Systems Archetypes and Generic Structures for Reservoir Management

Appendix

Simulation Equations

Stocks and Flows

Variable	Abbreviation	Formulations and Comments	Units
Reservoir Storage	R	$R(t) = R(0) + \int_0^t (F(x) - S(x))dx;\ R(0) = C(0)$	MCM

Reservoir storage, *R*, represents the total amount of water stored in reservoirs or other storage infrastructures. This amount increases by recharging rate, *F*, from precipitation, water transfers, or other means. According to the water demand, *D*, water will be released as water supply, *S*. *R* cannot exceed the storage capacity, *C*. The initial value for stored water is assumed to be equal to the initial storage capacity, *C0*. All the storage infrastructures are assumed to be full in $t{=}0$.

Variable	Abbreviation	Formulations and Comments	Units
Recharging Rate	F	$F = \min(S + \frac{(C(t) - R(t))}{d}, \frac{w}{d})$	MCM/Year

Recharging rate is the amount of water that annually inflows to reservoir storage infrastructures. Different forces control this inflow, including the amount of free capacity in storages in a year, $\frac{C(t)-R(t)}{rd}$, the annual amount of water released as supply in each time step, *S*, and the maximum available amount of surface water (carrying capacity) that can recharge the storages in each year, $\frac{w}{d}$.

Variable	Abbreviation	Formulations and Comments	Units
Water Supply	S	$S = min\ (D, \frac{R(t)}{k})$	MCM/Year

Water supply, *S*, in each time step equals to water demand, *D*. However, it cannot be more than total water stored in supply infrastructures, *R*, with a certain capacity, *C*. If demand exceeds the stored water, we can only supply as much as accumulated in the reservoir storage, *R*. The unfulfilled demand becomes water shortage.

Variable	Abbreviation	Formulations and Comments	Units
Storage Capacity	C	$C(t) = C(0) + \int_0^t T(x)\,dx;\ C(0) = 150$	MCM

The storage capacity, *C*, includes a range of infrastructure from big reservoirs to small water tanks. Storage capacity imposes the maximum possible water accumulation and therefore the cap for water supply in the system. When the need for supply exceeds the current storage capacity, public pressure requires additional capacity, *J*. Storage capacity can increase up to the total available surface water or carrying capacity, *w*, within the boundaries of system.

Construction Rate	T	$T = DELAY3(J, j)$	MCM/Year

The rate of change in storage capacity or construction rate is formulated as third-order delay of required additional capacity, *J*.

Population	P	$P(t) = P(0) + \int_0^t M(x)dx\,;\; P(0) = 100{,}000$	Person

The stock of population, *P*, accumulates the population net changes, *M*, over time. The initial population, *P0*, is assumed to be one million people.

Population Net Change	M	$M = P(t) * G/c$	Person/Year

In this generic model, population net changes, *M*, is only impacted by the socioeconomic growth, *G*, which in turn is derived from water availability, *A*. Other forces that govern population in real world are excluded here. *M* adds to total population when *G* is positive and decreases population when *G* is negative.

Vulnerability	V	$V(t) = V(0) + \int_0^t N(x)dx\,;\; V(0) = 0$	Dimensionless

The reservoir effect states that the construction of the reservoirs reduces the incentive for adaptive actions at individual or community levels. The lack of incentive for adaptive actions reduces the resiliency of the system against the negative impacts of water shortages during severe droughts. Excessive water supply increases dependency on water resources and makes the population more vulnerable to extreme water shortages. Vulnerability in the start time, *V0*, is assumed to be zero. That means the reservoir effect on the system is zero at $t=0$.

Vulnerability Change	N	$N = MAX\left(\frac{Q - V(t)}{a}, 0\right) + \min\left(\frac{Q - V(t)}{b}, 0\right)$	Dimensionless

The rate of change in vulnerability, *N*, changes by reservoir effect. When water availability is one or higher, people become more dependent. This extra vulnerability becomes a new norm after few years, *a*. However, when the society wants to adjust itself to drought situation, water dependency declines with a slower rate. This effect is known as stickiness in economics literature. Therefore, the rate of change in vulnerability is different when it is growing or decreasing. When $Q>V(t)$ the delay is *a* and when $Q<V(t)$ delay becomes *b*. *b* is always greater than *a*.

