (KAF PER YEAR)
CRLF - RIVER LEAKAGE FRACTION (UNITLESS)
LSWS - SURFACE STREAM SYSTEM STORAGE (KAF) [1.4]
AEGL - EFFECT OF GROUNDWATER ON LEAKAGE (UNITLESS) [1.13]
LGWV - GROUNDWATER STORAGE (KAF) [1.56]

Considering the bidirectional connection between groundwater and the river system, the leakage term is used to determine whether the surface water system is a gaining or a losing stream, which is based on groundwater storage. If groundwater storage volume exceeds the leakage threshold, this function generates a negative multiplier, which implies a reverse flow for the river leakage (i.e., gaining stream). Otherwise, the multiplier is negative, resulting in a losing stream. The shape of this function along with the uncertainty considerations are presented in Figure 1.3.

$$AEGL_t = 1 - CGLE_a \cdot \max(0, \frac{LGWV_t}{ALTD_t} - 1)^{CGLE_b} \tag{1.13}$$
$$1 < CGLE < 5 \tag{1.14}$$
$$\tag{1.15}$$

AEGL - EFFECT OF GROUNDWATER ON LEAKAGE (UNITLESS)
CGLE - GROUNDWATER LEAKAGE EXPONENTS (UNITLESS)
LGWV - GROUNDWATER STORAGE (KAF) [1.56]
ALTD - LEAKAGE THRESHOLD (KAF) [1.16]

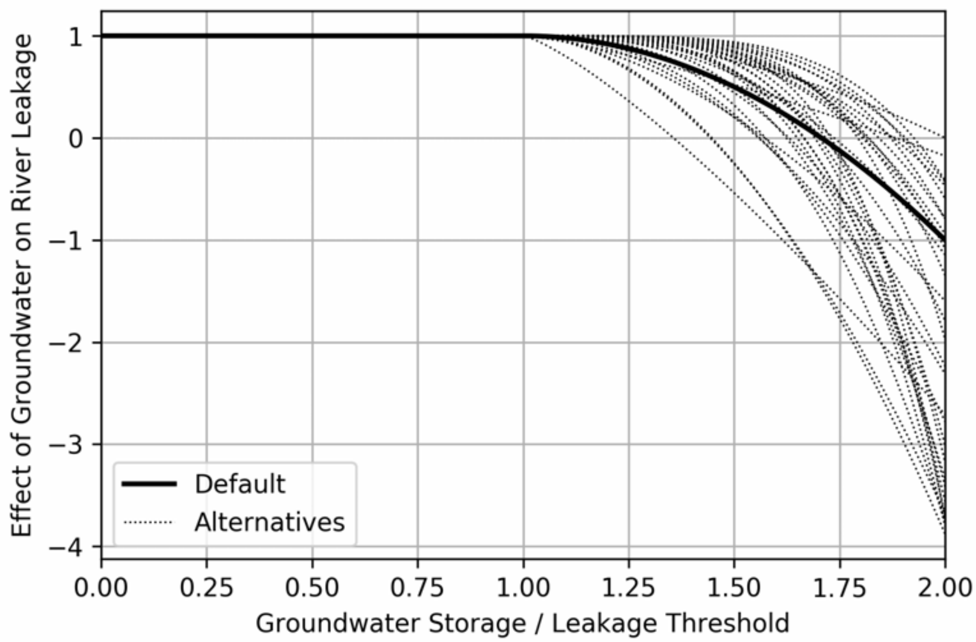


Figure 1.3: Effect of groundwater level on the river leakage rate (Equation 1.13)

The leakage threshold is set to the initial groundwater storage value multiplied by the sum of one and the leakage threshold fraction. We use a calibrated value of 0.05 for the leakage threshold fraction.

$$ALTD_t = (1 + CLTD) \cdot LGWV_0 \tag{1.16}$$
$$0.02 < CLTD < 0.06$$

ALTD - LEAKAGE THRESHOLD (KAF)
CLTD - LEAKAGE THRESHOLD FRACTION (UNITLESS)
LGWV - GROUNDWATER STORAGE (KAF) [1.56]

The hydrology module interacts with the agriculture water use module. Since surface water withdrawals for water use categories other than agriculture in the LRG region are negligible (OSE, 2013), surface water withdrawals in this model are for irrigated agriculture only. Surface water withdrawals are determined from "ag water demand" within the agriculture water use sub-module.

Since surface water ET is partially dependent on the surface area of the Rio Grande River, this term fluctuates with the total storage of the surface water stock. Surface water ET is a small proportion of the total "mass loss" (Milly, Dunne, 2001) and we use an ET ratio to define this flow.

$$RRIE_t = CREV \cdot LSWS_t \tag{1.17}$$
$$0.05 < CREV < 0.15 \tag{1.18}$$

RRIE - EVAPORATION FROM SURFACE STREAM (KAF PER YEAR)
CREV - RIVER EVAPORATION FRACTION (PER YEAR)
LSWS - SURFACE STREAM SYSTEM STORAGE (KAF) [1.4]

Because most of the land adjacent to the river is irrigated land, we added the infiltration from surface water term, which adds water to the irrigated land soil moisture stock. Since the infiltration from the surface water term is affected by the characteristics of the Rio Grande River bed, we use a range of values to calibrate this term.

$$RISW_t = CINF \cdot LSWS_t \cdot \max(0, AESI_t) + LIRM_t \cdot \min(0, AESI_t) \tag{1.19}$$
$$0.05 < CINF < 0.20 \tag{1.20}$$

RISW - INFILTRATION FROM SURFACE STREAM (KAF PER YEAR)
CINF - INFILTRATION FRACTION (PER YEAR)
LSWS - SURFACE STREAM SYSTEM STORAGE (KAF) [1.4]
AESI - EFFECT OF SATURATION ON INFILTRATION (UNITLESS) [1.21]
LIRM - IRRIGATED LAND SOIL MOISTURE (KAF PER YEAR) [1.28]

The effect of saturation on infiltration is a function of saturated soil moisture. Soil conductivity changes as soil water conditions change from irrigation and ET process. The physics of the system is used to calculate the difference between infiltration in unsaturated and saturated soils. In unsaturated soil, less infiltration occurs as water pressure head declines (Zhan, Ng, 2004). Infiltration in saturated soil follows Darcy's law (Mohanty et al., 1996). In this model, we simplify the infiltration function by omitting soil conductivity, pressure head, and empirical coefficients in numerical model. From the summary of infiltration characters, we normalized the infiltration function with soil water content. If the water soil constant of irrigated land produces enough water potential, then less infiltration from the surface water stock flows into the irrigated land soil moisture. The effect of saturation on infiltration is presented by Equation 1.21 and illustrated in Figure 1.4.

$$AESI_t = \frac{2}{\left(1 + \frac{LSWS_t}{(1 + CINE_a) \cdot ASSM_t}\right)^{CINE_b}} - 1 \tag{1.21}$$
$$0 < CINE_a < 1 \tag{1.22}$$
$$3 < CINE_b < 8 \tag{1.23}$$

```
AESI - EFFECT OF SATURATION ON INFILTRATION (UNITLESS)
LSWS - SURFACE STREAM SYSTEM STORAGE (KAF) [1.4]
CINE - INFILTRATION EXPONENTS (UNITLESS)
ASSM - SATURATED SOIL MOISTURE (KAF) [1.24]
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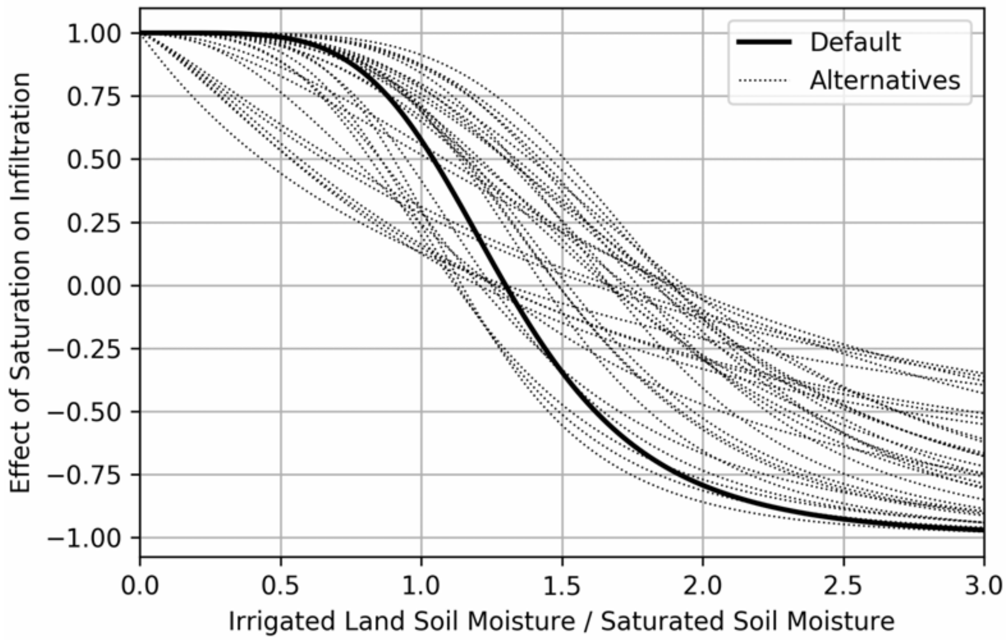


Figure 1.4: Effect of soil moisture saturation on infiltration rate (Equation 1.21)

Soil is the functional medium for the infiltration process. In the valleys of the study area and adjacent to the river, there are gravelly and sandy deposits derived from upland plains. According to a historical soil survey, soil textures in the Mesilla Valley are up to 70% silt loam, fine sandy loam, clay, and gravelly sandy loam (Nelson, Holmes, 1912). Although soil texture varies throughout the region, a simplified homogeneous texture is assumed here as loam, consistent through the depth of the soil, which ranges from 2 to 4 feet. The previous soil experiment study in this area showed that the soil water content ranges from 0.05 to 0.48, field capacity ranges from 0.12 to 0.27, and wilting point ranges from 0.03 to 0.06 through 80 cm soil depth (Deb et al., 2011). The saturated soil moisture is calculated as follows.

$$ASSM_t = CISC \cdot AISV_t \tag{1.24}$$

$$AISV_t = CSDE \cdot LIRL_t \tag{1.25}$$

$$0.3 < CISC < 0.5 \tag{1.26}$$

$$2.0 < CSDE < 4.0 \tag{1.27}$$

ASSM - SATURATED SOIL MOISTURE (KAF)
CISC - IRRIGATED SOIL SATURATION CAPACITY (UNITLESS)
AISV - IRRIGATED SOIL VOLUME (KAF)
CSDE - SOIL DEPTH (FT)
LIRL - IRRIGATED LAND (ACRE) [3.9]

## 1.2 Irrigated land soil moisture

In arid areas, it is impossible to develop agriculture without irrigation. As such, irrigation is critical in the LRG region, where the local economy is dependent on agriculture. Agricultural water use accounts for about 90% of total water consumption in New Mexico (Sabol et al., 1987). In the LRG region, water for irrigation is sourced from surface water (managed by Elephant Butte project) and groundwater. Section 1.4 explains the mechanism through which the groundwater interacts with the irrigated and non-irrigated land soil moisture. This section describes the causal structure of the mechanisms that involve the irrigated land soil moisture as a sub-module of the hydrology module. This structure is depicted in Figure 1.5.

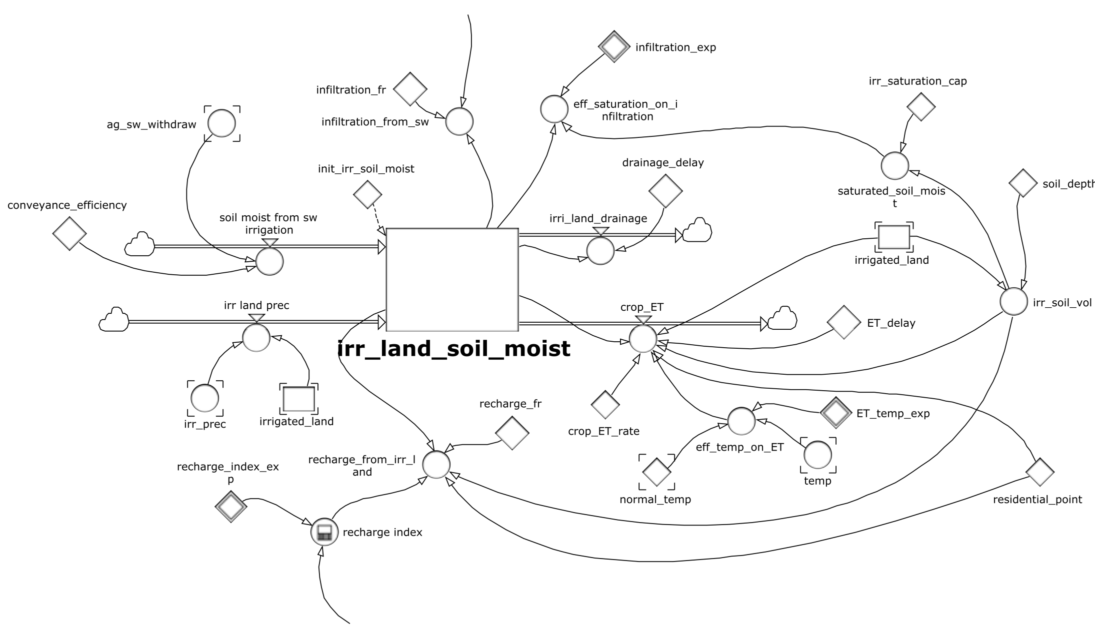


Figure 1.5: Causal structure of the hydrology module – irrigated land soil moisture

In this model, irrigated soil moisture is defined as a stock. The main hydrological activity is derived by irrigation and precipitation. The irrigation ditch systems of New Mexico have been around for a long time (Ackerly, 1992). Unlined earthen ditches are inherent, and the renewal projects on ditches are not affordable for many local communities. As a result, conveyance losses from ditches are significant.

$$LIRM_t = LIRL_{t-dt} + (RISW_{t-dt} + CCOE \cdot RSAU_{t-dt} + RGAU_{t-dt} + RILP_{t-dt} - RILD_{t-dt} - RCET_{t-dt} + RILR_{t-dt}) \cdot dt \quad (1.28)$$

$$100 < LIRM_0 < 300 \quad (1.29)$$

$$0.4 < CCOE < 0.6 \quad (1.30)$$

LIRM - IRRIGATED LAND SOIL MOISTURE (KAF)
RISW - INFILTRATION FROM RIVER CHANNEL TO IRRIGATED LAND (KAF PER YEAR) [1.19]
CCOE - CONVEYANCE EFFICIENCY (UNITLESS)
RSAU - SURFACE WATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR) [2.30]
RGAU - GROUNDWATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR) [2.2]
RILP - PRECIPITATION IN IRRIGATED SOIL (KAF PER YEAR) [1.31]
RILD - DRAINAGE OF IRRIGATED LAND (KAF PER YEAR) [1.32]
RCET - CROP EVAPOTRANSPIRATION (KAF PER YEAR) [1.35]
RILR - RECHARGE FROM IRRIGATED LAND (KAF PER YEAR) [1.42]

Because the distribution of rainfall intensity within the LRG region varies with topography, precipitation falling on agricultural lands is calculated independently. This is significant because the highest records of precipitation through the region usually occur in the peaks of the Organ and Franklin Mountains (Conover, 1954). To avoid biasing the agricultural land precipitation estimates, the USGS National Land Cover Dataset was used in conjunction with the PRISM dataset to run zonal statistics on agricultural lands within the LRG region.

$$RILP_t = DIPR_t \cdot LIRM_t \quad (1.31)$$

RILP - PRECIPITATION IN IRRIGATED SOIL (KAF PER YEAR)
DIPR - IRRIGATION PRECIPITATION DATA (FT PER YEAR) [Table 8.1]
LIRM - IRRIGATED LAND SOIL MOISTURE (KAF)1.28]

Drainage is a salvation in the LRG region. Drainage construction has been developed since the 1920s. Drainage from irrigated land is released into the surface water stock (Bloodgood, 1921).

$$RILD_t = \frac{LIRM_t - CREP \cdot ASSM_t}{CDRD} \quad (1.32)$$

$$0.01 < CREP < 0.05 \quad (1.33)$$

$$0.01 < CDRD < 1.00 \quad (1.34)$$

RILD - DRAINAGE OF IRRIGATED LAND (KAF PER YEAR)
LIRM - IRRIGATED LAND SOIL MOISTURE (KAF)1.28]

ASSM - SATURATED SOIL MOISTURE (KAF) [1.24]
CREP - SOIL RESIDENTIAL POINT (UNITLESS)
CDRD - DRAINAGE DELAY (YEAR)

There is a positive relationship between irrigation ET and crop biomass (Samani et al., 2007). Therefore, we simplify the irrigation ET function using a single ET rate that encompasses a mixture of crops and multiply this rate by irrigated acreage (Weeden, 1999). We also include the effect that temperature has on irrigation ET, as described following (see Equation 1.38).

$$RCET_t = \min\left(CETR \cdot LIRL_t, \frac{LIRM_t - CREP \cdot AISV_t}{CETD}\right) \cdot AETE_t \tag{1.35}$$

$$1.00 < CETR < 4.00 \tag{1.36}$$

$$0.01 < CETD < 1.00 \tag{1.37}$$

RCET - CROP EVAPOTRANSPIRATION (KAF PER YEAR)
CETR - COMMON EVAPOTRANSPIRATION RATE (FT PER YEAR)
LIRL - IRRIGATED LAND (ACRE) [3.9]
LIRM - IRRIGATED LAND SOIL MOISTURE (KAF)[1.28]
CREP - SOIL RESIDENTIAL POINT (UNITLESS) [1.33]
AISV - IRRIGATED SOIL VOLUME (KAF) [1.25]
CETD - EVAPOTRANSPIRATION DELAY (YEAR)
AETE - TEMPERATURE EFFECT ON EVAPOTRANSPIRATION (UNITLESS) [1.38]

The effect that temperature has on ET could be simulated by the equation of Hargreaves and Samani, which calculates a reference ET from the maximum and minimum temperatures of a given area (Hargreaves, Samani, 1985). This equation indicates the positive relationship between temperature and reference ET. The shape of this equation is shown in Figure 1.6.

$$AETE_t = \frac{CETE_a + 1}{CETE_a + e^{\left(CETE_b\left(1 - \frac{DTEM_t}{CTEM}\right)\right)}} \tag{1.38}$$

$$0 < CETE_a < 1 \tag{1.39}$$

$$2 < CETE_b < 5 \tag{1.40}$$

$$14 < CTEM < 18 \tag{1.41}$$

AETE - TEMPERATURE EFFECT ON EVAPOTRANSPIRATION (UNITLESS)
CETE - ET TEMPERATURE EXPONENTS (UNITLESS)
DTEM - AVERAGE YEARLY TEMPERATURE DATA (DEGREES) [Table 8.1]
CTEM - NORMAL YEARLY TEMPERATURE (DEGREES)

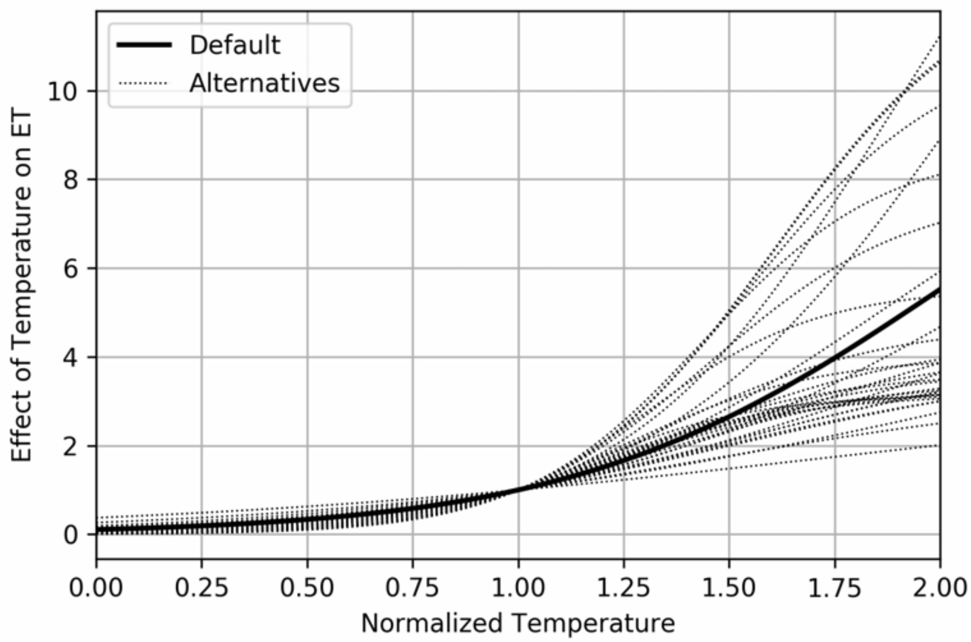


Figure 1.6: Effect of temperature on evapotranspiration (Equation 1.38)

The main cause of the rapid rise of the groundwater table in the LRG region is attributed to percolation from irrigation. Groundwater recharge intensity depends on the amount of irrigation in the irrigated fields (Hai-Long et al., 2012). Previous studies showed that the seepage from rivers and ditches to groundwater was relatively small (NMSU, 1920). Recharge patterns from irrigation to groundwater is a key variable in this study. Deep percolation from irrigation was studied in several Northern New Mexico sites(Fernald et al., 2010). This study suggests that about 21% of deep percolation is attributed to seepage from the irrigated fields (Fernald et al., 2010). Therefore, recharge from irrigated land is defined as a function of irrigated land and groundwater conditions. As groundwater level declines, potential recharge capacity increases. This relationship is presented in Equation 1.43 and Figure 1.7.

$$RILR_t = CREF \cdot (LIRM_t - CREP \cdot ASSM_t) \cdot AREI_t \tag{1.42}$$

$$AREI_t = \frac{1}{1 + CERI_a \cdot \left(\dfrac{LGWV_t}{LGWV_0}\right)^{CERI_b}} \tag{1.43}$$

$$0.1 < CREF < 0.2 \tag{1.44}$$

$$3 < CERI < 8 \tag{1.45}$$

`RILR - RECHARGE FROM IRRIGATED LAND (KAF PER YEAR)`

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CREF - RECHARGE FRACTION (UNITLESS)
LIRM - IRRIGATED LAND SOIL MOISTURE (KAF)1.28]
CREP - IRRIGATED SOIL RESIDENTIAL POINT (UNITLESS) [1.33]
ASSM - SATURATED SOIL MOISTURE (KAF) [1.24]
AREI - RECHARGE INDEX (UNITLESS)
CERI - RECHARGE INDEX EXPONENTS (UNITLESS)
LGWV - GROUNDWATER STORAGE (KAF) [1.56]
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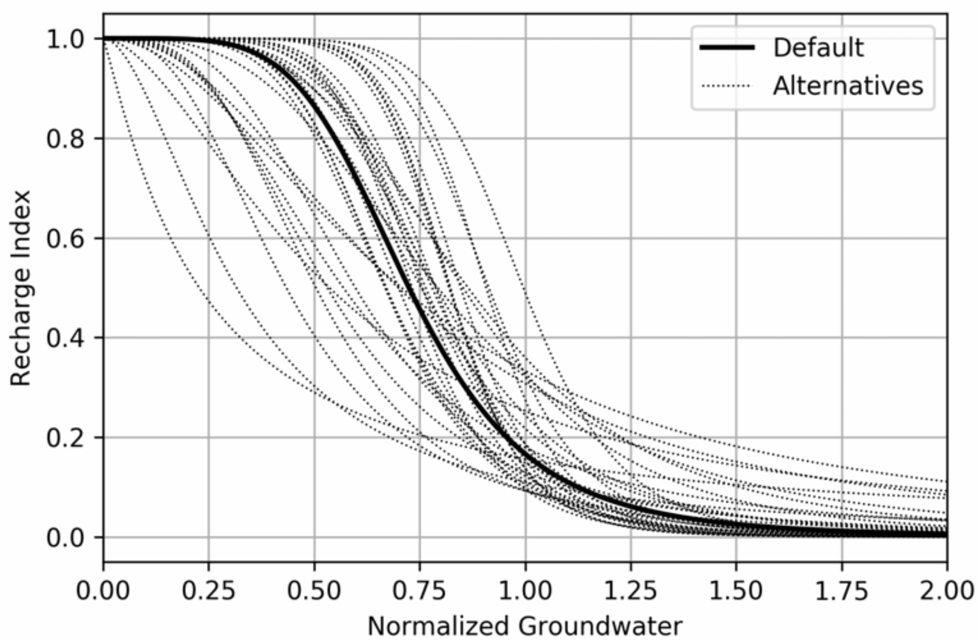


Figure 1.7: Recharge index as a function of groundwater level (Equation 1.43)

## 1.3 Non-irrigated land soil moisture

Non-irrigated land plays a critical role in the return flow function and ET loss of precipitation. Non-irrigated land ET accounts for over 90% of precipitation in the LRG region (Reynolds et al., 2000; Schlesinger, Jasechko, 2014).

Runoff generation in non-irrigated land follows the soil physics criterion: the construction and infrastructure decide the soil parameters, which are different from irrigated land. In urban areas, a considerable proportion of the land is paved, which means that soil pore space is less for construction practices, and excess flow goes as runoff to the surface water stock. The causal structure of this module is presented in Figure 1.8.

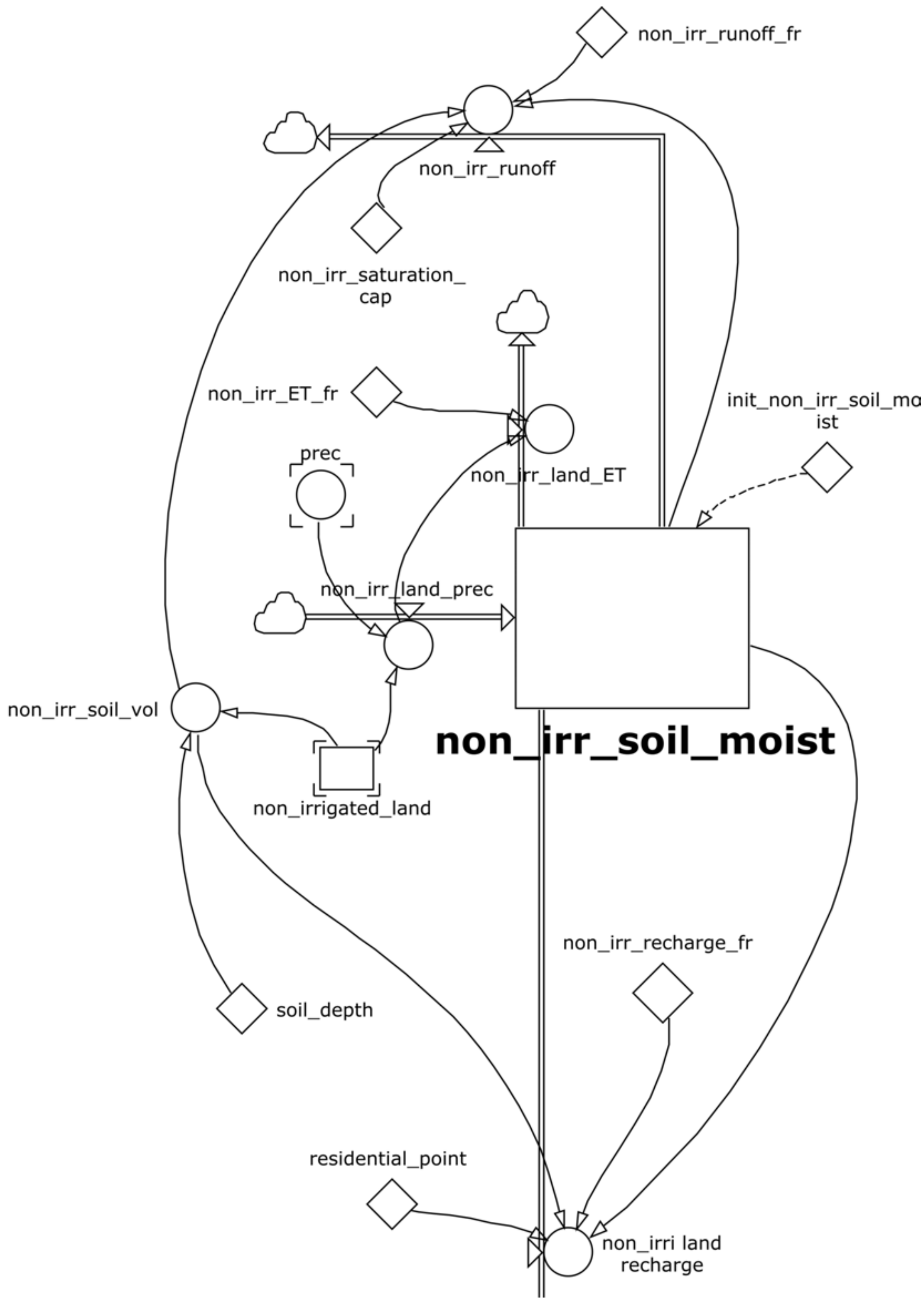


Figure 1.8: Causal structure of the hydrology module – non-irrigated land soil moisture

$$LNIM_t = LNIM_{t-dt} + (RNIP_{t-dt} - RNIS_{t-dt} - RNET_{t-dt} - RNIR_{t-dt}) \cdot dt \quad (1.46)$$

$$2,000 < LNIM_0 < 4,000 \quad (1.47)$$

$$RNIP_t = DIPR_t \cdot LNIL_t \quad (1.48)$$

$$RNIS_t = CNRF \cdot \max(0, LNIM_t - CNIS \cdot ANIV_t) \quad (1.49)$$

$$RNET_t = CNEF \cdot RNIP_t \quad (1.50)$$

$$RNIR_t = CNRE \cdot \max(0, LNIM_t - CREP \cdot ANIV_t) \quad (1.51)$$

$$ANIV_t = LNIL_t \cdot CSDE \quad (1.52)$$

$$0.25 < CNIS < 0.45 \quad (1.53)$$

$$0.1 < CNRF < 0.8 \quad (1.54)$$

$$0.9 < CNEF < 0.98 \quad (1.55)$$

LNIM - NON-IRRIGATED LAND SOIL MOISTURE (KAF)
RNIP - PRECIPITATION IN NON-IRRGATED SOIL (KAF PER YEAR) [1.48]
DIPR - IRRIGATION PRECIPITATION DATA (FT PER YEAR) [Table 8.1]
LNIL - NON-IRRIGATED LAND (ACRE) [3.11]
RNIS - RUNOFF GENERATION OF NON IRRIGATED (KAF PER YEAR) [1.49]
CNRF - NON-IRRIGATED LAND RUNOFF FRACTION (UNITLESS)
CNIS - NON-IRRIGATED SOIL SATURATION CAPACITY (UNITLESS)
ANIV - NON-IRRIGATED SOIL VOLUME (KAF) [1.52]
RNET - EVAPOTRANSPIRATION FROM NON-IRRIGATED SOIL MOISTURE (KAF PER YEAR)
CNEF - NON-IRRIGATED LAND ET FRACTION (UNITLESS)
RNIR - RECHARGE FROM NON-IRRIGATED SOIL (KAF PER YEAR)
CNRE - NON-IRRIGATED LAND RECHARGE FRACTION (UNITLESS)
CREP - SOIL RESIDENTIAL POINT (UNITLESS) [1.33]
CSDE - SOIL DEPTH (FEET) [1.27]

The non-irrigated land module could be further developed in terms of land cover, urban landscape projects, and local hydraulic facilities. Also, the corresponding components developed in the non-irrigated land module will change the amount of recharge to groundwater.

## 1.4 Groundwater

As presented in Figure 1.9, this section describes the causal structure that involves groundwater storage. As a critical water source in arid and semiarid areas, groundwater provides water for municipal, industrial, domestic, and agricultural users. Groundwater pumping is a supplemental source that is used when surface water is in shortage. Groundwater withdrawals are the main outflows of the groundwater stock. Further, groundwater storage is influenced by local hydro-geology and the amount of recharge and discharge.

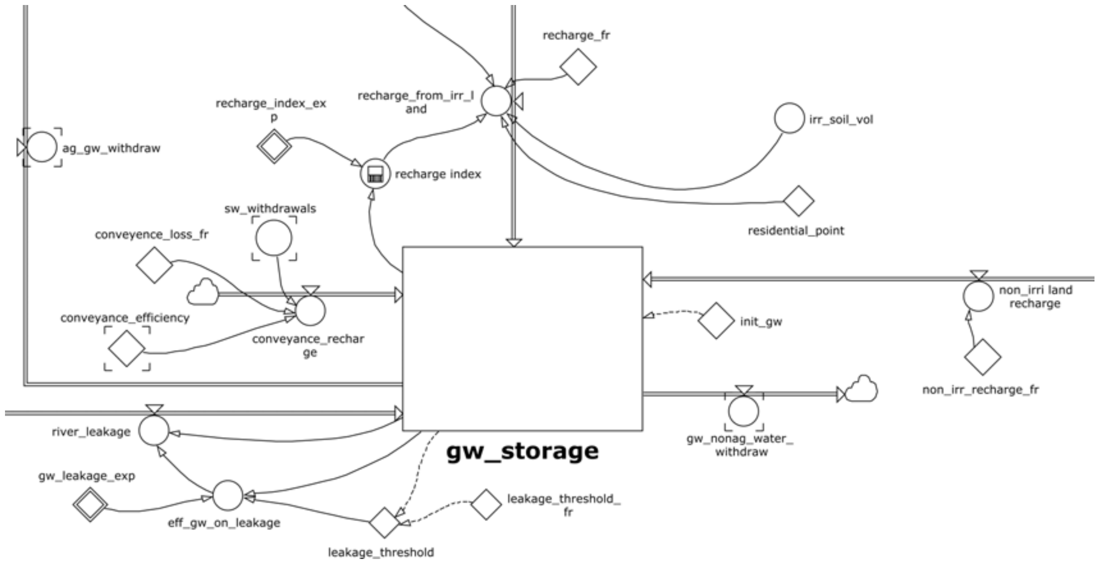


Figure 1.9: Causal structure of the hydrology module – groundwater

Recharge sources to groundwater have been classified as: infiltration of precipitation; seepage from ditches, laterals, and the Rio Grande River; irrigation in fields; and groundwater flow from uplands. The majority of recharge is derived from seepage and deep percolation from irrigation (Leggat et al., 1963). Conover (1954) estimates the amount of excess irrigation over crop demand was about 17% of surface water diversion. In regards to recharge via seepage from ditches and laterals and irrigation in fields in this region, it has been suggested that conveyance efficiency is 54% and that on-farm irrigation efficiency is 64% (Ahadi et al., 2013). This suggests that 46% (1 - conveyance efficiency) of water in ditches and laterals and 36% (1 - on-farm efficiency) of the water applied to fields is available to recharge.

It is hard to define the accurate percentage of recharge into groundwater from these sources. For example, during periods with a surface water shortage, groundwater is used to meet irrigation demands. Locally, this can cause conveyance losses to increase. However, there are boundaries to qualify and quantify irrigation recharge.

To characterize the historical net difference between recharge and discharge rates, we assume river seepage and recharge from the soil body to be a function of normalized groundwater level. The seepage of ditches was defined as a proportion of conveyance loss.

It is difficult to estimate groundwater storage with technical measurement or through model simulation. It has been proposed that the Mesilla Basin has 65 MAF (Million Acre Feet) of groundwater storage [Hawley et al., 2001; Witcher et al., 2004; Hawley, 2016, cited in Page, 2018] that is smaller than 300 mg/L total dissolved solids (Wilson et al., 1981, p. 54). Since the Mesilla Basin is a reasonable representation of the LRG region, we assume an initial value of 65000 KAF for the groundwater stock.

$$LGWV_t = LGWV_{t-dt} + (RCOR_{t-dt} + RRIL_{t-dt} + RILR_{t-dt} + RNIR_{t-dt} - RGAU_{t-dt} - RGNA_{t-dt}) \cdot dt \tag{1.56}$$

$$6e5 < LGWV_0 < 7e5 \tag{1.57}$$

LGWV - GROUNDWATER STORAGE (KAF)
RCOR - RECHARGE FROM CONVEYANCE LOSS (KAF PER YEAR) [1.58]
RRIL - LEAKAGE FROM RIVER CHANNEL TO GROUNDWATER (KAF PER YEAR) [1.11]
RILR - RECHARGE FROM IRRIGATED LAND (KAF PER YEAR) [1.42]
RNIR - RECHARGE FROM NON-IRRIGATED SOIL (KAF PER YEAR) 1.51]
RGAU - GROUNDWATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR) [2.2]
RGNA - GROUNDWATER NON-AGRICULTURE WATER WITHDRAWAL (KAF PER YEAR) [2.38]

As discussed above, recharge from conveyance loss is defined as a proportion of conveyance loss. Obviously, the sum of conveyance efficiency and conveyance loss fraction should be less than 1. The conveyance loss fraction represents the "missing water" in ditches such as evaporation.

$$RCOR_t = (1 - CCOE - CCOF) \cdot RSAU_t \tag{1.58}$$

$$0.2 < CCOF < 0.4 \tag{1.59}$$

RCOR - RECHARGE FROM CONVEYANCE LOSS (KAF PER YEAR)
CCOE - CONVEYANCE EFFICIENCY (UNITLESS) [1.30]
CCOF - CONVEYANCE LOSS FRACTION (UNITLESS)
RSAU - SURFACE WATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR) [2.30]

# Chapter 2

# Water Use

Total water use in the model is categorized as agriculture and non-agriculture uses. Agriculture use includes irrigation and livestock water use. Non-agriculture use includes public, domestic, commercial, industrial, mining, and power water use. This classification is inspired by the fact that majority of water is used by agriculture (particularly, irrigation). For example, from 1975–2010, about 92% of the total water used was consumed by agriculture. Figure 2.1 shows dynamics of water use in the LRG region during that period for different use categories. Next two sections describe structure of each water use sub-module in details.

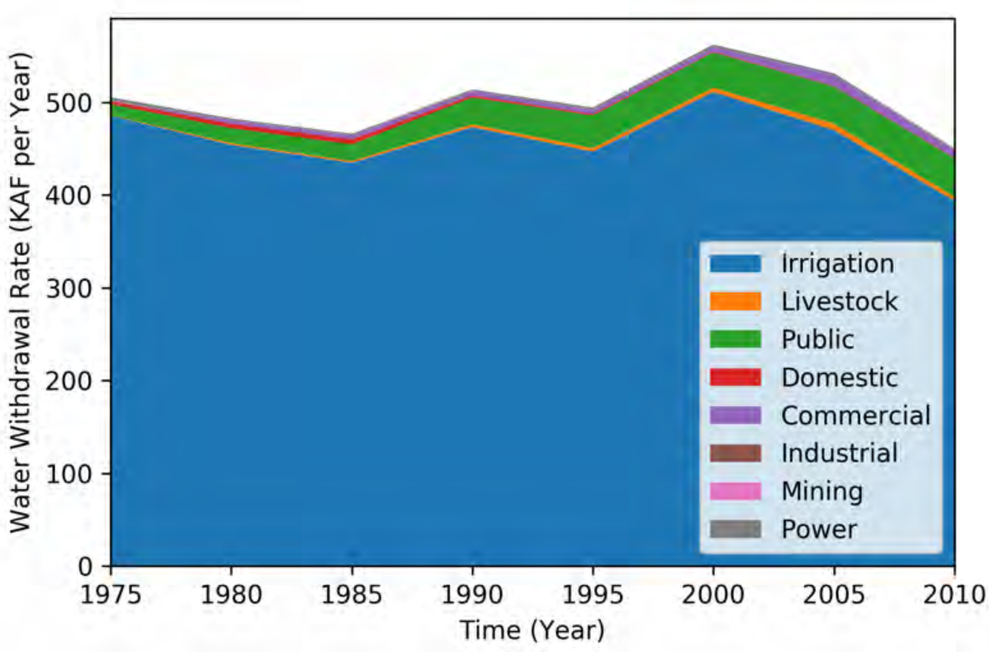


Figure 2.1: Water withdrawal dynamics for different use categories in the LRG (OSE, 2013)

## 2.1 Agriculture Water Use

This module calculates the amount of water that is used in the agriculture sector. Causal structure of the module is presented in Figure 2.2.

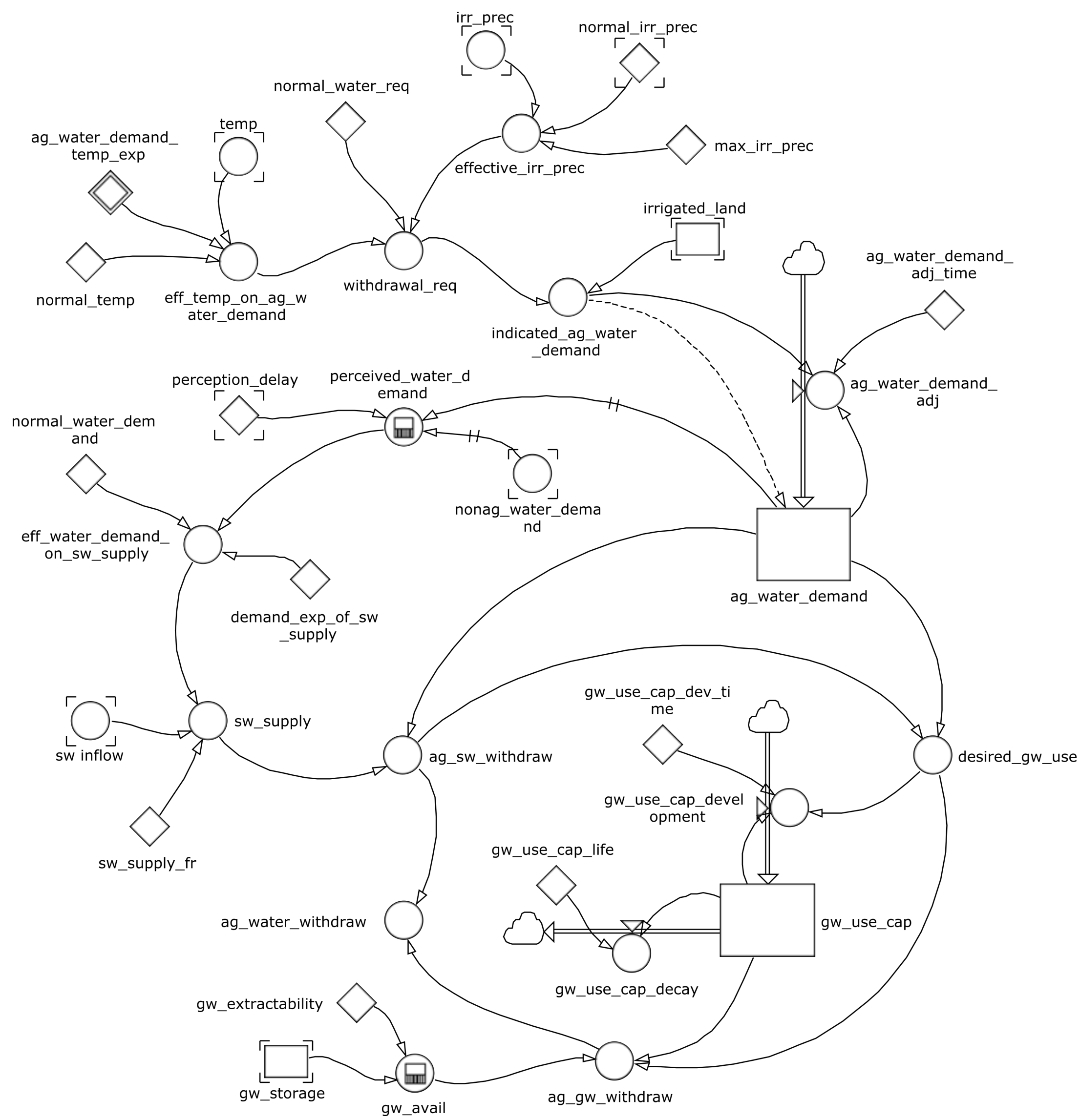


Figure 2.2: Causal structure of the agriculture water use module

Total water withdrawal in the agriculture sector is a sum of surface water and groundwater agricultural withdrawals:

$$AAWU_t = RGAU_t + RSAU_t \tag{2.1}$$

AAWU - WATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR)

RGAU - GROUNDWATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR) [2.2]
RSAU - SURFACE WATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR) [2.30]

Groundwater withdrawal is bounded by groundwater availability and groundwater withdrawal capacity.

$$RGAU_t = \min(LGWC_t, ADGW_t) \cdot AGWA_t \tag{2.2}$$

RGAU - GROUNDWATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR)
LGWC - GROUNDWATER WITHDRAWAL CAPACITY (KAF PER YEAR) [2.5]
ADGW - DESIRED GROUNDWATER WITHDRAWAL (KAF PER YEAR) [2.11]
AGWA - GROUNDWATER AVAILABILITY (UNITLESS) [2.3]

Availability of groundwater is a nonlinear function of groundwater storage. According to expert opinion, only 10% of the current groundwater storage is extractable with current technological means [Hawley et al., 2001, cited in Page, 2018]. It is assumed that current groundwater storage is relatively close to its initial value at 1969. As groundwater depletes, its availability drops. When the storage reaches 90% of the initial level, the availability multiplier approaches zero. Default and alternative shapes of this function in response to variation in extractability fraction are shown in Figure 2.3.

$$AGWA_t = \frac{2\left(\dfrac{LGWV_t}{LGWV_0} + CGWE - 1\right)}{\dfrac{LGWV_t}{LGWV_0} + 2 \cdot CGWE - 1} \tag{2.3}$$

$$0.05 < CGWE < 0.25 \tag{2.4}$$

AGWA - GROUNDWATER AVAILABILITY (UNITLESS)
LGWV - GROUNDWATER STORAGE (KAF) [1.56]
CGWE - FRACTION OF GROUNDWATER THAT IS EXTRACTABLE (UNITLESS)

Groundwater withdrawal capacity refers to the infrastructure that is needed for the groundwater pumping. This mainly includes wells that need to be dug and the associated equipment that makes pumping possible. It is assumed that this infrastructure is sufficient for the current demand but for any additional unit of groundwater demand, it takes some time for the capacity to be developed and ready to use. Aging of the capacity is also taken into consideration, i.e., the capacity decays over time if it is not maintained. Capacity development occurs whenever current capacity is lower than desired capacity.

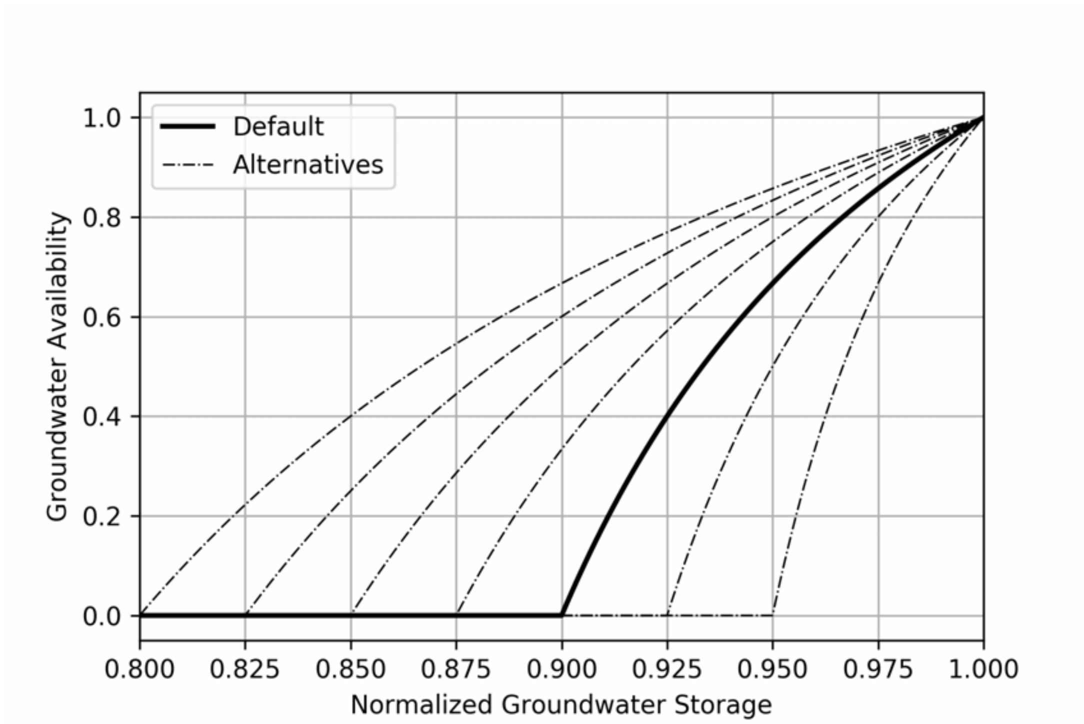


Figure 2.3: Groundwater availability function (Equation 2.3)

$$LGWC_t = LGWC_{t-dt} + (RGWI_{t-dt} - RGWO_{t-dt}) \cdot dt \tag{2.5}$$

$$RGWI_t = \frac{\max(0, ADGW_t - LGWC_t)}{CGWI} \tag{2.6}$$

$$RGWO_t = \frac{LGWC_t}{CGWO} \tag{2.7}$$

$$25 < LGWC_0 < 100 \tag{2.8}$$

$$0.25 < CGWI < 2 \tag{2.9}$$

$$2 < CGWO < 10 \tag{2.10}$$

```
LGWC - GROUNDWATER WITHDRAWAL CAPACITY (KAF PER YEAR)
RGWI - GROUNDWATER WITHDRAWAL CAPACITY DEVELOPMENT (KAF PER YEAR PER
   YEAR)
RGWO - GROUNDWATER WITHDRAWAL CAPACITY DECAY (KAF PER YEAR PER YEAR)
ADGW - DESIRED GROUNDWATER WITHDRAWAL (KAF PER YEAR) [2.11]
CGWI - GROUNDWATER WITHDRAWAL CAPACITY DEVELOPMENT TIME (YEAR)
CGWO - GROUNDWATER WITHDRAWAL CAPACITY DECAY TIME (YEAR)
```

Farmers usually prefer surface water over groundwater for their use because of its quality and also because groundwater withdrawals are associated with pumping costs.

Therefore, it is assumed here that priority of use is with the surface water. Any water demand surplus is then met from the groundwater supply.

$$ADGW_t = \max(0, LAWD_t - RSAU_t) \tag{2.11}$$

ADGW - DESIRED GROUNDWATER WITHDRAWAL (KAF PER YEAR)
LAWD - WATER DEMAND FOR AGRICULTURE (KAF PER YEAR) [2.12]
RSAU - SURFACE WATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR) [2.30]

Water demand for agriculture is a delayed multiplication of irrigated land and water required per acre. The process is delayed because water demand in previous years is usually used by farmers as a reference for their current water demand. The delay function is represented by a smoothing mechanism as following (see Footnote [1] for more details of smoothing functions).

$$LAWD_t = LAWD_{t-dt} + \frac{AAWD_{t-dt} - LAWD_{t-dt}}{CAWT} \cdot dt \tag{2.12}$$

$$AAWD_t = \frac{LIRL_t \cdot AWRQ_t}{1000} \tag{2.13}$$

$$500 < LAWD_0 < 700 \tag{2.14}$$

$$0.25 < CAWT < 5 \tag{2.15}$$

LAWD - WATER DEMAND FOR AGRICULTURE (KAF PER YEAR)
AAWD - INDICATED WATER DEMAND FOR AGRICULTURE (KAF PER YEAR)
CAWT - AG WATER DEMAND ADJUSTMENT TIME (YEAR)
LIRL - IRRIGATED LAND (ACRE) [3.9]
AWRQ - AG WATER WITHDRAWAL REQUIREMENT (FT PER YEAR) [2.16]

Agriculture water withdrawal requirement refers to the amount of water that is required to be withdrawn from surface water and/or groundwater in order to sustain the desired level of agricultural yield that is expected from a unit of irrigated land. There is an average water requirement for irrigation (2.17) but what farmers actually need to withdraw could be higher or lower than this reference value. The actual water requirement first depends on temperature. The higher the temperature, the more water would be needed to sustain the same level of yield. Another factor affecting withdrawal demand

[1]Note that in most of the delay functions in this model, a smoothing mechanism is used instead of high order delay functions. A smoothing function works as a goal seeking mechanism where the delayed variable approaches the actual (indicated) variable during the assigned delay time. For the current example, let us assume that wages are in equilibrium (i.e., wages are equal to indicated wages). Once a distortion occurs, say by a jump in unemployment, the indicated wages decline at the same instance. Wages may drop but not as low as the indicated wages. Instead, they start to approach the indicated wages slowly. Over the adjustment period (the assigned delay time), this gap closes gradually until they become equal again

is effective precipitation. If the water requirement could be satisfied by the effective precipitation, then no withdrawal would be necessary. However, this is not usually the case in the LRG region. In this region, total water requirement is usually greater than the effective precipitation. So, the withdrawal requirement could be estimated by the following equation:

$$AWRQ_t = AGRQ_t \cdot AETW_t - AEIP_t \tag{2.16}$$

AWRQ - AG WATER WITHDRAWAL REQUIREMENT (FT PER YEAR)
AGRQ - AG WATER REQUIREMENT (FT PER YEAR) [2.17]
AETW - EFFECT OF TEMPERTATURE ON AG WATER DEMAND (UNITLESS) [2.24]
AEIP - EFFECTIVE IRRIGATION PRECIPITATION (FT PER YEAR) [2.27]

The average water requirment depends on the crop profile of the region. If this profile is dominated by water-intensive crops, then average requirement is relative high. In the previous version of the LRG model, we assumed that this average is constant during the simulation time. In this new version, we have updated the model to include a more realistic assumption. Here, we assume that the crop pattern changes over time depending on water availability. If available water per acre (2.21) increases, farmers will choose to grow more of water-intensive crops such as pecan that are more profitable than other crops. The greater share of water-intensive crops means a higher average crop water requirement. So, we can write:

$$AGRQ_t = \min\left(CWRQ_a, \frac{CWRQ_b}{CCOE \cdot (1 + e^{-CWRM \cdot LWSA_t})}\right) \tag{2.17}$$

$$3 < CWRQ_a < 8 \tag{2.18}$$

$$3 < CWRQ_b < 8 \tag{2.19}$$

$$0 < CWRM < 1 \tag{2.20}$$

AGRQ - AG WATER REQUIREMENT (FT PER YEAR)
LWSA - PERCEIVED WATER SUPPLY PER ACRE (FT PER YEAR) [2.21]
CWRQ - AG WATER REQUIREMENT EXPONENT (FT PER YEAR)
CWRM - AG WATER REQUIREMENT MULTIPLIER (YEAR PER FT)

Here, $CWRQ_a$ is a policy parameter to set the maximum water requirement. If this value is high, it means that we allow the system to grow a significant amount of water-intensive crop. $CWRQ_b/CCOE$, in contrast, is a natural limit to the water requirement indicating the capacity of the region to take water-intensive crops.

Water supply per acre then could easily be calculated by dividing agriculture water withdrawals by irrigated land. We also use an exponential average of this value to take into account the delay in human perceptions of long-term changes.

$$LWSA_t = LWSA_{t-dt} + \frac{\dfrac{AAWU_{t-dt}}{LIRL_{t-dt}} - LWSA_{t-dt}}{CWSA} \tag{2.21}$$

$$LWSA_0 = \frac{AAWU_0}{LIRL_0} \tag{2.22}$$

$$1 < CWSA < 8 \tag{2.23}$$

```
LWSA - PERCEIVED WATER SUPPLY PER ACRE (FT PER YEAR)
AAWU - AG WATER USE (KAF PER YEAR) [2.1]
LIRL - IRRIGATED LAND (ACRE) [3.9]
CWSA - WATER SUPPLY PERCEPTION TIME (YEAR)
```

Effect of temperature on agriculture water demand is a normalized nonlinear function. The first derivative of the function is always positive, ensuring a direct relationship between temperature and water demand. For values below normal temperature, the second derivative is positive; and for values above the normal temperature, it is negative; meaning that marginal water demand diminishes as the temperature rises to higher levels. Figure 2.4 shows default shape of the function along with some examples of alternative forms, as parameters of the function could change in a certain range. The horizontal axis of the figure is limited to a range that includes ±40% of the normal temperature. Historical temperature in the LRG region has been between 15° to 17.5° Celsius with an average of around 16° (OSE, 2017). Hence, the selected range covers any realistic possibilities.

$$AETW_t = \frac{CETW_a + 1}{CETW_a + e^{CETW_b\left(1-\dfrac{DTEM_t}{CTEM}\right)}} \tag{2.24}$$

$$0.2 < CETW_a < 0.6 \tag{2.25}$$

$$4 < CETW_b < 6 \tag{2.26}$$

```
AETW - EFFECT OF TEMPERTATURE ON AG WATER DEMAND (UNITLESS)
CETW - EXPONENTS FOR EFFECT OF TEMPERATURE ON AG WATER DEMAND (UNITLESS)
DTEM - AVERAGE YEARLY TEMPERATURE DATA (DEGREES) [Table 8.1]
CTEM - NORMAL YEARLY TEMPERATURE (DEGREES) [1.41]
```

Effective irrigation precipitation is the amount of precipitation that is added to and stored in the soil. As explained earlier, effective precipitation can be used for irrigation and water needed beyond that level should be withdrawn from stocks of surface water or groundwater. The USBR method expresses effective rainfall as a percentage of the total monthly rainfall. As summarized in Table 2.1, with each 1-inch increment in rainfall, there is a corresponding decrease in the percentage of monthly effective rainfall (Stamm, 1967, table 46).

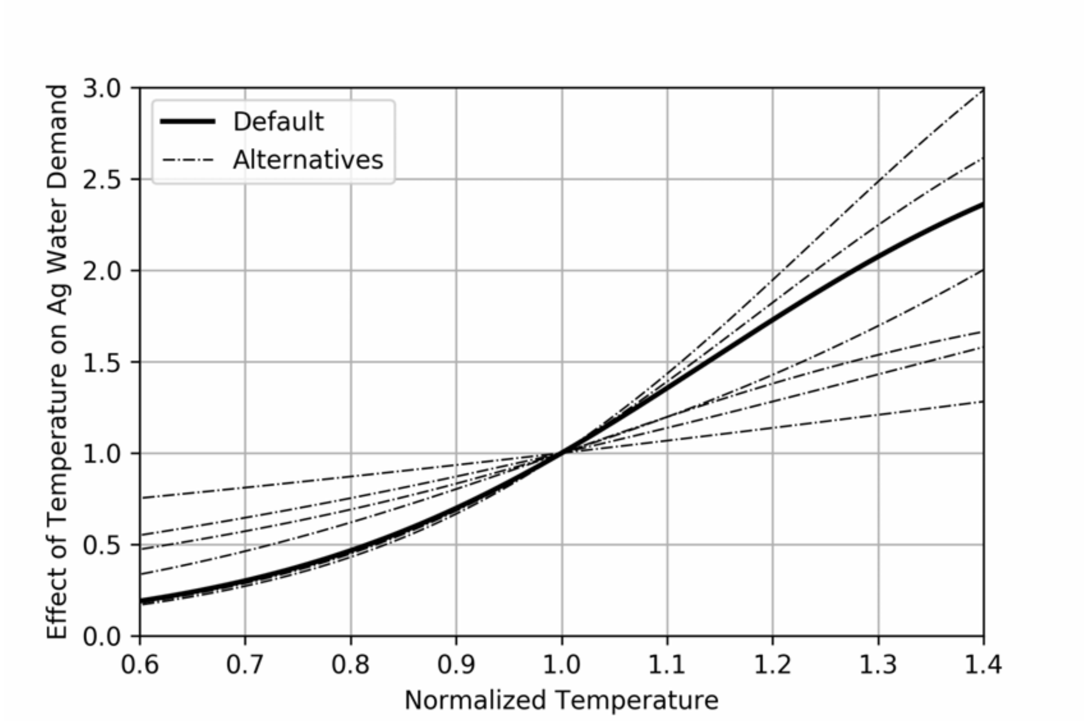


Figure 2.4: Effect of temperature on ag water demand (Equation 2.24)

Table 2.1: Effective rainfall as a function of actual rainfall (Source: Stamm (1967, table 46))

| Monthly Rainfall ($R$) (inches) | Effective Rainfall ($R_e$) (inches) |
|---|---|
| $1 \leq R$ | $R_e = 0.95R$ |
| $1 \leq R \leq 2$ | $R_e = 0.95 + 0.90(R - 1)$ |
| $2 \leq R \leq 3$ | $R_e = 1.85 + 0.82(R - 2)$ |
| $3 \leq R \leq 4$ | $R_e = 2.67 + 0.65(R - 3)$ |
| $4 \leq R \leq 5$ | $R_e = 3.32 + 0.45(R - 4)$ |
| $5 \leq R \leq 6$ | $R_e = 3.77 + 0.25(R - 5)$ |
| $R > 6$ | $R_e = 4.02 + 0.05(R - 6)$ |

This function, nevertheless, is discrete. To make it usable in the LRG model, this function needs to be converted to a continuous form. The following function is designed to replicate similar behavior:

$$AEIP_t = \frac{2 \cdot CMIP}{1 + e^{-\frac{DIPR_t}{CIPR}}} - CMIP \tag{2.27}$$

$$CMIP = 4.64 \tag{2.28}$$

$$CIPR = 2.30 \tag{2.29}$$

```
AEIP - EFFECTIVE IRRIGATION PRECIPITATION (FT PER YEAR)
CMIP - MAXIMUM IRRIGATION PRECIPITATION (FT PER YEAR)
DIPR - IRRIGATION PRECIPIATION DATA (FT PER YEAR) [Table 8.1]
CIPR - NORMAL IRRIGATION PRECIPITATION (FT PER YEAR)
```

Figure 2.5 demonstrates how well this function reproduces data points of the Table 2.1.

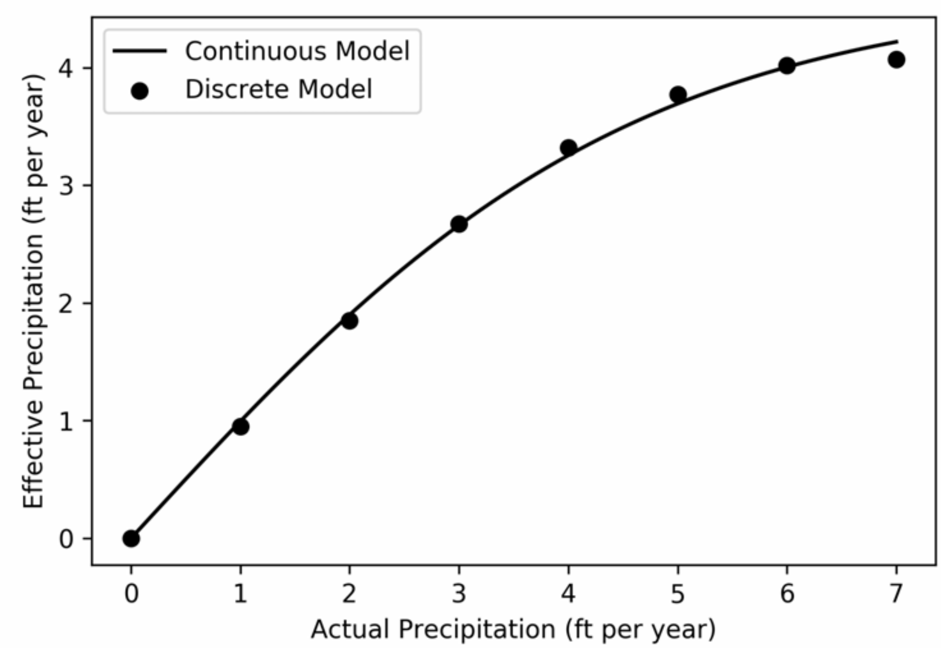


Figure 2.5: Continuous vs discrete model for prediction of effective precipitation (Equation 2.27)

Farmers withdraw as much surface water for agriculture as they need. Any withdrawal, nonetheless will be subject to availability of surface water supply.

$$RSAU_t = \min(LAWD_t, ASWS_t) \tag{2.30}$$

RSAU - SURFACE WATER WITHDRAWAL FOR AGRICULTURE (KAF PER YEAR)
LAWD - WATER DEMAND FOR AGRICULTURE (KAF PER YEAR) [2.12]
ASWS - SUPPLY OF SURFACE WATER (KAF PER YEAR) [2.31]

Supply of surface water depends on the surface water inflow which is driven by the scenarios generated by the NMDSWB. This supply rate is regulated by the Elephant Butte Irrigation District (EBID). It is assumed that EBID allocates a constant fraction of total surface water inflow to the region to be withdrawn for their use. Demand pressure, however, can influence EBID's allocation scheme as explained later.

$$ASWS_t = CSWI \cdot DSWI_t \cdot AEDS_t \tag{2.31}$$

$$0.4 < CSWI < 0.7 \tag{2.32}$$

ASWS - SUPPLY OF SURFACE WATER (KAF PER YEAR)
CSWI - SURFACE WATER SUPPLY FRACTION (UNITLESS)
DSWI - SURFACE WATER INFLOW (KAF PER YEAR) [Table 8.1]
AEDS - EFFECT OF WATER DEMAND PRESSURE ON SURFACE WATER SUPPLY (UNITLESS) [2.33]

Surface water supply may be higher or lower than its normal level depending on the pressure from the demand side. This behavior is formulated by a nonlinear function of normalized water demand with positive first derivative and negative second derivative. Shape of the function is illustrated in Figure 2.6.

$$AEDS_t = \left( \frac{2 \cdot LPWD_t / CNWD}{1 + LPWD_t / CNWD} \right)^{CEDS} \tag{2.33}$$

$$500 < CNWD < 600 \tag{2.34}$$

$$0 < CEDS < 2 \tag{2.35}$$

AEDS - EFFECT OF WATER DEMAND PRESSURE ON SURFACE WATER SUPPLY (UNITLESS)
LPWD - PERCEIVED WATER DEMAND (KAF PER YEAR) [2.36]
CNWD - NORMAL WATER DEMAND (KAF PER YEAR)
CEDS - DEMAND EXPONENT OF SURFACE WATER SUPPLY (UNITLESS)

Finally, perceived water demand is a simple smoothing of total water demand.

$$LPWD_t = LPWD_{t-dt} + \frac{LAWD_{t-dt} + ANAW_{t-dt} - LPWD_{t-dt}}{CPER} \cdot dt \tag{2.36}$$

$$LPWD_0 = LAWD_0 \tag{2.37}$$

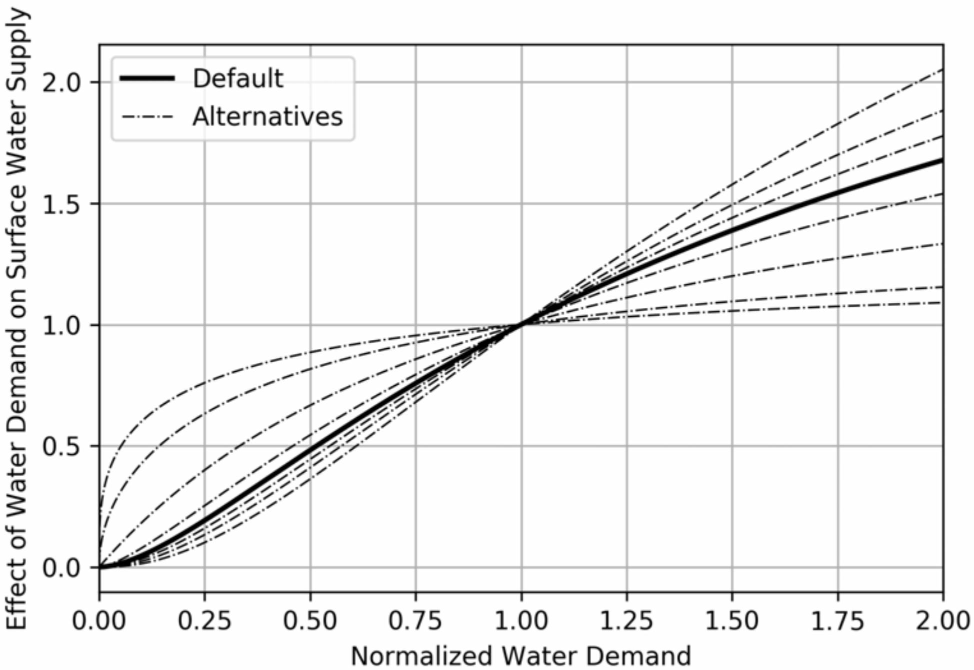


Figure 2.6: Effect of water demand pressure on surface water supply (Equation 2.33)

LPWD - PERCEIVED WATER DEMAND (KAF PER YEAR)
LAWD - WATER DEMAND FOR AGRICULTURE (KAF PER YEAR) [2.12]
ANAW - WATER DEMAND FOR NON-AGRICULTURE USE (KAF PER YEAR) [2.39]
CPER - PERCEPTION DELAY (YEAR) [6.7]

## 2.2 Non-agriculture Water Use

Water use in the non-agriculture sector is estimated in this module. All non-agriculture water demand in the LRG region is met by the groundwater supply. Causal structure of the module is presented in Figure 2.7.

Groundwater non-agriculture withdrawal is equal to its demand as long as groundwater is available. As groundwater storage depletes, groundwater availability declines, which leads to an imbalance between supply and demand of non-agriculture withdrawals.

$$RGNA_t = ANAW_t \cdot AGWA_t \tag{2.38}$$

RGNA - NON-AGRICULTURE GROUNDWATER WITHDRAWAL (KAF PER YEAR)
ANAW - WATER DEMAND FOR NON-AGRICULTURE USE (KAF PER YEAR) [2.39]
AGWA - GROUNDWATER AVAILABILITY (UNITLESS) [2.3]

Water demand for non-agriculture use is simply a multiplication of per capita non-agriculture water demand and population.

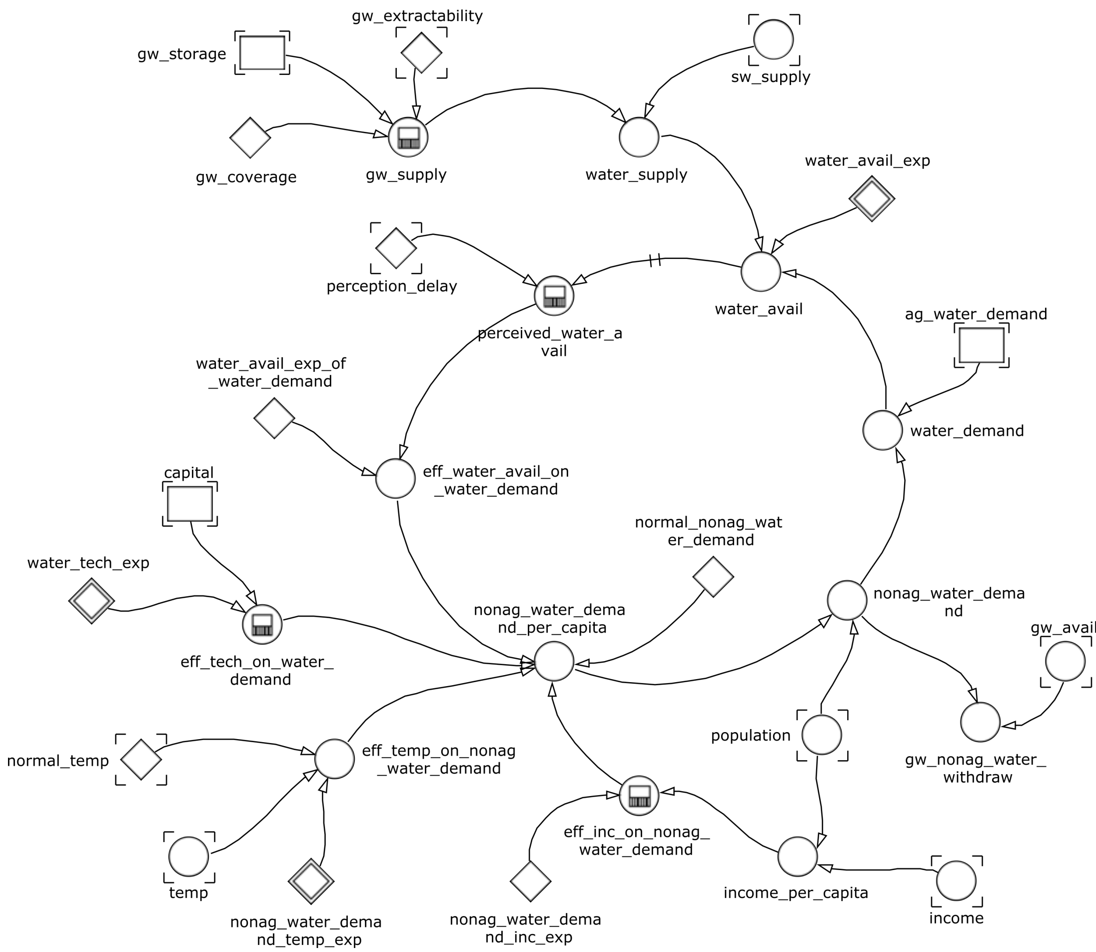


Figure 2.7: Causal structure of the non-agriculture water use module

$$ANAW_t = ANAP_t \cdot APOP_t \tag{2.39}$$

ANAW - WATER DEMAND FOR NON-AGRICULTURE USE (KAF PER YEAR)
ANAP - NON-AGRICULTURE WATER DEMAND PER CAPITA (KAF PER YEAR PER PERSON) [2.40]
APOP - TOTAL POPULATION (PERSON) [6.1]

Per capita non-agriculture water demand is a function of four factors: economic activities per person, technology, temperature, and perception of water availability. These effects multiply by the normal per capita non-agriculture water demand to yield the final per capita demand. Historically, non-agriculture water demand has been within the range 19 to 54 KAF per year (OSE, 2013). Dividing this value by the average population in the same period (about 150 thousands people) provides us with a plausible range of variation for the normal per capita non-agriculture water demand in Equation 2.41.

$$ANAP_t = CNAW \cdot AEIN_t \cdot AETN_t \cdot AEMN_t \cdot AEWN_t \tag{2.40}$$

$$0.0001 < CNAW < 0.0004 \tag{2.41}$$

ANAP - NON-AGRICULTURE WATER DEMAND PER CAPITA (KAF PER YEAR PER PERSON)
CNAW - NORMAL NON-AGRICULTURE WATER DEMAND PER CAPITA (KAF PER YEAR PER PERSON)
AEIN - EFFECT OF INCOME ON NONAG WATER DEMAND (UNITLESS) [2.42]
AETN - EFFECT OF TECHNOLOGY ON NONAG WATER DEMAND (UNITLESS) [2.45]
AEMN - EFFECT OF TEMPERATURE ON NONAG WATER DEMAND (UNITLESS) [2.49]
AEWN - EFFECT OF WATER AVAILABILITY ON NONAG WATER DEMAND (UNITLESS) [2.52]

As economic activities per person increases, ceteris paribus, per capita water demand increases too. Thus, the first derivative of this relationship must be positive. The second derivative, however, is negative; meaning that any additional increase in population or income will have smaller and smaller impact on non-agriculture water demand.

$$AEIN_t = \left(\frac{AIPC_t}{AIPC_0}\right)^{CEIN} \tag{2.42}$$

$$AIPC_t = \frac{AINC_t}{APOP_t} \tag{2.43}$$

$$0 < CEIN < 1 \tag{2.44}$$

AEIN - EFFECT OF INCOME ON NONAG WATER DEMAND (UNITLESS)
AIPC - INCOME PER CAPITA (1000 USD PER YEAR PER PERSON)
CEIN - EXPONENT FOR EFFECT OF INCOME ON WATER DEMAND (UNITLESS)
AINC - TOTAL INCOME (1000 USD PER YEAR) [4.32]
APOP - TOTAL POPULATION (PERSON) [6.1]

Technology is assumed to negatively impact water demand. Technological progress and its impact on water demand is a function of normalized capital as shown in Figure 2.8. Using adjustable parameters, this assumption can be tested in order to take uncertainty into account.

$$AETN_t = CETN_a + \frac{1 - CETN_a}{CETN_b^{\min\left(10, CETN_c \cdot \frac{LCAP_t}{LCAP_0}\right)}} \tag{2.45}$$

$$0.2 < CETN_a < 1 \tag{2.46}$$

$$1 < CETN_b < 5 \tag{2.47}$$

$$0 < CETN_c < 1 \tag{2.48}$$

AETN - EFFECT OF TECHNOLOGY ON NONAG WATER DEMAND (UNITLESS)
CETN - WATER USE TECHNOLOGY EXPONENTS (UNITLESS)
LCAP - CAPITAL (1000 USD) [4.22]

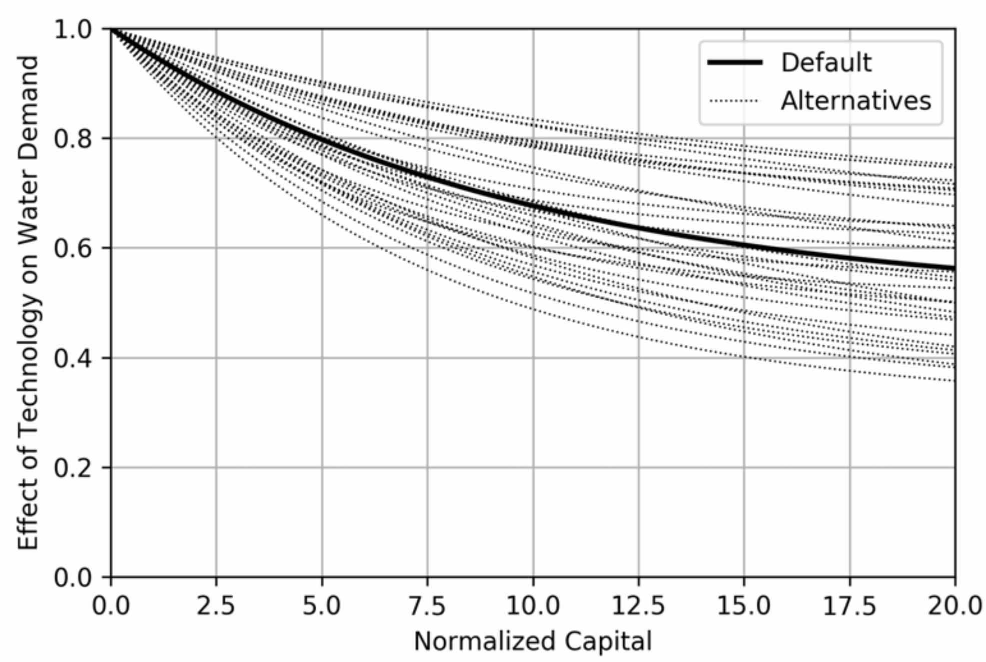


Figure 2.8: Effect of technology on non-agriculture water demand (Equation 2.45)

The effect of temperature on non-agriculture water demand is similar to the Equation [2.24] (effect of temperature on ag water demand – see also Figure 2.4). The only difference here is the parameter values that are set through calibration.

$$AEMN_t = \frac{CEMN_a + 1}{CEMN_a + e^{CEMN_b(1 - \frac{DTEM_t}{CTEM})}} \tag{2.49}$$

$$2 < CEMN_a < 3 \tag{2.50}$$

$$3 < CEMN_b < 5 \tag{2.51}$$

AEMN - EFFECT OF TEMPERTATURE ON NONAG WATER DEMAND (UNITLESS)
CEMN - EXPONENTS FOR EFFECT OF TEMPERATURE ON NONAG WATER DEMAND (UNITLESS)
DTEM - AVERAGE YEARLY TEMPERATURE DATA (DEGREES) [Table 8.1]
CTEM - NORMAL YEARLY TEMPERATURE (DEGREES) [1.41]

The effect of water availability on water demand is a simple nonlinear function of perceived water availability. As perceived water availability declines, water demand also declines. This process may happen through cultural channels. For example, local agencies may encourage the residents to consume less water in face of a shortage. The second derivative of the function is negative, meaning that higher water availability may increase water demand but not proportionately.

$$AEWN_t = {LPWA_t}^{CWAE} \tag{2.52}$$

$$0 < CWAE < 1 \tag{2.53}$$

AEWN - EFFECT OF WATER AVAILABILITY ON NONAG WATER DEMAND (UNITLESS)
LPWA - PERCEIVED WATER AVAILABILITY (UNITLESS) [2.54]
CWAE - WATER AVAILABILITY EXPONENT OF WATER DEMAND (UNITLESS)

Perceived water availability is simply a smooth of water availability index.

$$LPWA_t = LPWA_{t-dt} + \frac{APWA_{t-dt} - LPWA_{t-dt}}{CPER} \cdot dt \tag{2.54}$$

$$LPWA_0 = 1 \tag{2.55}$$

LPWA - PERCEIVED WATER AVAILABILITY (UNITLESS)
APWA - WATER AVAILABILITY (UNITLESS) [2.56]
CPER - PERCEPTION DELAY (YEAR) [6.7]

Water availability index is a function of supply-demand ratio as presented in Figure 2.9. When water supply capacity is equal to water demand, then water availability index is 1, meaning that potential supply of water is adequate for the current demand. As supply capacity declines below demand, the water availability declines but in a lower proportion. At extreme situations, where water is extremely scarce, water availability declines rapidly to control the water balance.

$$APWA_t = \left( \frac{\frac{AWAS_t}{AWAD_t} \cdot (1 + CPWA_a)}{\frac{AWAS_t}{AWAD_t} + CPWA_a} \right)^{CPWA_b} \tag{2.56}$$

$$0 < CPWA < 1 \tag{2.57}$$

```
APWA - WATER AVAILABILITY (UNITLESS)
AWAS - WATER SUPPLY CAPACITY (KAF PER YEAR) [2.59]
AWAD - WATER DEMAND (KAF PER YEAR) [2.58]
CPWA - WATER AVAILABILITY EXPONENTS (UNITLESS)
```

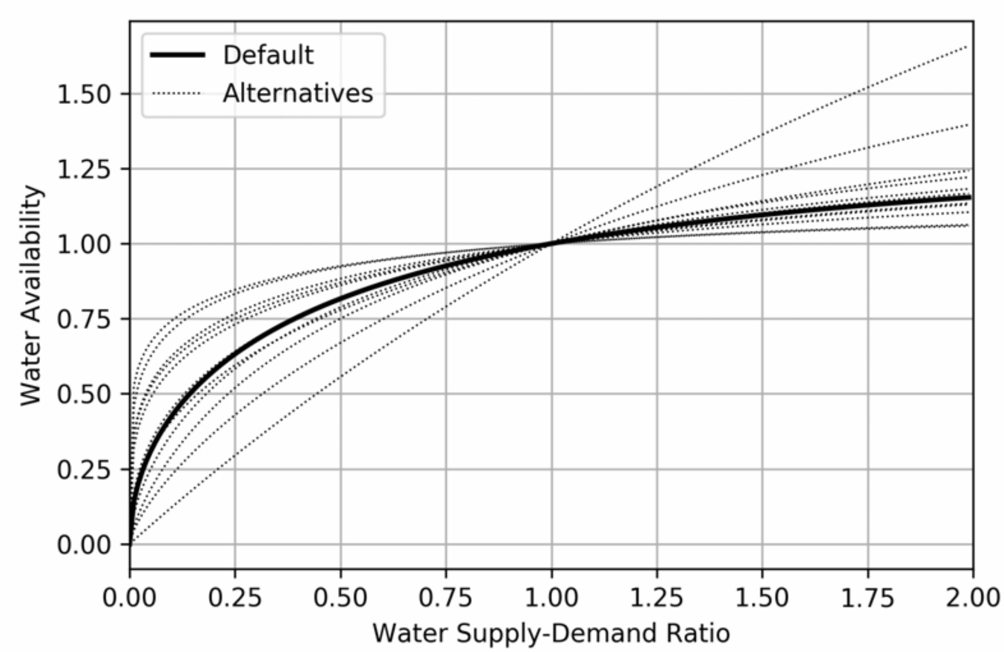


Figure 2.9: Water availability index (Equation 2.56)

Water demand is simply the sum of agriculture and non-agriculture water demands.

$$AWAD_t = LAWD_t + ANAW_t \tag{2.58}$$

```
AWAD - WATER DEMAND (KAF PER YEAR)
LAWD - WATER DEMAND FOR AGRICULTURE (KAF PER YEAR) [2.12]
ANAW - WATER DEMAND FOR NON-AGRICULTURE USE (KAF PER YEAR) [2.39]
```

Water supply represents the region's annual capacity of water supply. It is the sum of surface water and groundwater supplies.

$$AWAS_t = ASWS_t + AGWS_t \tag{2.59}$$

AWAS - WATER SUPPLY CAPACITY (KAF PER YEAR)
ASWS - SUPPLY OF SURFACE WATER (KAF PER YEAR) [2.31]
AGWS - SUPPLY OF GROUNDWATER (KAF PER YEAR) [2.60]

For surface water supply, see Equation 2.31. Groundwater supply capacity is a hypothetical variable that roughly estimates the amount of available groundwater per year for the region. To achieve this estimate, it is assumed that water policy makers have an imaginary groundwater coverage time in mind, say 300 years, over which they expect the groundwater storage to be preserved. Then, groundwater storage volume divided by this coverage time gives us an estimate of yearly groundwater supply that would last for that time span. Note that this variable (groundwater supply) is only used to provide a mental perception of water availability. This may be a hypothetical assumption, but arguably very close to reality of how framers' observation of groundwater level affects their and the decision makers' perception of water availability. In other words, no matter how we formulate the equations, level of groundwater storage is the variable that determines groundwater availability. Hence, we know at least that the causal relationship which is incorporated here is plausible. Uncertainty in the form of the function can be changed by applying variation in its parameters.

$$AGWS_t = \frac{LGWV_t - (1 - CGWE) \cdot LGWV_0}{CGWC} \tag{2.60}$$

$$100 < CGWC < 500 \tag{2.61}$$

AGWS - SUPPLY OF GROUNDWATER (KAF PER YEAR)
LGWV - GROUNDWATER STORAGE (KAF) [1.56]
CGWE - FRACTION OF GROUNDWATER THAT IS EXTRACTABLE (UNITLESS) [2.4]
CGWC - GROUNDWATER STORAGE COVERAGE TIME (YEAR)

# Chapter 3

# Agriculture Production

Causal structure of the agriculture production module is shown in Figure 3.1. This module calculates some important variables such as irrigated land and total agriculture (farm) income. Irrigated land is important because it is used to estimate water demand for irrigation and also agriculture production. Agriculture income is an indicator of wellbeing of farmers as well as a key factor in people's decision regarding keeping their farmland and thus, staying or leaving the agriculture sector. Agriculture income, as mentioned before, plays a critical role in driving economic activities of the region both directly and through backward and forward linkages.

There is an important positive feedback loop that could be responsible for growth or decline of the sector. As farmers expand their activities and irrigate more lands – ceteris paribus – their income increases. This also attracts more workforce to the sector, leading to its further expansion, thus increasing irrigated lands even more. This feedback loop passes through other modules of the model. Thus, some causal links that are discussed here – in particular, the link from `irrigated_land` to `ag_emp_fr` – are not visible in Figure 3.1.

There is also an important negative feedback loop in play here. As agriculture expands – ceteris paribus – more water would be required for irrigation. Assuming that supply of surface water is constant, depletion of groundwater resources to satisfy irrigation demand would be accelerated. Depletion of groundwater storage could lead to lower quality of water, thus, reducing agriculture yields. Consequently, agriculture income declines eventually causing the sector to shrink.

Agriculture income is inflation-adjusted monetary value of agriculture production. Earning income from agriculture is by nature a long process. Preparing land, growing, cultivating, and selling products on the market all take some time to translate to income. This time delay is considered to vary in a range of 0 to 3 years.

$$AAIN_t = AIAI_{t-CAIT} \tag{3.1}$$

$$0 < CAIT < 2 \tag{3.2}$$

```
AAIN - AG INCOME (1000 USD PER YEAR)
```

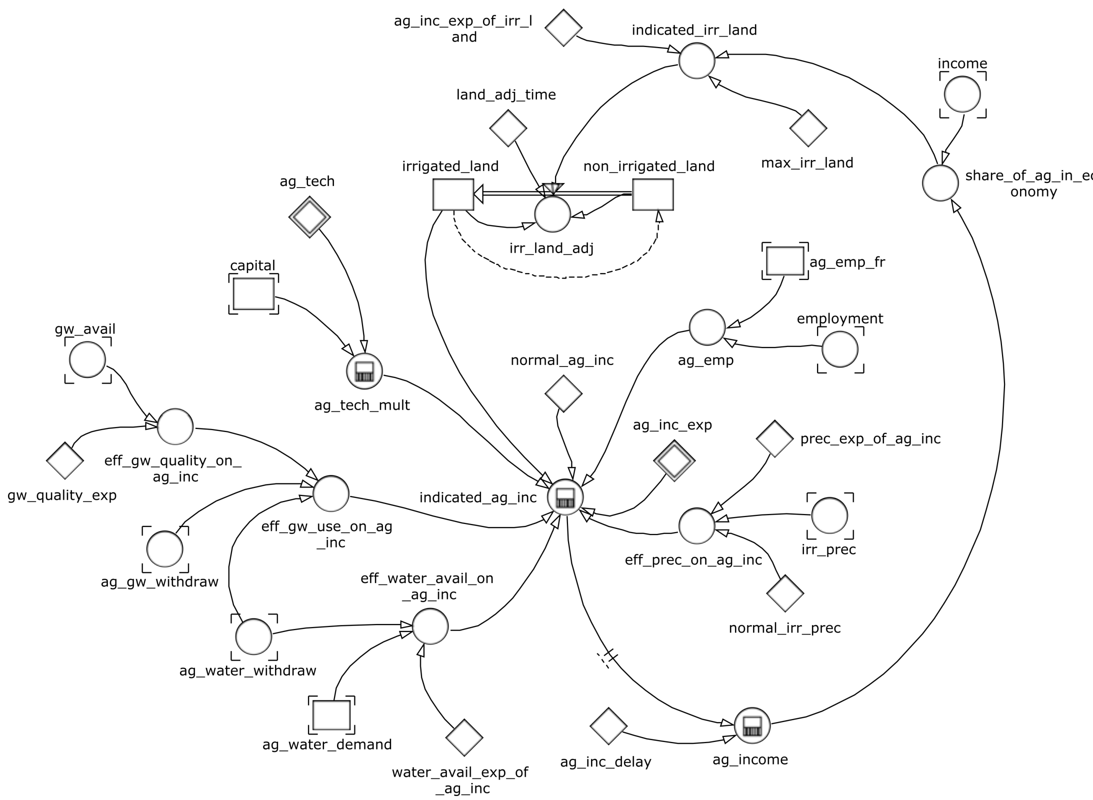


Figure 3.1: Causal structure of the agriculture production module

```
CAIT - AG INCOME DELAY (YEAR)
AIAI - INDICATED AG INCOME (1000 USD PER YEAR) [3.3]
```

Similar to the non-agriculture income (see Chapter 4), agriculture income is computed by a Cobb-Douglas production function that takes labor, land, crop pattern, water availability and quality, and climate conditions as drivers.

$$AIAI_t = CNAI \cdot AECI_t \cdot \left(\frac{AALA_t}{AALA_0}\right)^{CIAI_a} \cdot \left(\frac{LIRL_t}{LIRL_0}\right)^{CIAI_b} \cdot AEWA_t \cdot AEWI_t \cdot AEPA_t \tag{3.3}$$

$$13,000 < CNAI < 143,000 \tag{3.4}$$

$$0.3 < CIAI < 0.9 \tag{3.5}$$

```
AIAI - INDICATED AG INCOME (1000 USD PER YEAR)
CNAI - NORMAL AG INCOME (1000 USD PER YEAR)
AECI - EFFECT OF CROP PATTERN ON AGRICULTURE INCOME (UNITLESS) [3.6]
AALA - AG LABOR (PERSON) [3.8]
CIAI - AG PRODUCTION FUNCTION EXPONENTS (UNITLESS)
LIRL - IRRIGATED LAND (ACRE) [3.9]
AEWA - EFFECT OF GROUNDWATER USE ON AG INCOME (UNITLESS) [3.23]
AEWI - EFFECT OF WATER AVAILABILITY ON AG INCOME (UNITLESS) [3.21]
AEPA - EFFECT OF PRECIPITATION ON AG INCOME (UNITLESS) [3.19]
```

Farm income data is available from 1969 to 2016 from Bureau of Economic Analysis (2018c). Within this period, inflation adjusted farm income has been as low as 13 and as high as 143 million dollars per year. Therefore, normal agriculture income is set to be within that range.

In the previous version of the LRG model, techological progress was used to induce a S-shape growth in agriculture income. This assumption was deemed an oversimplification and is replaced here by a more realistic consideration that assumes the S-shape growth of agriculture income is driven by a similar pattern in growth of water-intensive crops such as pecan. Such crops are more profitable than other crops, despite their greater water use. As a result, the move of agriculture sector to these crops has increased total income significantly. After 2005 though, this growth has slowed down due to some water use restrictions that has reduced incentives for the expansion of such crops. To simulate the impact of crop pattern on agriculture income, agriculture water requirement (2.17) is used as a proxy. In fact, we implicitly assume that average water requirement represents the profitability of the crop profile of the region. However, our calibration shows that such a representation is not proportional. An increase in average water requirement increases farm income but with an increasing rate. Therefore, an exponential funtion with a relatively large exponent is used for this transformation.

$$AECI_t = \left(\frac{AGRQ_t}{AGRQ_0}\right)^{CECI} \tag{3.6}$$

$$7 < CECI < 10 \tag{3.7}$$

AECI - EFFECT OF CROP PATTERN ON AGRICULTURE INCOME (UNITLESS)
AGRQ - AG WATER REQUIREMENT (FT PER YEAR) [2.17]
CECI - CROP PATTERN INCOME ELASTICITY (UNITLESS)

Ag labor in Equation 3.3 represents total employment in the agriculture sector. This variable is simply a fraction of total employment. This fraction is an endogenous variable and will be explained later (see Equation [7.1]).

$$AALA_t = LALF_t \cdot AEMP_t \tag{3.8}$$

AALA - AG LABOR
LALF - AG LABOR FRACTION (UNITLESS) [7.1]
AEMP - EMPLOYMENT (PERSON) [4.4]

Irrigated land is another important production factor in the agriculture income function. It is assumed that total land is constant (about 2.4 million acres). A fraction of total land could be used for agriculture (irrigated land). The rest would be classified as non-agriculture (non-irrigated land). Land allocation can change over time but with a delay.

$$LIRL_t = LIRL_{t-dt} + RIRL_{t-dt} \cdot dt \tag{3.9}$$

$$100,000 < LIRL_0 < 130,000 \tag{3.10}$$

$$LNIL_t = LNIL_{t-dt} - RIRL_{t-dt} \cdot dt \tag{3.11}$$

$$LNIL_0 = 2,441,120 - LIRL_0 \tag{3.12}$$

$$RIRL_t = \frac{\min(LNIL_t, AIRL_t - LIRL_t)}{CIRT} \tag{3.13}$$

$$5 < CIRT < 15 \tag{3.14}$$

LIRL - IRRIGATED LAND (ACRE)
LNIL - NON-IRRIGATED LAND (ACRE)
RIRL - LAND ADJUSTMENT RATE (ACRE PER YEAR)
AIRL - INDICATED IRRIGATED LAND (ACRE) [3.15]
CIRT - LAND ADJUSTMENT TIME (YEAR)

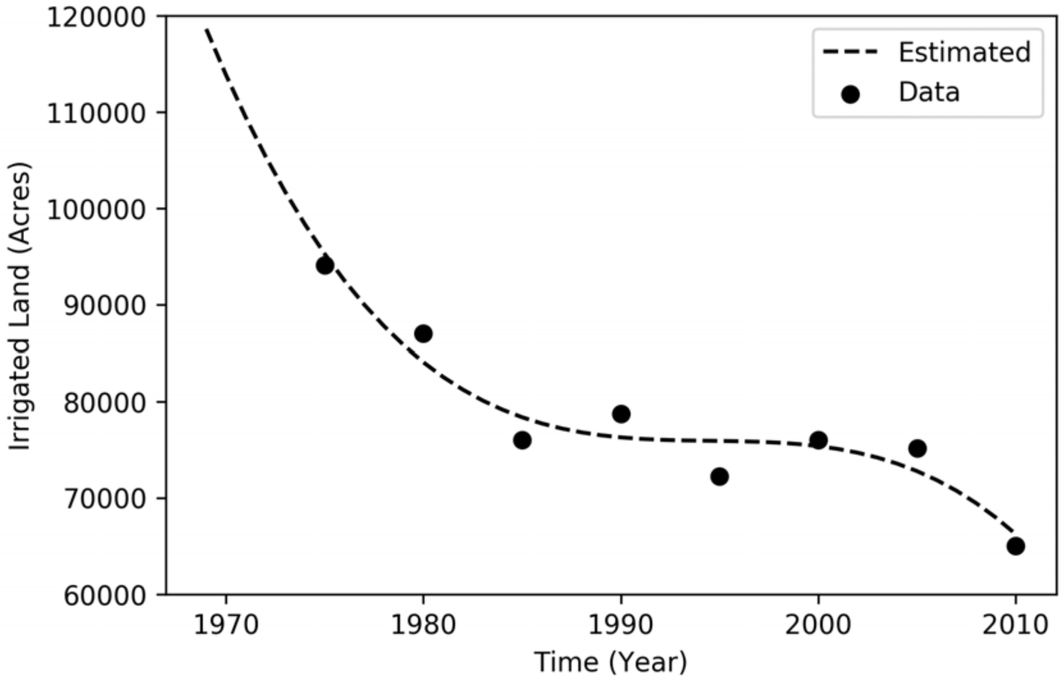


Figure 3.2: Trend of irrigated land in the lower Rio Grande region

The initial value of irrigated land is likely to be within the range (100, 130) kilo acres as the trend line in Figure 3.2 shows. The remainder of total land in the region ($2,441,120$ acres) is equal to the initial non-irrigated land value.

Irrigated land increases (decreases) over time as agriculture becomes more (less) attractive. Attractiveness of agriculture could be reflected by the portion of agriculture income within total income. The sensitivity of irrigated land to the agriculture income fraction could be adjusted by the parameter $CIEL$. The maximum amount of land to be used for agriculture is assumed to be within the range (160,170) kilo acres.

$$AIRL_t = CIRL \cdot ASAE_t^{CIEL} \tag{3.15}$$

$$160,000 < CIRL < 170,000 \tag{3.16}$$

$$ASAE_t = \frac{AAIN_t}{AINC_t} \tag{3.17}$$

$$0.1 < CIEL < 0.3 \tag{3.18}$$

```
AIRL - INDICATED IRRIGATED LAND (ACRE)
CIRL - MAXIMUM IRRIGATED LAND (ACRE)
ASAE - SHARE OF AG INCOME IN ECONOMY (UNITLESS)
AAIN - AGRICULTURE INCOME (1000 USD PER YEAR) [3.1]
AINC - TOTAL INCOME (1000 USD PER YEAR) [4.32]
CIEL - AG INCOME EXPONENT OF IRRIGATED LAND (UNITLESS)
```

Climate change might have an impact on agriculture income. This potential impact is shown here by precipitation, which can be greatly influenced by climate change. Lower precipitation indicates drought periods which may reduce agriculture income. The sensitivity of agriculture income to precipitation can be adjusted by the parameter $CPAI$. Here, irrigation precipitation data is used to drive this function. This data is not available for future scenarios but total precipitation is. However, our data analysis reveals that irrigation precipitation is usually around 96% of total precipitation. Thus, for future scenarios, a fraction of precipitation (96%) will be used as a proxy for irrigation precipitation. As mentioned earlier (see Section 1.2), since the amount of precipitation within the LRG region is spatially variable and is typically higher in the mountainous areas, precipitation falling on agricultural lands was calculated separately.

$$AEPA_t = \left(\frac{DIPR_t}{CIPR}\right)^{CPAI} \tag{3.19}$$

$$0 < CPAI < 2 \tag{3.20}$$

```
AEPA - EFFECT OF PRECIPITATION ON AG INCOME (UNITLESS)
DIPR - IRRIGATION PRECIPITATION DATA (FT PER YEAR) [Table 8.1]
CIPR - NORMAL IRRIGATION PRECIPITATION (FT PER YEAR)
CPAI - PRECIPITATION EXPONENT OF AG INCOME (UNITLESS)
```

Availability of water is another factor that affects agriculture income. If farmers receive as much water as they demand, this multiplier will be equal to 1, meaning that – ceteris paribus – agriculture income will not be affected. If farmer receive less water than what they demand, the multiplier is less than 1, meaning that agriculture income decreases. The sensitivity of this effect can be adjusted by the parameter $CEWI$.

$$AEWI_t = \left(\frac{AAWU_t}{LAWD_t}\right)^{CEWI} \tag{3.21}$$

$$0 < CEWI < 3 \tag{3.22}$$

```
AEWI - EFFECT OF WATER AVAILABILITY ON AG INCOME (UNITLESS)
AAWU - AG WATER USE (KAF PER YEAR) [2.1]
LAWD - AG WATER DEMAND (KAF PER YEAR) [2.12]
CEWI - WATER AVAILABILITY EXPONENT OF AG INCOME (UNITLESS)
```

Groundwater is a secondary source of supply for irrigation in the region. Farmers prefer to use surface water for irrigation because of its quality. Groundwater might be of lower quality, especially if the groundwater level is low. In such cases, salinity of groundwater could negatively affect the agriculture yield. The following function captures the effect of groundwater quality on agriculture income. Note that this effect is adjusted by the share of groundwater in total water use. If groundwater use is 0, then this function will become ineffective. As groundwater plays greater roles in the irrigation system, this function gains more weight.

$$AEWA_t = AEQI_t^{\frac{RGAU_t}{AAWU_t}} \tag{3.23}$$

AEWA - EFFECT OF GROUNDWATER USE ON AG INCOME (UNITLESS)
AEQI - EFFECT OF GROUNDWATER QUALITY ON AG INCOME (UNITLESS) [3.24]
RGAU - GROUNDWATER USE FOR AGRICULTURE (KAF PER YEAR) [2.2]
AAWU - AG WATER USE (KAF PER YEAR) [2.1]

The effect of groundwater quality on agriculture income is a simple nonlinear function of groundwater availability with adjustable sensitivity:

$$AEQI_t = AGWA_t^{CGWQ} \tag{3.24}$$

$$0 < CGWQ < 3 \tag{3.25}$$

AEQI - EFFECT OF GROUNDWATER QUALITY ON AG INCOME (UNITLESS)
AGWA - GROUNDWATER AVAILABILITY (UNITLESS) [2.3]
CGWQ - SENSITIVITY OF GROUNDWATER QUALITY FUNCTION (UNITLESS)

# Chapter 4

# Non-agriculture Production

This chapter explains the model structure of the "nonag production" module. Non-agriculture production has to be calculated endogenously inside the model boundary because it is an important driver of the water demand for non-agriculture use. The causal structure of this module is depicted in Figure 4.1.

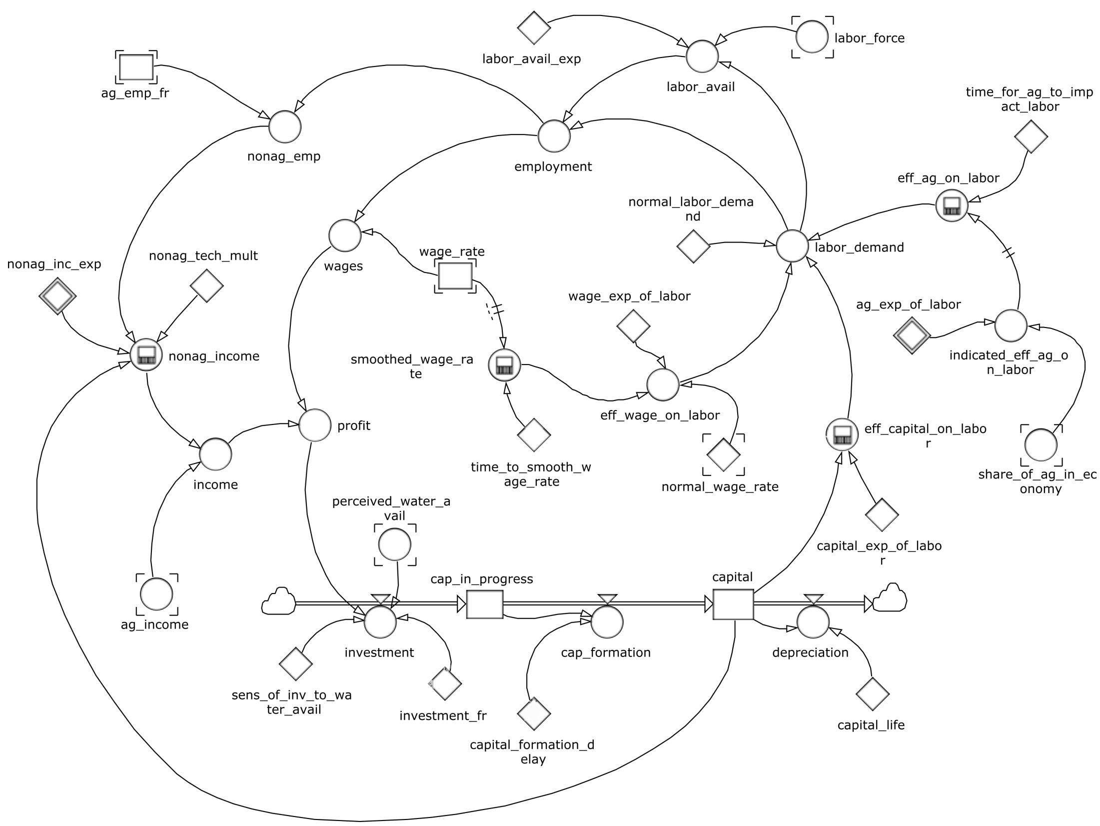


Figure 4.1: Causal structure of the non-agriculture production module

Basically, there are four major feedback loops in effect here. The first loop is a simple endogenous economic growth mechanism as follows: more (less) capital –> more (less) nonag income –> more (less) income –> more (less) profits –> more (less) investment –> more (less) capital. This is clearly a positive feedback loop, as an increase in income will lead to greater income in the following time periods.

The second feedback loop is positive: more (less) capital –> more (less) labor demand –> more (less) employment –> more (less) nonag employment –> more (less) nonag income –> more (less) income –> more (less) profits –> more (less) investment –> more (less) capital. An initial increase (decrease) in capital will lead to an increase (decrease) in capital in the following time periods.

The third feedback loop is a negative loop: more (less) capital –> more (less) labor demand –> more (less) employment –> more (less) wages –> less (more) profits –> less (more) investment –> less (more) capital. An initial increase (decrease) in capital will lead to a decrease (increase) in capital in the following time periods.

The forth feedback loop is slightly different from the third loop. However, this slight difference converts the loop from a negative to a positive one: more (less) capital –> more (less) labor demand –> less (more) labor availability –> less (more) employment –> less (more) wages –> more (less) profits –> more (less) investment –> more (less) capital. Essentially, an initial increase (decrease) in capital will lead to a further increase (decrease) in capital in the following time periods.

There are other feedback loops involved in this module but they go through other modules of the model. So, they are not shown explicitly in Figure 4.1. For example, as the economy grows – assuming the workforce pool remains unchanged – unemployment rates decline. This mechanism (see Chapter 5 for details) leads to higher wage rates, which reduces investment and labor demand. As a result, the economic growth slows down. Due to the time delays that are within these loops, fluctuations in wage and employment adjustments may occur. Such fluctuations are natural behavior of coupled major negative feedback loops with delays. However, depending on the power of each loop, the behavior of the module could be different.

Using inputs from other modules, the current module calculates real monetary value (adjusted for inflation)[1] of all economic production in the region excluding any agricultural production. This variable is called `nonag_income` and is formulated by a Cob-Douglas production function as is common in economics literature:

$$ANAI_t = CNAT \cdot \left(\frac{LCAP_t}{LCAP_0}\right)^{CNIP_a} \cdot \left(\frac{ANAE_t}{ANAE_0}\right)^{CNIP_b} \tag{4.1}$$

$$500,000 < CNAT < 800,000$$

$$0.3 < CNIP < 0.9 \tag{4.2}$$

[1] All data and parameters used in the model are adjusted for inflation. For some variables, this adjustment is already made by the original data provider. For other variables, we have adjusted the monetary values by using price indices. For example, agriculture income is adjusted by the farm producer price index (Farm PPI) (Federal Reserve Bank of St. Louis, 2018c) and non-agriculture income is adjusted by the industry producer price index (Industry PPI) (Federal Reserve Bank of St. Louis, 2018b). Other variables are adjusted by the consumer price index (CPI) (Federal Reserve Bank of St. Louis, 2018a).

```
ANAI - NONAG INCOME (1000 USD PER YEAR)
CNAT - NONAG TECHNOLOGY MULTIPLIER (1000 USD PER YEAR)
LCAP - CAPITAL (1000 USD) [4.22]
CNIP - NONAG INCOME PARAMETERS (UNITLESS)
ANAE - NONAG EMPLOYMENT (PERSON) [4.3]
```

Note that Equation 4.1 implies that $ANAI_0 = CNAT$. In other words, the non-agriculture technology multiplier is the equivalent of initial non-agriculture income. The initial non-agriculture income (at 1969) was 582 million dollars (at 1986 constant prices) per year. Therefore, $CNAT$ should be close to this value.

There are two production factors in this function: capital and labor. The function can take a more sophisticated form by including additional factors such as education, or endogenous technology[2]. However, these factors are not of interest in the current study; as such, they remain outside of the model's boundary.

Here, $CNIP_a$ and $CNIP_b$ are labor and capital productivity exponents, respectively. The technology multiplier determines the numerical magnitude of the production function. Normal values of capital and non-agriculture employment are used to normalize the production factors in the function. These parameters are estimated through calibration so that the model fits to actual data. However, the calibration is conducted with strict constraints for parameter ranges to make sure that the model does not violate physical or socioeconomic rules. For example, productivity exponents are calibrated within .3 and .8, which is a common range for a Cobb-Douglas function. To achieve an approximation for initial non-agriculture employment, some rudimentary estimations are conducted. There is historical data available for employment in agriculture and non-agriculture sectors from the Bureau of Economic Analysis [Bureau of Economic Analysis (2018a,b)]. This data is only for the period of 1990 to 2015. The initial simulation time of this model is 1969. However, the historical trends imply that the initial ratio of non-agricuture employment to total employment should be around 95%. Also, the population of Doña Ana county in 1969 was about 69 thousand (Bureau of Economic Analysis, 2018c). Employment and population data help to calculate workforce participation rates, which on average were around 43% from 1990–2015. Assuming a roughly similar participation rate for 1969, labor force should be about 29 thousand at the initial simulation time. Therefore, initial non-agriculture employment would be around 27 (= 29 * .95) thousand people.

In the model, `ag_emp` is a fraction of total employment. This fraction is shown by the variable `ag_labor_fr`, which is explained in Chapter 7. The rest of the labor will be employed in the non-agriculture sector.

$$ANAE_t = AEMP_t \cdot (1 - LALF_t) \tag{4.3}$$

```
ANAE - NONAG EMPLOYMENT (PERSON)
AEMP - EMPLOYMENT (PERSON) [4.4]
LALF - AG EMPLOYMENT FRACTION (UNITLESS) [7.1]
```

[2]Technology is only a constant parameter in the current version of the model.

Total employment is equal to labor demand but it is also limited by labor supply, which is represented by the labor availability indicator. In other words, labor would be employed as demanded but it cannot exceed the labor supply.

$$AEMP_t = ALAD_t \cdot ALAA_t \tag{4.4}$$

```
AEMP - EMPLOYMENT (PERSON)
ALAD - LABOR DEMAND (PERSON) [4.8]
ALAA - LABOR AVAILABILITY (UNITLESS) [4.5]
```

In cases that labor force ($ALAF$) is lower than demand ($ALAD$), the labor availability indicator would be less than 1, so that total employment would reflect such a labor shortage. The sensitivity of this function could be adjusted by its parameter ($CLAA$), which should be greater than 1 [3]. This will ensure that employment will always remain smaller than the labor force. It is also assumed that not all the labor pool will be available for employment at each period of time. This is because of the imperfect information and other limitations that prevent a perfect match of labor supply and demand. Maximum fraction of available labor is considered to be greater than 95% and less than 100%.

$$ALAA_t = \min\left(1, \frac{CMLA \cdot ALAF_t}{ALAD_t}\right)^{CLAA} \tag{4.5}$$

$$CLAA > 1 \tag{4.6}$$

$$.95 < CMLA < 1 \tag{4.7}$$

```
ALAA - LABOR AVAILABILITY (UNITLESS)
CMLA - MAXIMUM LABOR AVAILABILITY (UNITLESS)
ALAF - LABOR FORCE (PERSON) [5.10]
ALAD - LABOR DEMAND (PERSON) [4.8]
CLAA - LABOR AVAILABILITY EXPONENT (UNITLESS)
```

Labor demand increases as production capacity (capital) expands and (or) wage rates decline. Furthermore, the share of agriculture within the economy, $ASAE$ (see Equation 3.17) may have a positive impact on labor demand. In the labor demand equation, base labor demand ($CLAD$) is the base of the function. The number of jobs in 1969 was 26608 (Bureau of Economic Analysis, 2018c). Therefore, $CLAD$ must be below this value as historical data shows that labor grows over time. The actual value of this parameter is estimated through calibration to be within 15K–27K.

$$ALAD_t = CLAD \cdot AEWL_t \cdot LEAL_t \cdot AECL_t \tag{4.8}$$

$$15,000 < CLAD < 27,000 \tag{4.9}$$

[3]For the model to stay robust in extreme conditions, this parameter should always be greater than 1 because for values below 1, the labor availability indicator would become larger than the labor supply-demand ratio in cases of labor shortage. This will lead to negative unemployment rates.

ALAD - LABOR DEMAND (PERSON)
CLAD - BASE LABOR DEMAND (PERSON)
AEWL - EFFECT OF WAGE RATE ON LABOR DEMAND (UNITLESS) [4.10]
LEAL - EFFECT OF SHARE OF AG IN ECONOMY ON LABOR DEMAND (UNITLESS) [4.14]
AECL - EFFECT OF CAPITAL ON LABOR DEMAND (UNITLESS) [4.20]

Wage rate has a negative impact on labor demand. As wage rates increase, employers tend to demand less for labor. This effect is shown by a simple nonlinear function (Equation 4.10). Like many other functions in this model, the shape of this function can be adjusted by its parameter (here, `wage_exponent_of_labor`). Also note that the smooth of wage rate is used instead of `wage_rate`, reflecting the fact that it takes some time for wages to affect the labor market.

$$AEWL_t = \left(\frac{CWRN}{LSWR_t}\right)^{CWEL} \tag{4.10}$$

$$1 < CWEL < 5 \tag{4.11}$$

AEWL - EFFECT OF WAGE RATE ON LABOR DEMAND (UNITLESS)
CWRN - NORMAL WAGE RATE (1000 USD PER PERSON PER YEAR)
LWAR - WAGE RATE (1000 USD PER PERSON PER YEAR) [5.1]
LSWR - SMOOTHED WAGE RATE (1000 USD PER PERSON PER YEAR) [4.12]
CWEL - WAGE EXPONENT OF LABOR DEMAND (UNITLESS)

Normal real wage rate ($CWRN$) is used to normalize the effect of wage rate. Time series data of the real wage rate is not available. However, total wages are available (Bureau of Economic Analysis, 2018c). Chapter 8.1 explains how wage rates are driven from available data. The data ranges from 1990–2016. During this period, the real wage rate varies from 13–18 thousand dollars per person per year as Figure 4.2 shows. As such, the range (13,18) has been used in the calibrations for this parameter.

The smoothed wage rate is a simple smoothing function of wage rate. Smoothing time ($CTSW$) represents time delay for labor market to adjust to changes in wages. This should normally be within a range of 1 to 5 years. The ultimate value is decided by calibration.

$$LSWR_t = LSWR_{t-dt} + \frac{LWAR_{t-dt} - LSWR_{t-dt}}{CTSW} \cdot dt \tag{4.12}$$

$$1 < CTSW < 5 \tag{4.13}$$

LSWR - SMOOTHED WAGE RATE (1000 USD PER PERSON PER YEAR)
LWAR - WAGE RATE (1000 USD PER PERSON PER YEAR) [5.1]
CTSW - TIME TO SMOOTH WAGE RATE (YEAR)

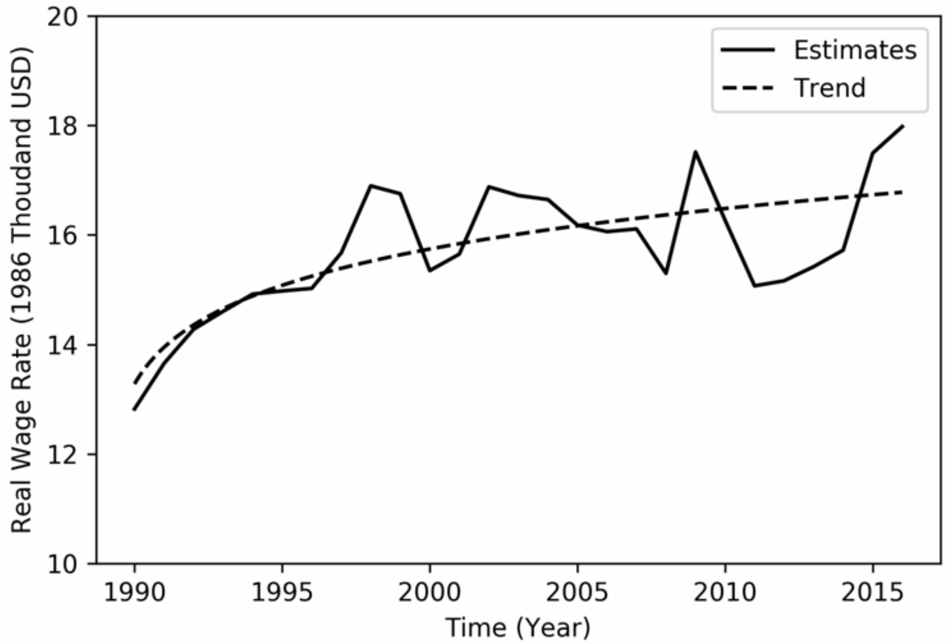


Figure 4.2: Real wage rate trend (authors' estimates based on BEA's data (Bureau of Economic Analysis, 2018c))

The effect of agriculture on total labor demand is based on the theory of "agricultural-demand-led-industrialization" (ADLI) developed by Adelman (1984) and Vogel (1994). Expansion of agriculture can lead to "backward and forward linkages" (Hirschman, 1958; Rothschild, Sen, 2013) through activities such as investment in irrigation, roads, bridges, storage facilities, canals, research and development in seeds, cultivation techniques, animal breeding, and conservation and sustainability methods. This will increase the demand for workforce in these sectors. It has been shown that a \$100 increase in agricultural output may lead to an additional \$80 of total output due to increased demand for both consumer goods and farming inputs (Cypher, 2014). This effect is shown below by a nonlinear function (Equations 4.14 and 4.16). The shape of the function is illustrated in Figure 4.3. Note that the share of agriculture affects the labor demand with a delay. This is because forward and backward linkages usually take a long time to form and develop.

$$LEAL_t = LEAL_{t-dt} + \frac{AEAL_{t-dt} - LEAL_{t-dt}}{CTAL} \cdot dt \tag{4.14}$$

$$LEAL_0 = 1 \tag{4.15}$$

$$AEAL_t = \left( \frac{2}{1 + e^{CEAL_a \left(1 - \frac{ASAE_t}{0.05}\right)}} \right)^{CEAL_b} \tag{4.16}$$

$$1 < CTAL < 5 \tag{4.17}$$

$$1 < CEAL_a < 5 \tag{4.18}$$

$$0.1 < CEAL_b < 1 \tag{4.19}$$

LEAL - EFFECT OF SHARE OF AG IN ECONOMY ON LABOR DEMAND (UNITLESS)
AEAL - INDICATED EFFECT OF SHARE OF AG IN ECONOMY ON LABOR DEMAND (UNITLESS)
CTAL - TIME FOR AG TO IMPACT LABOR DEMAND (YEAR)
ASAE - SHARE OF AG INCOME IN ECONOMY (UNITLESS) [3.17]
CEAL - EXPONENTS OF EFFECT OF AG ON LABOR DEMAND (UNITLESS)

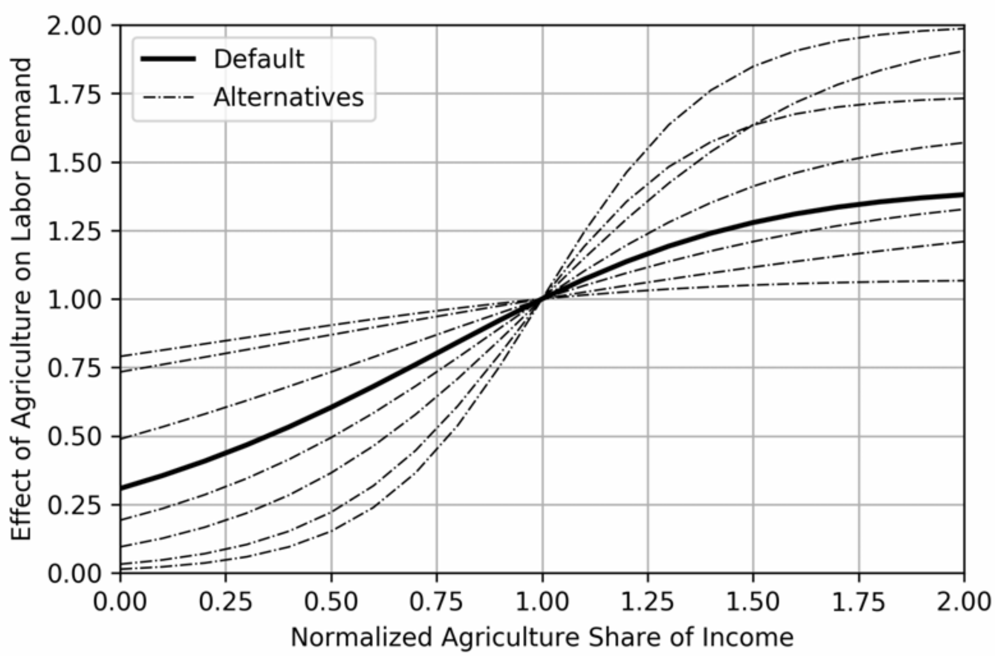


Figure 4.3: Effect of agriculture on total labor demand (Equation 4.16)

The production capacity of the region, represented by `capital` ($LCAP$), should also play a role in demand for labor. As `capital` grows, there should be more demand for labor. This assumption is formulated as a multiplier in the `labor_demand` function (shown previously in Equation 4.8) by a simple nonlinear function:

$$AECL_t = \left(\frac{LCAP_t}{LCAP_0}\right)^{CCEL} \tag{4.20}$$

$$0.1 < CCEL < 1 \tag{4.21}$$

```
AECL - EFFECT OF CAPITAL ON LABOR DEMAND (UNITLESS)
LCAP - CAPITAL (1000 USD) [4.22]
CCEL - CAPITAL EXPONENT OF LABOR DEMAND (UNITLESS)
```

In the model, `capital` represents monetary value of all types of income-generating assets such as infrastructure, commercial and industrial capital, plant and equipment, etc. These assets accumulate over time through investment and deplete through depreciation and decay. Capital accumulation occurs with a delay as depicted in Figure 4.1. That is, capital investment goes first into a stock that is called here "capital in progress" ($LCIP$). These investments could be regarded as capital development plans that are not yet realized. These investments then form the actual capital ($LCAP$) through the rate "capital formation" ($RCIP$). This selection is due to the fact that any investment requires some time to be added to the active production capacity, hence becoming available for real production of goods and services. Here, it is assumed that the average time delay for capital development is within a possible range of 2 to 10 years.

Data for capital is not available. For initialization of these stocks, hypothetical numbers are used. This selection is acceptable because only a normalized value of `capital` is used in the model. In fact, in all instances where `capital` is used, it is divided by its initial level ($LCAP_0$). Therefore, what matters in the model is only relative changes of `capital` and not its absolute value.

Capital life ($CCAL$) is an average time delay for the production capacity to age and retire. Because capital is highly aggregated and represents many different forms of capital, it is very difficult to estimate. Some forms of capital could last for a long time but others may be discarded after very short periods of time. A possible range of (5, 15) years is selected for this parameter.

A fraction of total profit will be invested every year. This parameter ($CINV$) can theoretically vary from 0 to 1 and is estimated here by calibration.

Investment might be affected by water availability as well. This effect does not impact the model behavior in the historical period of simulation (1969–2016). However, it may come into effect in the future as groundwater levels decline. The sensitivity of investment to such changes could be changed as a scenario test. For the base case, it is assumed to be 1.

$$LCAP_t = LCAP_{t-dt} + (RCIP_{t-dt} - RDEP_{t-dt}) \cdot dt \tag{4.22}$$

$$RDEP_t = \frac{LCAP_t}{CCAL} \tag{4.23}$$

$$5 < CCAL < 15 \tag{4.24}$$

$$RCIP_t = \frac{LCIP_t}{CCFD} \tag{4.25}$$

$$LCIP_t = LCIP_{t-dt} + (RINV_{t-dt} - RCIP_{t-dt}) \cdot dt \tag{4.26}$$

$$RINV_t = \max(0, APRO_t) \cdot CINV \cdot AGWA_t{}^{CSIG} \tag{4.27}$$

$$2 < CCFD < 5 \tag{4.28}$$

$$0 < CINV < 1 \tag{4.29}$$

$$0 < CSIG < 2 \tag{4.30}$$

```
LCAP - CAPITAL (1000 USD)
RDEP - CAPITAL DEPRECIATION (1000 USD PER YEAR)
CCAL - CAPITAL LIFE (YEAR)
RCIP - CAPITAL FORMATION RATE (1000 USD PER YEAR)
LCIP - CAPITAL IN PROGRESS (1000 USD)
RINV - CAPITAL INVESTMENT (1000 USD PER YEAR)
CCFD - CAPITAL FORMATION DELAY (YEAR)
CINV - INVESTMENT FRACTION (UNITLESS)
CSIG - SENSITIVITY OF INVESTMENT TO WATER AVAILABILITY (UNITLESS)
APRO - PROFIT (1000 USD PER YEAR) [4.31]
AGWA - GROUNDWATER AVAILABILITY (UNITLESS) [2.3]
```

Profit ($APRO$) is a simple accounting equation representing all forms of `income` ($AINC$) excluding `wages` ($AWAG$):

$$APRO_t = AINC_t - AWAG_t \tag{4.31}$$

```
APRO - PROFIT (1000 USD PER YEAR)
AINC - TOTAL INCOME (1000 USD PER YEAR) [4.32]
AWAG - WAGES (1000 USD PER YEAR) [4.33]
```

Income is also an accounting equation, representing a sum of agriculture and non-agriculture income:

$$AINC_t = AAIN_t + ANAI_t \tag{4.32}$$

```
AINC - TOTAL INCOME (1000 USD PER YEAR)
AAIN - AG INCOME (1000 USD PER YEAR) [3.1]
ANAI - NONAG INCOME (1000 USD PER YEAR) [4.1]
```

Finally, wages ($AWAG$) is simply a multiplication of wage rate ($LWAR$) and employment ($AEMP$):

$$AWAG_t = LWAR_t \cdot AEMP_t \tag{4.33}$$

AWAG - WAGES (1000 USD PER YEAR)
LWAR - WAGE RATE (1000 USD PER PERSON PER YEAR) [5.1]
AEMP - EMPLOYMENT (PERSON) [4.4]

# Chapter 5

# Wage

This chapter explains the wage module in which wage and unemployment rates are calculated. The structure of the module is illustrated in Figure 5.1.

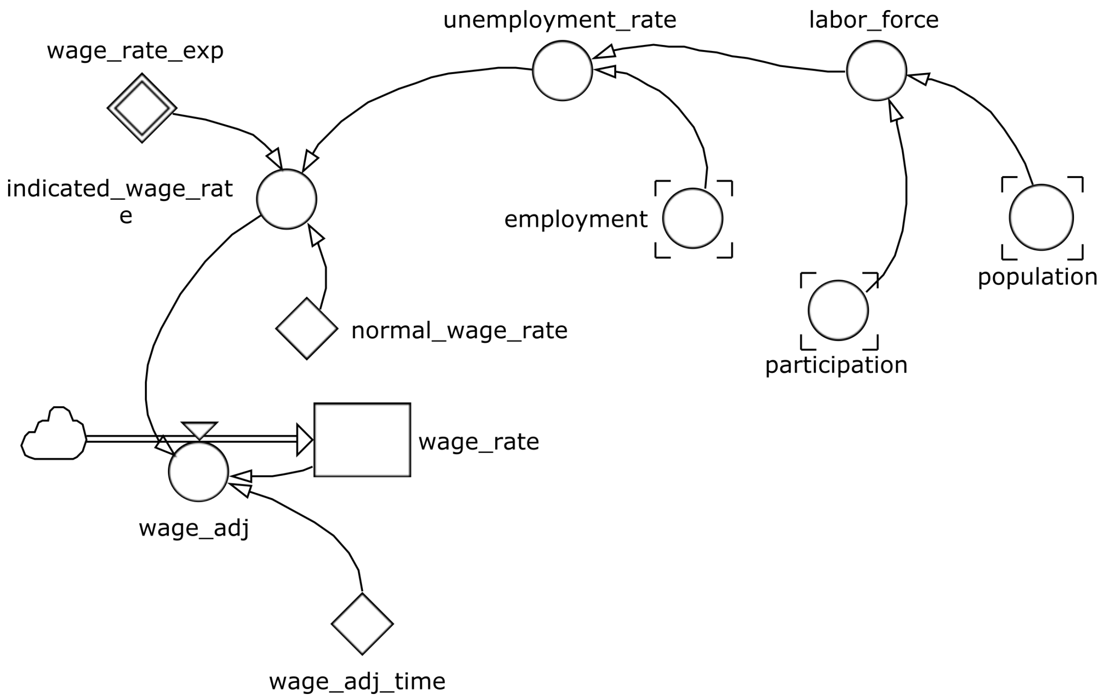


Figure 5.1: Causal structure of the wage module

Wage rate is a stock that adjusts itself to its indicated rate ($AWAR$), a value that is determined by the market forces. Historically, wage rate has varied from 13 to 18 thousand dollars (inflation adjusted) per year per person (based on authors' calculation of BEA data (Bureau of Economic Analysis, 2018c,a,b)). Therefore, the initial value of wage is calibrated within this range. The adjustment occurs with a delay, which is estimated by calibrating within the range of 1 to 5 years [1]. Long adjustment time for wage rates reflect the fact that in the real world, wages are usually different from the optimum levels due to socio-political distortions. These distortions depend on the political power of negotiation sides whether they are labor unions, capital owners, state or federal governments, etc.

$$LWAR_t = LWAR_{t-dt} + \frac{AWAR_{t-dt} - LWAR_{t-dt}}{CWAR} \cdot dt \tag{5.1}$$

$$13 < LWAR_0 < 18 \tag{5.2}$$

$$1 < CWAR < 5 \tag{5.3}$$

```
LWAR - WAGE RATE (1000 USD PER PERSON PER YEAR)
AWAR - INDICATED WAGE RATE (1000 USD PER PERSON PER YEAR) [5.4]
CWAR - WAGE RATE ADJUSTMENT TIME (YEAR)
```

Indicated wage rate itself is a nonlinear function of unemployment rate. Figure 5.2 depicts how unemployment rate may impact the wage rate. Multiplication of such effect by the normal wage rate ($CWRN$) yields indicated wage rates ($AWAR$) as shown by Equation 5.4. $CWRN$ potentially varies from 13 to 18 thousand dollars per person per year (see the documentation for Equation 4.10). Variation in parameters of this function creates alternative shapes for the effect of unemployment rate on wage rate as we see in Figure 5.2. Note that wage rate cannot go below a minimum wage rate which is imposed by the parameter 5.6. When unemployment rate approaches 1, the wage rate approaches $CWRN \cdot CWRP_a$.

$$AWAR_t = CWRN \cdot \left( CWRP_a + \frac{(1 - CWRP_a)}{\left(\frac{AUNM_t}{0.05}\right)^{CWRP_b}} \right) \tag{5.4}$$

$$13 < CWRN < 18 \tag{5.5}$$

$$0.8 < CWRP_a < 1 \tag{5.6}$$

$$3 < CWRP_b < 6 \tag{5.7}$$

(5.8)

```
AWAR - INDICATED WAGE RATE (1000 USD PER PERSON PER YEAR)
CWRN - NORMAL WAGE RATE (1000 USD PER PERSON PER YEAR)
LWAR - WAGE RATE (1000 USD PER PERSON PER YEAR) [5.1]
CWRP - WAGE RATE PARAMETERS (UNITLESS)
AUNM - UNEMPLOYMENT RATE (UNITLESS) [5.9]
```

Unemployment rate is a straightforward ratio of total unemployment by total labor force:

$$AUNM_t = 1 - \frac{AEMP_t}{ALAF_t} \tag{5.9}$$

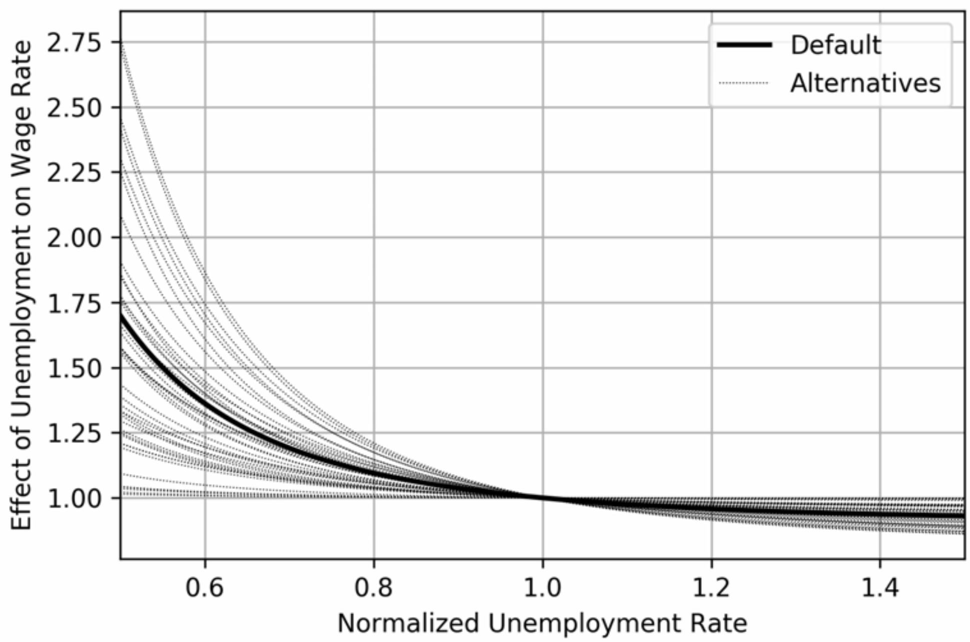


Figure 5.2: Effect of unemployment on wage rate (Equation 5.4)

`AUNM - UNEMPLOYMENT RATE (UNITLESS)`
`AEMP - EMPLOYMENT (PERSON)` [4.4]
`ALAF - LABOR FORCE (PERSON)` [5.10]

Total labor force is simply defined as the product of total population and the labor participation rate ($DPAR$), which is driven exogenously by historical data.

$$ALAF_t = APOP_t \cdot DPAR_t \tag{5.10}$$

`ALAF - LABOR FORCE (PERSON)`
`APOP - TOTAL POPULATION (PERSON)` [6.1]
`DPAR - LABOR PARTICIPATION RATE (UNITLESS)` [Table 8.1]

# Chapter 6

# Population

This module estimates the total human population within the LRG region. Figure 6.1 shows the causal structure of the module. Since population dynamics is not the focus of this study, a highly aggregated structure is designed to capture the dynamics.

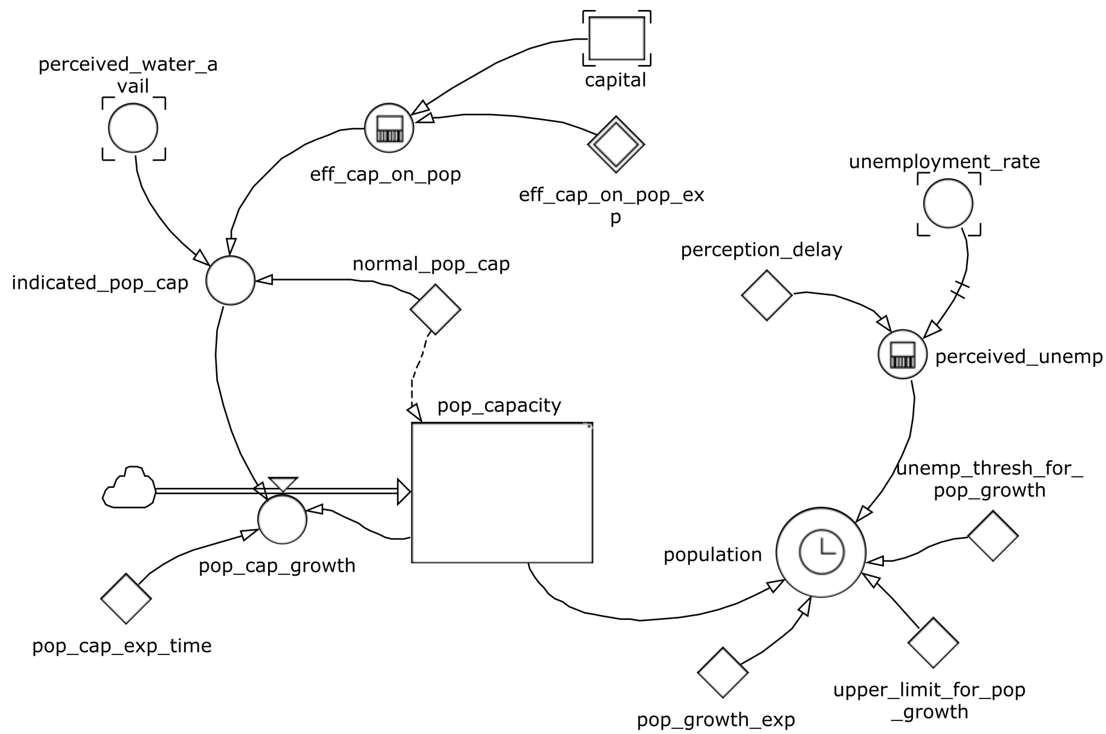


Figure 6.1: Causal structure of the population module

A logistic function is used to calculate population over time. Population growth rate in this function is negatively affected by unemployment rate. The significance of this effect is already tested by econometric analysis conducted by the authors.

$$APOP_t = \frac{LPCA_t}{1 + CPOP \cdot e^{(LUNM_t - CUTH)(t-t_0) \cdot CMPG}} \tag{6.1}$$

$$2 < CPOP < 3 \tag{6.2}$$

$$0.25 < CUTH < 0.35 \tag{6.3}$$

$$0.15 < CMPG < 0.25 \tag{6.4}$$

```
APOP - TOTAL POPULATION (PERSON)
LPCA - POPULATION CAPACITY (PERSON) [6.8]
CPOP - POPULATION GROWTH EXPONENT (UNITLESS)
CUTH - UNEMPLOYMENT THRESHOLD FOR POPULATION GROWTH (UNITLESS)
LUNM - PERCEIVED UNEMPLOYMENT RATE (UNITLESS) [6.5]
CMPG - UPPER LIMIT FOR POPULATION GROWTH RATE (PER YEAR)
```

Although simple, this function is powerful in reproducing many different modes of behavior. It is also tested for robustness to make sure that it can generate realistic behavior under extreme conditions. For example, if unemployment increases to a high rate (greater than the parameter $CUTH$), the population growth rate would become negative. Parameters of the function are estimated through calibration within the noted range above.

Perceived unemployment rate is simply the smooth average of unemployment rate over a time constant:

$$LUNM_t = LNUM_{t-dt} + \frac{AUNM_{t-dt} - LUNM_{t-dt}}{CPER} \cdot dt \tag{6.5}$$

$$0.01 < LUNM_0 < 0.10 \tag{6.6}$$

$$3 < CPER < 8 \tag{6.7}$$

```
LUNM - PERCEIVED UNEMPLOYMENT RATE (UNITLESS)
AUNM - UNEMPLOYMENT RATE (UNITLESS) [5.9]
CPER - PERCEPTION DELAY (YEAR)
```

The carrying capacity of the region for population ($LPCA$) can increase as infrastructure in the region expands. This may also be affected by availability of water resources. These effects multiply by normal population capacity and then will be realized with a delay to form the actual population capacity. Normal population capacity is considered to be a figure close to current population of the region (215 thousand people).

$$LPCA_t = LPCA_{t-dt} + \frac{APCA_{t-dt} - LPCA_{t-dt}}{CPGT} \cdot dt \tag{6.8}$$

$$200,000 < LPCA_0 < 250,000 \tag{6.9}$$

$$1 < CPGT < 5 \tag{6.10}$$

$$APCA_t = CPCA \cdot AGWA_t \cdot AECP_t \tag{6.11}$$

$$200,000 < CPCA < 250,000 \tag{6.12}$$

```
LPCA - POPULATION CAPACITY (PERSON)
APCA - INDICATED POPULATION CAPACITY (PERSON)
CPGT - POPULATION CAPACITY EXPANSION TIME (YEAR)
CPCA - NORMAL POPULATION CAPACITY (PERSON)
AGWA - GROUNDWATER AVAILABILITY (UNITLESS) [2.3]
AECP - EFFECT OF CAPITAL ON POPULATION CAPACITY (UNITLESS) [6.13]
```

Capital ($LCAP$) is used to drive the effect of infrastructure on population growth ($AECP$). The shape of this function along with some example alternative shapes that could be achieved with different parameter settings is shown in Figure 6.2.

$$AECP_t = \frac{1 - \dfrac{CECP_a}{1 + CECP_b \cdot (\dfrac{LCAP_t}{LCAP_0})^{CECP_c}}}{1 - \dfrac{CECP_a}{1 + CECP_b}} \tag{6.13}$$

$$0.25 < CECP_a < 0.75 \tag{6.14}$$

$$1 < CECP_b < 2 \tag{6.15}$$

$$1 < CECP_c < 2 \tag{6.16}$$

```
AECP - EFFECT OF CAPITAL ON POPULATION CAPACITY (UNITLESS)
CECP - PARAMETERS FOR EFFECT OF CAPITAL ON POPULATION CAPACITY (UNITLESS)
LCAP - CAPITAL (1000 USD) [4.22]
```

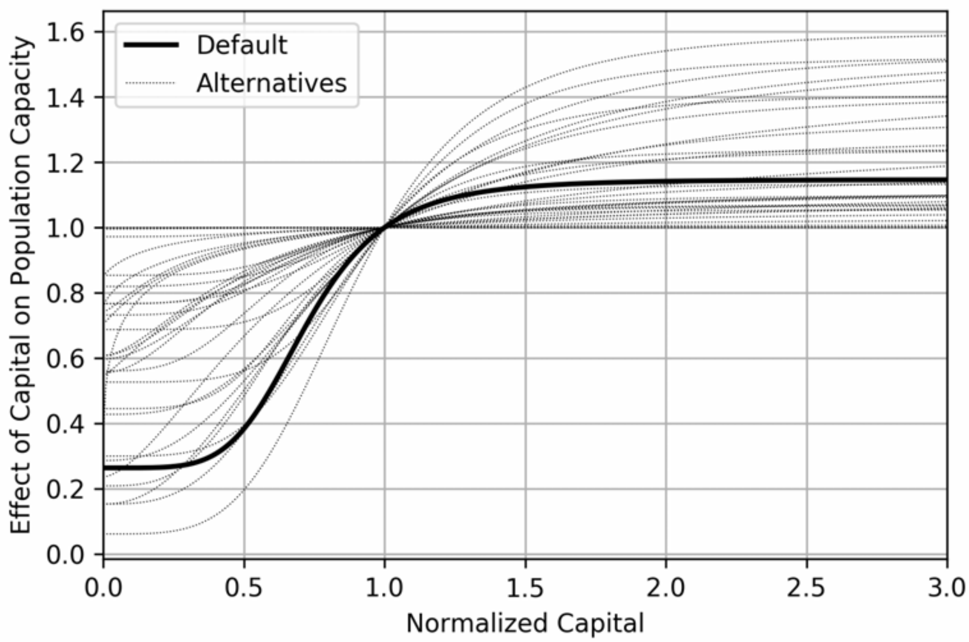


Figure 6.2: Effect of capital on population capacity (Equation 6.13)

# Chapter 7

# Labor Allocation

This module determines the allocation of labor between two major production sectors of the model: agriculture and non-agriculture. The causal structure of the module is shown in Figure 7.1.

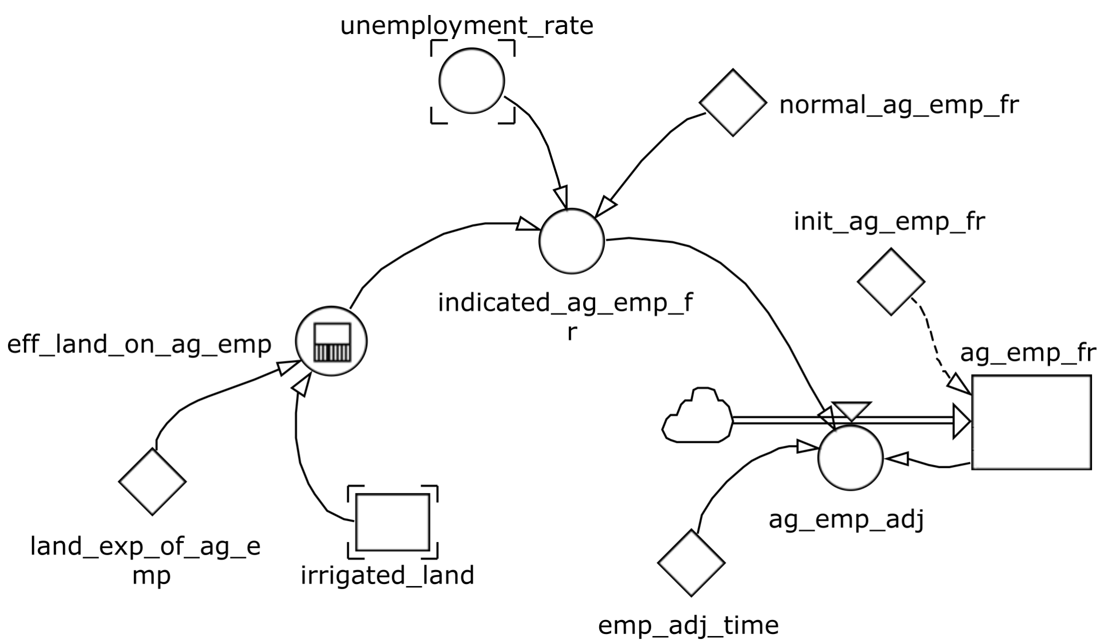


Figure 7.1: Causal structure of the labor allocation module

The agriculture labor fraction (`ag_emp_fr`) represents the portion of total employment within agriculture. The rest of the labor (1 - `ag_emp_fr`) will then be employed in the non-agriculture sector. Many residents in the LRG region work in both agriculture and non-agriculture sectors at the same time. Therefore, this agricutlure employment fraction could be considered as a fraction of total time that all employed individuals spend in agriculture in contrast to total time that is spent in the non-agriculture sector.

It is assumed that labor allocation occurs with a delay. Therefore, a smooth adjustment process is considered to take place with a time constant varying from 0 to 5 years.

The total number of jobs in 1969 has been estimated to be 26608, while farm jobs were 2665 (Bureau of Economic Analysis, 2018a). This yields a farm job fraction of about 10%. Assuming that agriculture employment follows the same figures, the initial agriculture employment fraction ($LALF_0$) could be within the range of (8–12) percent. The normal agriculture employment fraction ($CALF$ in Equation 7.5) should follow this same rule.

$$LALF_t = LALF_{t-dt} + \frac{AALF_{t-dt} - LALF_{t-dt}}{CALT} \cdot dt \tag{7.1}$$

$$0.08 < LALF_0 < 0.12 \tag{7.2}$$

$$0.1 < CALT < 5 \tag{7.3}$$

```
LALF - AG EMPLOYMENT FRACTION (UNITLESS)
AALF - INDICATED AG EMPLOYMENT FRACTION (UNITLESS) [7.4]
CALT - LABOR ADJUSTMENT TIME (YEAR)
```

It is assumed that unemployment rate and irrigated land are the two factors that affect the agriculture employment fraction. As unemployment rates increase, individuals will have more leisure time, allowing for more time spent in the agriculture sector. As more land is allocated to agriculture and gets irrigated, more labor will be needed to work in agriculture. Table 7.1 presents our econometric analysis supporting these assumptions. Results of the Ordinary Least Square regression reveals that the majority of variation in the agricutlure employment fraction ($Y$) could be explained by unemployment rate ($X_1$) and the amount of irrigated land ($X_2$)[1].

Nonlinear, slightly more complex relationships are used here in order to improve prediction capability of the model:

$$AALF_t = (CALF \cdot AELL_t)^{1-AUNM_t} \tag{7.4}$$

$$0.05 < CALF < 0.12 \tag{7.5}$$

```
AALF - INDICATED AG EMPLOYMENT FRACTION (UNITLESS)
CALF - NORMAL AG EMPLOYMENT FRACTION (UNITLESS)
AELL - EFFECT OF IRRIGATED LAND ON AG EMPLOYMENT (UNITLESS) [7.6]
AUNM - UNEMPLOYMENT RATE (UNITLESS) [5.9]
```

In this equation, employment rate appears as the power of the effect of irrigated land that is multiplied by the normal agriculture employment fraction. This formulation implies that higher levels of unemployment gives a lower weight to the pure economic drivers, which forces the labor to seek jobs in more primitive settings. In an extreme

[1]Actual data points of irrigated land are not sufficient for a reliable regression analysis as there are only 8 data points available for this variable. Therefore, interpolated estimations of irrigated land (as shown in Figure 3.2) are used instead of the actual data.

Table 7.1: OLS regression results for agriculture employment fraction

| | | | |
|---|---|---|---|
| Dep. Variable: | $Y$ | R-squared: | 0.660 |
| Model: | OLS | Adj. R-squared: | 0.630 |
| Method: | Least Squares | F-statistic: | 22.29 |
| Date: | Tue, 20 Feb 2018 | Prob (F-statistic): | 4.14 (-06) |
| Time: | 09:41:48 | Log-Likelihood: | 115.81 |
| No. Observations: | 26 | AIC: | -225.6 |
| Df Residuals: | 23 | BIC: | -211.9 |
| Df Model: | 2 | | |
| Covariance Type: | nonrobust | | |

| | coef | std err | t | P > t | [0.025 | 0.975] |
|---|---|---|---|---|---|---|
| Intercept | -0.0068 | 0.007 | -0.991 | 0.332 | -0.021 | 0.007 |
| $X_1$ | 0.1715 | 0.044 | 3.861 | 0.001 | 0.080 | 0.263 |
| $X_2$ | 4.505 (-07) | 9.12 (-08) | 4.941 | 0.000 | 2.62 (-07) | 6.39 (-07) |

| | | | |
|---|---|---|---|
| Omnibus: | 0.804 | Durbin-Watson: | 0.719 |
| Prob(Omnibus): | 0.669 | Jarque-Bera (JB): | 0.824 |
| Skew: | 0.352 | Prob(JB): | 0.662 |
| Kurtosis: | 2.484 | Cond. No. | 5.41 (+06) |

case, when the unemployment rate is 100%, the agriculture employment fraction goes to 1, regardless of the numerical value of irrigated land. This occurs because no other occupation other than agriculture will be available for the labor force. On the other hand, when unemployment is zero (or very small), the economic drivers (here, irrigated land) solely determine the fraction of labor who will be working in the agriculture sector. In other words, as unemployment rates decline, the labor allocation becomes closer and closer to its optimal level (in terms of economic productivity), whereas high unemployment rates force the labor to move and work in agriculture even though they may not be needed there. The latter reflects a case of suboptimal, low-productive workforce allocation caused by unemployment. In fact, higher unemployment rates distort the optimal allocation due to excess of available time for the individuals.

Finally, the effect of irrigated land on agriculture employment fraction is a simple nonlinear function that can be seen below:

$$AELL_t = \left(\frac{LIRL_t}{LIRL_0}\right)^{CLEL} \tag{7.6}$$

$$1 < CLEL < 4 \tag{7.7}$$

```
AELL - EFFECT OF IRRIGATED LAND ON AG EMPLOYMENT (UNITLESS)
LIRL - IRRIGATED LAND (ACRE) [3.9]
CLEL - LAND EXPONENT OF AG EMPLOYMENT (UNITLESS)
```

# Chapter 8

# Model Inputs

## 8.1 Data

The model uses several data sources for parameter estimation, confidence building tests, and driving exogenous variables. This section describes these sources and the variables that use them. Table 8.1 summarizes the information regarding data sources and exogenous variables. Please note that hydrology data are not listed here as they come from the New Mexico Dynamic Statewide Water Budget [NMWRRI (2018)].

Most of the data are directly retrieved from formal data sources as cited in Table 8.1. However, some data was not readily available. For these variables, the formula that is used to derive them are also listed in the "Definition / Source" column of Table 8.1.

The only variables that may need more clarification are agriculture and non-agriculture employment. Formal data for these variables do not exist. However, these are important variables that must be calculated and validated in the model. To resolve this issue, we have used the data for jobs in farm and non-farm sectors. From these variables, we can calculate the fraction of jobs that are available in each sector and use it as proxy for the ratio of employment in each sector. By multiplying these ratios by total employment, we can estimate the numbers of employment in each sector.

Table 8.1: Data sources, definitions, and estimation

| **Variable** | **Description** | **Definition / Source** |
|---|---|---|
| PPI farm | producer price index for farm production | (Federal Reserve Bank of St. Louis, 2018c) |
| PPI industry | producer price index for industrial production | (Federal Reserve Bank of St. Louis, 2018b) |
| CPI | consumer price index | (Federal Reserve Bank of St. Louis, 2018a) |
| income | total personal income | (Bureau of Economic Analysis, 2018c) |
| ag income | income in agriculture sector | (Bureau of Economic Analysis, 2018c) |

Continued on next page

Continued from previous page

| Variable | Description | Definition / Source |
|---|---|---|
| nonag income | income in non-agriculture sector | (Bureau of Economic Analysis, 2018c) |
| real ag income | inflation-adjusted income in ag sector | `100 * ag_income / PPI_farm` |
| real nonag income | inflation-adjusted income in nonag sector | `100 * nonag_income / PPI_industry` |
| real income | inflation-adjusted total income | `real_ag_income + real_nonag_income` |
| wages | total wages paid to labor | (Bureau of Economic Analysis, 2018c) |
| profit | any form of income other than wages | `income - wages` |
| real profit | inflation-adjusted profit | `profit * real_income / income` |
| real wages | inflation-adjusted wages | `real_income - real_profit` |
| population | population | (Bureau of Economic Analysis, 2018c) |
| labor force | people who are ready and willing to work | (U.S. Bureau of Labor Statistics, 2018) |
| employment | people who are employed | (U.S. Bureau of Labor Statistics, 2018) |
| unemployment rate | unemployment rate | (U.S. Bureau of Labor Statistics, 2018) |
| jobs | number of jobs available | (Bureau of Economic Analysis, 2018a,b) |
| ag jobs | available farming jobs | (Bureau of Economic Analysis, 2018a,b) |
| nonag jobs | available non-farming jobs | (Bureau of Economic Analysis, 2018a,b) |
| ag jobs fraction | ratio of ag jobs to total jobs | `ag_jobs / jobs` |
| ag employment | people employed in farming jobs | `employment * ag_jobs_fraction` |
| nonag employment | people employed in non-farming jobs | `employment * (1 - ag_jobs_fraction)` |
| participation | workforce participation | `labor_force / population` |
| wage rate | inflation-adjusted wage rate | `real_wages / employment` |

## 8.2 Parameters

Table 8.2: Model parameters and initial values sorted by module name

| Name | Module | Description | Min | Default | Max |
|---|---|---|---|---|---|
| CAIT | Ag Production | AG INCOME DELAY (YEAR) | 0 | 1 | 2 |
| CECI | Ag Production | CROP PATTERN INCOME ELASTICITY | 7 | 9 | 10 |
| CEWI | Ag Production | WATER AVAILABILITY EXPONENT OF AG INCOME (UNITLESS) | 0 | 1 | 3 |
| CGWQ | Ag Production | SENSITIVITY OF GROUNDWATER QUALITY FUNCTION (UNITLESS) | 0 | 2 | 3 |
| $CIAI_a$ | Ag Production | AG PRODUCTION FUNCTION EXPONENTS (UNITLESS) | 0.3 | 0.6 | 0.9 |
| $CIAI_b$ | Ag Production | AG PRODUCTION FUNCTION EXPONENTS (UNITLESS) | 0.3 | 0.6 | 0.9 |
| CIEL | Ag Production | AG INCOME EXPONENT OF IRRIGATED LAND (UNITLESS) | 0.1 | 0.28 | 0.3 |
| CIRL | Ag Production | MAXIMUM IRRIGATED LAND (ACRE) | 160000 | 167000 | 170000 |
| CIRT | Ag Production | LAND ADJUSTMENT TIME | 5 | 10 | 15 |
| CNAI | Ag Production | NORMAL AG INCOME (1000 USD PER YEAR) | 13000 | 47000 | 143000 |
| CPAI | Ag Production | PRECIPITATION EXPONENT OF AG INCOME (UNITLESS) | 0 | 0.8 | 2 |
| $LIRL_0$ | Ag Production | INITIAL IRRIGATED LAND (ACRE) | 110000 | 120000 | 130000 |
| CAWT | Ag Water Use | AG WATER DEMAND ADJUSTMENT TIME (YEAR) | 0.25 | 0.5 | 5 |
| CEDS | Ag Water Use | DEMAND EXPONENT OF SURFACE WATER SUPPLY (UNITLESS) | 0 | 1.8 | 2 |
| $CETW_a$ | Ag Water Use | EXPONENTS FOR EFFECT OF TEMPERATURE ON AG WATER DEMAND (UNITLESS) | 0.2 | 0.5 | 0.6 |
| $CETW_b$ | Ag Water Use | EXPONENTS FOR EFFECT OF TEMPERATURE ON AG WATER DEMAND (UNITLESS) | 4 | 5 | 6 |
| CGWE | Ag Water Use | FRACTION OF GROUNDWATER THAT IS EXTRACTABLE (UNITLESS) | 0.05 | 0.1 | 0.25 |
| CGWI | Ag Water Use | GROUNDWATER WITHDRAWAL CAPACITY DEVELOPMENT TIME (YEAR) | 0.25 | 1 | 2 |
| CGWO | Ag Water Use | GROUNDWATER WITHDRAWAL CAPACITY DECAY TIME (YEAR) | 2 | 6 | 10 |
| CIPR | Ag Water Use | NORMAL IRRIGATION PRECIPITATION (FT PER YEAR) | – | 2.3 | – |
| CMIP | Ag Water Use | MAXIMUM IRRIGATION PRECIPITATION (FT PER YEAR) | – | 4.64 | – |
| CNWD | Ag Water Use | NORMAL WATER DEMAND (KAF PER YEAR) | 500 | 540 | 600 |

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| Name | Module | Description | Min | Default | Max |
|---|---|---|---|---|---|
| CSWI | Ag Water Use | SURFACE WATER SUPPLY FRACTION (UNITLESS) | 0.4 | 0.55 | 0.7 |
| CTEM | Ag Water Use | NORMAL YEARLY TEMPERATURE (DEGREES) | 14 | 15 | 18 |
| $CWRQ_a$ | Ag Water Use | AG WATER REQUIREMENT PARAMETER (FT PER YEAR) | 3 | 6.5 | 8 |
| $CWRQ_b$ | Ag Water Use | AG WATER REQUIREMENT PARAMETER (FT PER YEAR) | 3 | 3.9 | 8 |
| CWRM | Ag Water Use | AG WATER REQUIREMENT MULTIPLIER (YEAR PER FT) | 0 | 0.25 | 1 |
| CWSA | Ag Water Use | WATER SUPPLY PERCEPTION TIME | 1 | 5 | 8 |
| $LGWC_0$ | Ag Water Use | GROUNDWATER WITHDRAWAL CAPACITY (KAF PER YEAR) | 25 | 50 | 100 |
| CCOE | Hydrology | CONVEYANCE EFFICIENCY (UNITLESS) | 0.4 | 0.52 | 0.6 |
| CCOF | Hydrology | CONVEYANCE LOSS FRACTION (UNITLESS) | 0.2 | 0.33 | 0.4 |
| CDRD | Hydrology | DRAINAGE DELAY (YEAR) | 0.04 | 0.06 | 0.1 |
| $CERI_a$ | Hydrology | EXPONENT FOR RECHARGE INDEX (UNITLESS) | 3 | 5 | 8 |
| $CERI_b$ | Hydrology | EXPONENT FOR RECHARGE INDEX (UNITLESS) | 3 | 5 | 8 |
| $CETE_a$ | Hydrology | TEMPERATURE EXPONENT (UNITLESS) | 0 | 0.1 | 1 |
| $CETE_b$ | Hydrology | TEMPERATURE EXPONENT (UNITLESS) | 2 | 2.31 | 5 |
| CETR | Hydrology | COMMON EVAPOTRANSPIRATION RATE (FT PER YEAR) | 1 | 2 | 4 |
| $CGLE_a$ | Hydrology | GROUNDWATER LEAKAGE EXPONENT CONSTANT (UNITLESS) | 1 | 2 | 5 |
| $CGLE_b$ | Hydrology | GROUNDWATER LEAKAGE EXPONENT CONSTANT (UNITLESS) | 1 | 2 | 5 |
| $CINE_a$ | Hydrology | INFILTRATION EXPONENT (UNITLESS) | 0 | 0.3 | 1 |
| $CINE_b$ | Hydrology | INFILTRATION EXPONENT (UNITLESS) | 3 | 5 | 8 |
| CINF | Hydrology | INFILTRATION FRACTION (PER YEAR) | 0.05 | 0.1 | 0.2 |
| CIRF | Hydrology | IRRIGATION RETURN FRACTION | 0.7 | 0.82 | 0.9 |
| CISC | Hydrology | IRRIGATED SOIL SATURATION CAPACITY (UNITLESS) | 0.3 | 0.5 | 0.5 |
| CLTD | Hydrology | LEAKAGE THRESHOLD FRACTION (UNITLESS) | 0.02 | 0.05 | 0.06 |
| CNAF | Hydrology | NON AGRICULTURE WATER RETURN FRACTION (UNITLESS) | 0.1 | 0.37 | 0.4 |

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| Name | Module | Description | Min | Default | Max |
|---|---|---|---|---|---|
| CNEF | Hydrology | NON-IRRIGATED LAND ET FRACTION (UNITLESS) | 0.9 | 0.945 | 0.98 |
| CNIS | Hydrology | NON-IRRIGATED SOIL SATURATION CAPACITY (UNITLESS) | 0.25 | 0.36 | 0.45 |
| CNRE | Hydrology | NON-IRRIGATED LAND RECHARGE FRACTION (UNITLESS) | 0.01 | 0.03 | 0.1 |
| CNRF | Hydrology | NON-IRRIGATED LAND RUNOFF FRACTION (UNITLESS) | 0.1 | 0.32 | 0.8 |
| CREF | Hydrology | RECHARGE FRACTION (UNITLESS) | 0.1 | 0.15 | 0.2 |
| CREP | Hydrology | SOIL RESIDENTIAL POINT (UNITLESS) | 0.01 | 0.01 | 0.05 |
| CREP | Hydrology | EVAPOTRANSPIRATION DELAY (YEAR) | 0.06 | 0.06 | 0.1 |
| CREV | Hydrology | RIVER EVAPORATION FRACTION (PER YEAR) | 0.05 | 0.05 | 0.15 |
| CRLF | Hydrology | RIVER LEAKAGE FRACTION (UNITLESS) | 0 | 0.01 | 0.1 |
| CSDE | Hydrology | SOIL DEPTH (FT) | 2 | 3 | 4 |
| CSOF | Hydrology | SURFACE OUTFLOW FRACTION (PER YEAR) | 0.8 | 0.9 | 0.95 |
| $LGWV_0$ | Hydrology | GROUNDWATER STORAGE (KAF) | 600000 | 651000 | 700000 |
| $LIRM_0$ | Hydrology | IRRIGATED SOIL MOISTURE | 100 | 180 | 300 |
| $LNIM_0$ | Hydrology | NON-IRRIGATED SOIL MOISTURE (KAF) | 2000 | 2600 | 4000 |
| $LRES_0$ | Hydrology | RESERVOIR STORAGE (KAF) | – | 0 | – |
| LSWS _0 | Hydrology | SURFACE STREAM SYSTEM STORAGE (KAF) | 150 | 330 | 700 |
| CALF | Labor | NORMAL AG EMPLOYMENT FRACTION (UNITLESS) | 0.05 | 0.06 | 0.12 |
| CALT | Labor | LABOR ADJUSTMENT TIME (YEAR) | 0.1 | 0.25 | 5 |
| CLEL | Labor | LAND EXPONENT OF AG EMPLOYMENT (UNITLESS) | 1 | 1.5 | 4 |
| $LALF_0$ | Labor | AG EMPLOYMENT FRACTION (UNITLESS) | 0.08 | 0.08 | 0.12 |
| CCAL | Nonag Production | CAPITAL LIFE (YEAR) | 5 | 8 | 15 |
| CCEL | Nonag Production | CAPITAL EXPONENT OF LABORD DEMAND (UNITLESS) | 0.1 | 0.5 | 1 |
| CCFD | Nonag Production | CAPITAL FORMATION DELAY (YEAR) | 2 | 3.38 | 5 |
| $CEAL_a$ | Nonag Production | EXPONENTS OF EFFECT OF AG ON LABOR DEMAND (UNITLESS) | 1 | 3 | 5 |
| $CEAL_b$ | Nonag Production | EXPONENTS OF EFFECT OF AG ON LABOR DEMAND (UNITLESS) | 0.1 | 0.5 | 1 |
| CINV | Nonag Production | INVESTMENT FRACTION (UNITLESS) | 0 | 0.08 | 1 |

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| Name | Module | Description | Min | Default | Max |
|---|---|---|---|---|---|
| CLAD | Nonag Production | BASE LABOR DEMAND (PERSON) | 15000 | 21247 | 27000 |
| CNAT | Nonag Production | NONAG TECHNOLOGY MULTIPLIER (1000 USD PER YEAR) | 500000 | 723434.4 | 800000 |
| $CNIP_a$ | Nonag Production | NONAG INCOME PARAMETERS (UNITLESS) | 0.3 | 0.9 | 0.9 |
| $CNIP_b$ | Nonag Production | NONAG INCOME PARAMETERS (UNITLESS) | 0.3 | 0.34 | 0.9 |
| CSIG | Nonag Production | SENSITIVITY OF INVESTMENT TO WATER AVAILABILITY (UNITLESS) | 0 | 0.5 | 2 |
| CTAL | Nonag Production | TIME TO SMOOTH EFFECT OF SHARE OF AG IN ECONOMY ON LABOR DEMAND (YEAR) | 1 | 2.5 | 5 |
| CTSW | Nonag Production | TIME TO SMOOTH WAGE RATE (YEAR) | 1 | 2 | 5 |
| CWEL | Nonag Production | WAGE EXPONENT OF LABOR DEMAND (UNITLESS) | 1 | 4 | 5 |
| $LCAP_0$ | Nonag Production | CAPITAL (1000 USD) | 100000 | 150000 | 300000 |
| $LCIP_0$ | Nonag Production | CAPITAL IN PROGRESS (1000 USD) | 10000 | 54500 | 100000 |
| CEIN | Nonag Water Use | EXPONENT FOR EFFECT OF INCOME ON WATER DEMAND (UNITLESS) | 0 | 0.378 | 1 |
| $CEMN_a$ | Nonag Water Use | EXPONENTS FOR EFFECT OF TEMPERATURE ON NONAG WATER DEMAND (UNITLESS) | 2 | 2.66 | 3 |
| $CEMN_b$ | Nonag Water Use | EXPONENTS FOR EFFECT OF TEMPERATURE ON NONAG WATER DEMAND (UNITLESS) | 3 | 5 | 5 |
| $CETN_a$ | Nonag Water Use | WATER USE TECHNOLOGY EXPONENTS (UNITLESS) | 0.2 | 0.5 | 1 |
| $CETN_b$ | Nonag Water Use | WATER USE TECHNOLOGY EXPONENTS (UNITLESS) | 1 | 2 | 5 |
| $CETN_c$ | Nonag Water Use | WATER USE TECHNOLOGY EXPONENTS (UNITLESS) | 0 | 0.15 | 1 |
| CGWC | Nonag Water Use | GROUNDWATER STORAGE COVERAGE TIME (YEAR) | 100 | 300 | 500 |
| CNAW | Nonag Water Use | NORMAL NON-AGRICULTURE WATER DEMAND PER CAPITA (KAF PER YEAR PER PERSON) | 0.0001 | 0.00025 | 0.0004 |
| $CPWA_a$ | Nonag Water Use | WATER AVAILABILITY EXPONENTS (UNITLESS) | 0 | 1 | 1 |
| $CPWA_b$ | Nonag Water Use | WATER AVAILABILITY EXPONENTS (UNITLESS) | 0 | 0.5 | 1 |
| CWAE | Nonag Water Use | WATER AVAILABILITY EXPONENT OF WATER DEMAND (UNITLESS) | 0 | 0.5 | 1 |

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| Name | Module | Description | Min | Default | Max |
|---|---|---|---|---|---|
| $CECP_a$ | Population | PARAMETERS FOR EFFECT OF CAPITAL ON POPULATION CAPACITY (UNITLESS) | 0.25 | 0.5 | 0.75 |
| $CECP_b$ | Population | PARAMETERS FOR EFFECT OF CAPITAL ON POPULATION CAPACITY (UNITLESS) | 1 | 1.475 | 2 |
| $CECP_c$ | Population | PARAMETERS FOR EFFECT OF CAPITAL ON POPULATION CAPACITY (UNITLESS) | 1 | 1.3 | 2 |
| CMPG | Population | UPPER LIMIT FOR POPULATION GROWTH RATE (PER YEAR) | 0.15 | 0.2 | 0.25 |
| CPCA | Population | NORMAL POPULATION CAPACITY (PERSON) | 200000 | 233378 | 250000 |
| CPER | Population | PERCEPTION DELAY (YEAR) | 3 | 5 | 8 |
| CPGT | Population | POPULATION CAPACITY EXPANSION TIME (YEAR) | 1 | 1 | 5 |
| CPOP | Population | POPULATION GROWTH EXPONENT (UNITLESS) | 2 | 2.37 | 3 |
| CUTH | Population | UNEMPLOYMENT THRESHOLD FOR POPULATION GROWTH (UNITLESS) | 0.25 | 0.291 | 0.35 |
| $LPCA_0$ | Population | POPULATION CAPACITY (PERSON) | 200000 | 236288 | 250000 |
| CWAR | Wage | WAGE RATE ADJUSTMENT TIME (YEAR) | 1 | 4 | 5 |
| CWRN | Wage | NORMAL WAGE RATE (1000 USD PER PERSON PER YEAR) | 13 | 15.1 | 18 |
| $CWRP_a$ | Wage | WAGE RATE PARAMETERS (UNITLESS) | 0.8 | 0.9 | 1 |
| $CWRP_b$ | Wage | WAGE RATE PARAMETERS (UNITLESS) | 3 | 5 | 6 |
| $LWAR_0$ | Wage | WAGE RATE (1000 USD PER PERSON PER YEAR) | 13 | 13.9 | 18 |

## 8.3 Scenarios

As discussed earlier, for historical periods, exogenous drivers are usually supplied by actual data. This however, does not work for the future periods of simulations. Some assumptions must be made for how these drivers will change in the future. This section explains how each exogenous variable for the future scenarios are designed.

### 8.3.1 Workforce participation

Workforce participation changes over time but this variable is outside of the endogenous model boundary and is inserted as an exogenous driver. The historical part of the simulation is fed with the available data. For future scenario projections, this variable is held constant at it last data point i.e. 44%. Different future dynamic behaviors such as step rise, decline, cyclical change with a constant, increasing, decreasing mean, and different amplitudes and frequencies could be also tested.

### 8.3.2 Temperature

The default (base case) future scenario for the "temperature" variable is derived from the UKMO climate model, which is one of four climate models used by the NMDSWB to provide future estimates (through year 2099) of temperature, precipitation, and surface water stream flows that cross into New Mexico's state boundary. These climate models are derived from Global Circulation Model runs that span three different greenhouse gas emissions scenarios (NMWRRI, 2018). NCAR is a low emissions scenario, UKMO is a moderate emissions scenario, and MPIM and GFDL are high emissions scenarios that have been dynamically downscaled in New Mexico for use by researchers involved in the Statewide Water Assessment (NMWRRI, 2018). Alternative scenarios for the "temperature" variable in this model include those driven from the GFDL, MPIM, and NCAR climate models. In general, the higher emissions scenario climate models predict higher temperatures than the lower emissions scenario climate models.

### 8.3.3 Precipitation

Similar to the temperature, future scenarios of precipitation is fed by outputs of the climate models (UKMO, GFDL, MPIM, and NCAR). The UKMO's data is used for the default case. This could easily be switched to other cases by the end user. Precipitation estimates between the different climate models are highly variable. Lower emission scenario climate models do not necessarily predict more precipitation than higher emission scenario climate models.

### 8.3.4 Irrigation precipitation

Future scenarios are available for precipitation, but not for irrigation precipitation[1]. Thus, we try to estimate irrigation precipitation based upon precipitation scenarios. Historically, irrigation precipitation has been about 92% to 100% of total precipitation. As Figure 8.1 shows, historically, there is a cyclical trend in irrigation precipitation to total precipitation ratio. Such relationship could be reproduced by a sine wave function as below:

$$y = 0.96 + 0.035 \sin\left(0.24\pi(t - t_0) + 6\right) \tag{8.1}$$

Here, $y$ represents the ratio of irrigation precipitation to total irrigation and $t$ is simulation time. Figure 8.1 compares the output of this function with actual data.

Then, $y$ is multiplied by the precipitation of a given future scenario option to generate the corresponding scenarios for irrigation precipitation. Using different parameters for the $y$ function, we can test even more variations of irrigation precipitation.

[1] For explanation on how these are different variables see Section 1.2.

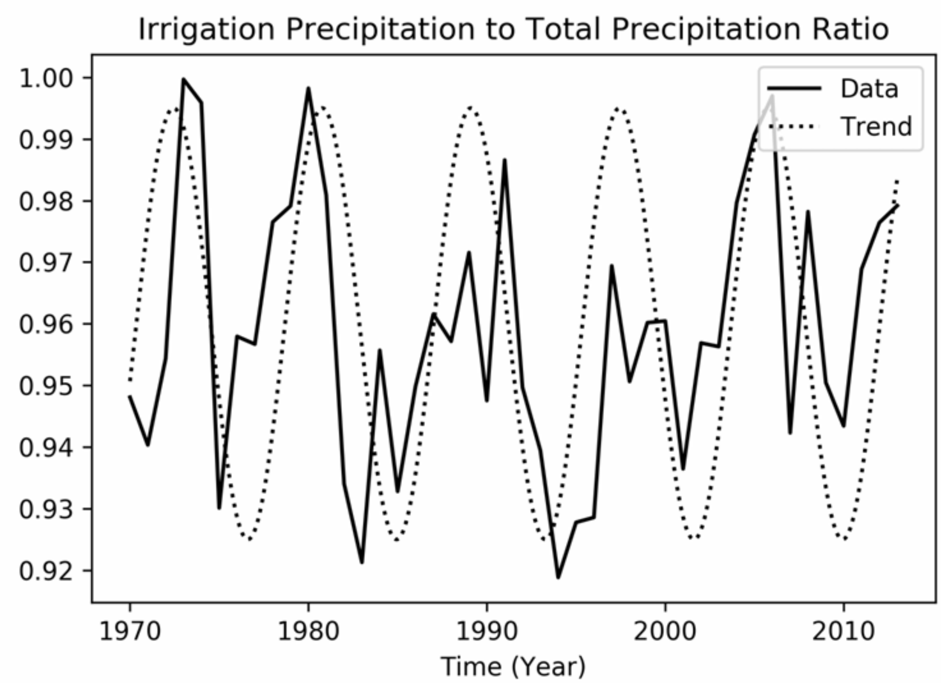


Figure 8.1: Estimated vs actual irrigation precipitation to total precipitation ratio

### 8.3.5 Surface water inflow

Surface water inflow is another exogenous variable of the model that is driven by historical data. Future dynamic behavior of this variable comes from various climate models that are available (UKMO, GFDL, MPIM, and NCAR). UKMO estimates are used for the default simulation. Much like the different precipitation estimates associated with these climate models, the stream flow estimates that cross into the state of New Mexico are also variable. Since surface water inflow into the LRG region predominantly comes via the Rio Grande River from Caballo reservoir releases, the surface water inflow estimates used in this model that are associated with the four different climate models are also influenced by the NMDSWB model structure.

# Chapter 9

# Model Outputs

One of the confidence building tests for any modeling effort is to see if the model can replicate observed behavior of the real system. Here, 14 variables of the model are selected as representative of the overall behavior of the model to be tested against historical data. In this selection, 7 variables are from the hydrology and water use modules and 7 variables are from the rest of the model, thus paying equal attention to water and non-water (socioeconomic) modules. Variables from the water modules include Groundwater Storage, Runoff, Crop ET, Non-Agriculture Return Flow, Non-Agriculture Groundwater Withdrawals, Agriculture Groundwater Withdrawals, and Agriculture Surface Water Withdrawals. Socioeconomic variables are Agriculture Income, Irrigated Land, Agriculture Employment, Non-Agriculture Income, Non-Agriculture Employment, Wages, and Population.

To evaluate the model's capability in replicating historical behavior, some statistics are needed. Sterman (1984) recommends Theil's inequality statistics to be used for system dynamics models as it provides not only the quality of fit, but also indicates sources of bias in a model's outputs. Theil's inequality coefficient ($U$) is an index from 0 to 1 where 0 indicates perfect fit of a model's output to actual data while 1 represents absolute inequality between them (Bliemel, 1973; Leuthold, 1975). Theil also breaks down MSE (Mean Squared Error) to three components: error caused by unequal mean ($U^M$), error caused by unequal variance ($U^S$), and error caused by unequal covariance ($U^C$). Sum of these components equals to 1, meaning that each represents a fraction of MSE. Sterman (1984) argues that system dynamics models should try to minimize $U$, $U^M$, and $U^S$ (thus, maximizing $U^C$). Small $U$ means little deviation of a model's output from the actual points of data. Small $U^M$ means that among the deviations, little could be attributed to systematic bias. And, small $U^S$ means that the model's output and actual data probably have a similar trend. Therefore, a small $U$ and a large $U^C$ indicate that the model's output are reproducing the overall mean and trend of the data while matching the data points reasonably well.

Table 9.1 shows the Theil's statistics for the selected model's outputs. For most of the variables in the table, $U$ is below 10%. In fact, only 4 variables exist with a $U$ greater than 9%. These are Runoff, Agriculture Groundwater Withdrawals, Agriculture Surface Water Withdrawals, and Agriculture Income.

Table 9.1: Theil's inequality statistics for the model outputs

| Variables | $U$ | $U^M$ | $U^S$ | $U^C$ |
|---|---|---|---|---|
| Groundwater Storage[1] | 0.0003 | 0.0063 | 0.1434 | 0.8503 |
| Runoff[7] | 0.3706 | 0.0514 | 0.0169 | 0.9316 |
| Crop ET[7] | 0.0898 | 0.0118 | 0.1160 | 0.8722 |
| Non-Agriculture Return Flow[7] | 0.0528 | 0.0483 | 0.0037 | 0.9480 |
| Non-Agriculture Groundwater Withdrawals[2] | 0.0557 | 0.0523 | 0.0034 | 0.9443 |
| Agriculture Groundwater Withdrawals[8] | 0.4094 | 0.0049 | 0.0117 | 0.9834 |
| Agriculture Surface Water Withdrawals[8] | 0.2261 | 0.2121 | 0.0556 | 0.7322 |
| Agriculture Income | 0.3283 | 0.0013 | 0.0101 | 0.9886 |
| Irrigated Land[8] | 0.0423 | 0.0025 | 0.0117 | 0.9858 |
| Agriculture Employment | 0.0684 | 0.1099 | 0.0969 | 0.7932 |
| Non-Agriculture Income | 0.0611 | 0.0115 | 0.0191 | 0.9694 |
| Non-Agriculture Employment | 0.0259 | 0.0123 | 0.0037 | 0.9840 |
| Wages | 0.0764 | 0.3277 | 0.0210 | 0.6513 |
| Population | 0.0172 | 0.0002 | 0.0039 | 0.9959 |

Among these variables, Runoff is compared with NMDSWB estimations rather than actual data[7]. Therefore, point-by-point estimation error may not be very problematic. What matters the most here is to prediction of trend which is satisfactory as majority of the bias is accumulated in $U^C$ (93%).

Large bias for the withdrawals variables is mainly due to the fact that there are only 8 data points available for them. Even these variables, however, have large $U^C$, and very small $U^S$ indicating that the general trend of the data is captured reasonably well. $U^M$ for the agriculture surface water withdrawals is about 21%. This shows that there might be a vertical gap between the simulation and actual data that could be probably resolved by a small adjustment in parameters – this is left for the next round of calibration.

Finally, agriculture income also presents a large $U$ that could be due to the extreme irregularities of the data (see Figure 9.2). The irregularities could be due to the crop market volatility. Since the crop market dynamics are out of the model's boundary their effect cannot be captured. Thus, the model's inability to explain all the variations in the agriculture income may not be a weakness of the model as we are interested only on internal drivers of the system's behavior, at least at this initial stage of development[3].

Graphical representations of the model's goodness of fit are shown in Figures 9.1 (water variables) and 9.2 (socioeconomic variables). Note that 2 variables from the Table 9.1 are omitted only because of the page limit.

[7]Actual data for this variable is not directly available. Hence, the estimations produced by the New Mexico Dynamic Statewide Water Budget (NMDSWB) (NMWRRI, 2018) is used for the validation purposes.

[8]Only 8 data points are available for this variable.

[3]Addition of crop market forces to the model could be an interesting direction to take. Depending on the available resources, we may tackle this issue in our next steps.

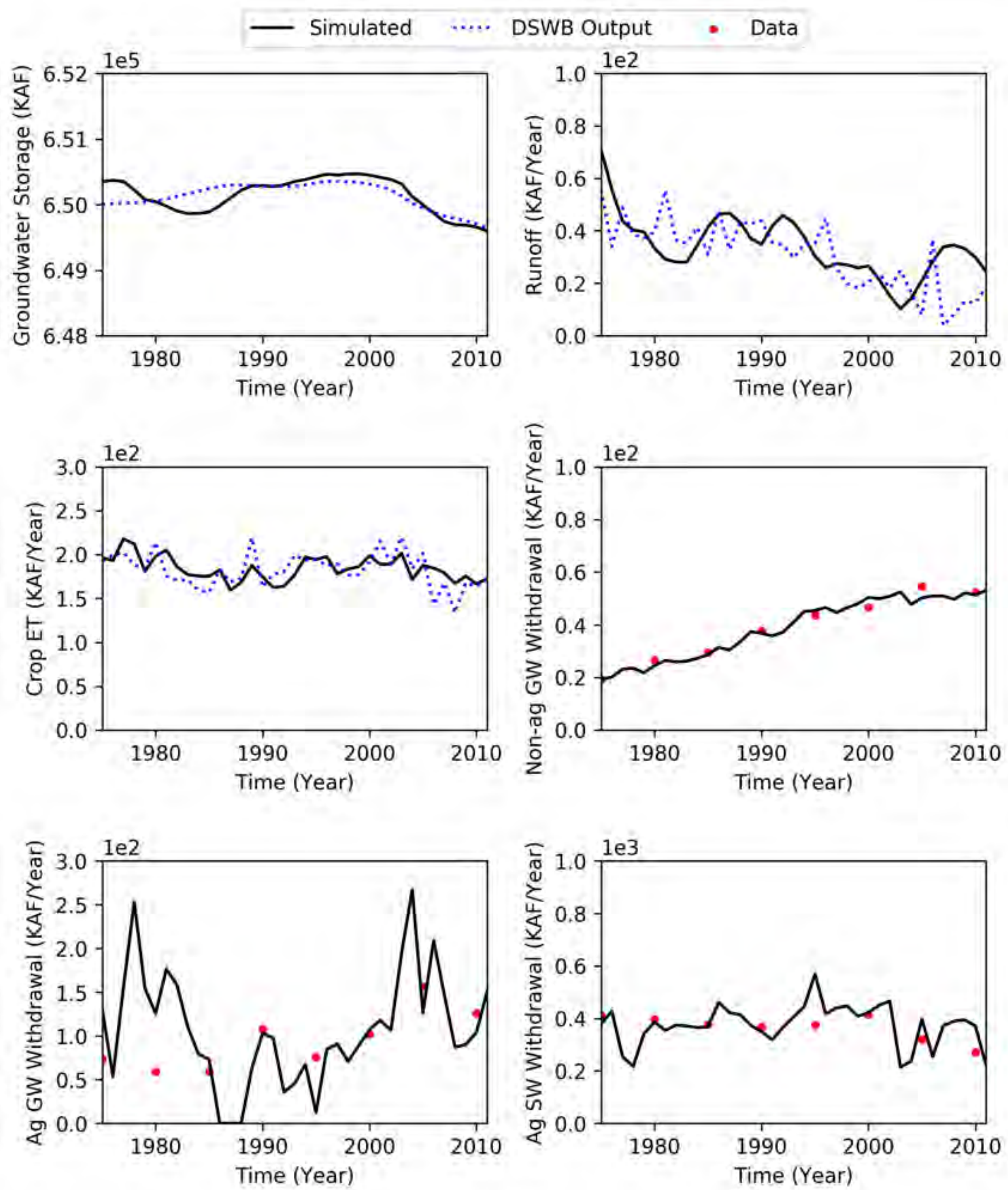


Figure 9.1: Behavior reproduction results (water variables)

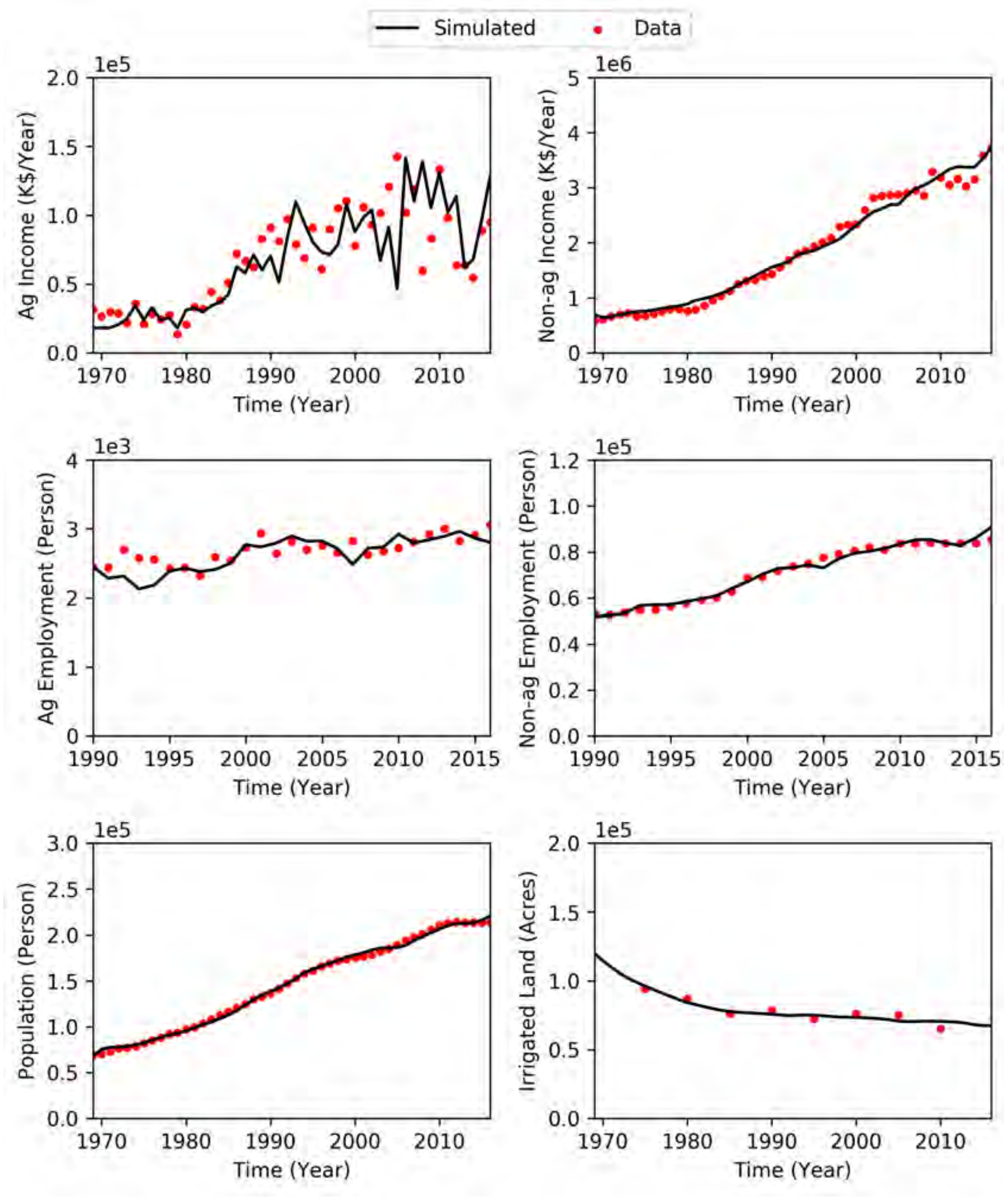


Figure 9.2: Behavior reproduction results (socioeconomic variables)

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