Auxiliary Variables

Variable	Abbreviation	Formulations and Comments	Units
Economic Damage	E	$E = H * (1 + V(t))$	Million Dollar

In this hypothetical model, the system confronts a certain extent of economic damage, *1+V(t)*, for each percentage of shortage ratio, *H*. The total economic damages also depends on the vulnerability of the society in each time step, *V(t)*. When *V(t)* increases or decreases, the economic damage linearly changes accordingly. Economic damage is normalized here. The absolute amount of damage can be acquired if *H* multiplied by an average dollar amount of each percentage of shortage ratio.

Potential Addition to Capacity	K	$K = MAX\ (0\ , w - C(t))$	MCM

The remaining amount of surface water that has not been stored yet. Potential addition to capacity dictates the maximum capacity of new infrastructures.

Public Pressure	L	$L = E * p$	Pressure

For each percentage of normalized economic damage during shortage period, presumably the society will put an average pressure on government to build more infrastructure for further water supply. Therefore the total pressure is a function of economic damage. This function is assumed to be linear.

Required Additional Capacity	J	$J = \text{IF THEN ELSE}\ (\text{L} < \text{t}, 0, \text{K/h})$	MCM/Year

We assumed that if public pressure, *L*, exceeds a normal threshold for a society, *t*, the government would try to resolve the source of dissatisfaction, water shortage. To do so, the government increases water supply by constructing more capacity for storage. However, there is a natural limit for expansion of infrastructures. This limit is addressed in the potential addition to capacity, *K*. When *K* cannot support more water, *J* will be zero as well.

Socioeconomic Growth	G	$G = SMOOTH\ (\ \ln(A + f)^{g}\ \ , e\ )$	Dimensionless

Socioeconomic growth, *G*, is a function water availability, *A*. This function is not linear. This nonlinearity is captured by the log normal function. When water is abundant the *G* will be positive and during severe water shortages *G* will be negative. The economy grows even during small tolerable water shortage, *f*. The rate of socioeconomic growth varies in different societies. This rate is addressed by the exponent *g*. The higher the growth exponent, the faster the society changes. The smooth function is used because there is an information delay between changes in water availability and changes in socioeconomic growth.

Vulnerability from Reservoir Effect	Q	$Q = v * \ln(A)$	Dimensionless

When water becomes abundant people become more dependent on water. Therefore, Q is a function of water availability. This function is nonlinear. This rate of vulnerability change, v, varies in different societies. The greater the vulnerability multiplier, v, the higher the rate of changes in vulnerability.

Water Availability	A	$A = \frac{R(t)}{i} * D$	Dimensionless

Water availability is the ratio of available water stored in reservoirs, *R*, over the total demand, *D*. When this ratio is below one, water shortage takes place. In that case, there is not enough water in the reservoirs to meet the demand. In this model, water availability is the main input for calculating socioeconomic growth and vulnerability.

Water Demand	D	$D = z * P(t) * u$	MCM/Year

Water demand is calculated based on the average demand per person per year, *z*, multiplied by the total population, *P*. The total demand is the sum of individual demands. Constant *u* is used to change the units from liter to MCM.

Water Shortage	H	$H = MAX(0, 1 - A)$	Dimensionless

When water availability, *A*, is below one, water shortage takes place. In that case, there is not enough water in the reservoirs to meet the demand. Water shortage is one when there is no water in the system (*A=0*); and it is zero when *A* equals to or is greater than one.

Constants

Variable	Abbreviation	Formulations and Comments	Units
Annual Storage	i	1	Year

To calculate water availability, *w*, water demand should be compared to the annual water stored in the reservoir. Constant *i* adjusts the unit consistency in calculation of *w*.

Carrying Capacity	w	500	MCM

The total amount of surface water that can be stored and consumed later. This amount depends on the boundaries of a system. If water transfer from other resources that are miles away becomes an option, this amount increases. However, at the end, there still exists a maximum amount that can be utilized in a system.

Construction Delay	j	4	Year

The average delay in construction of different sorts of water storage facilities, including reservoirs, dams, water tanks and towers, etc.

Delay for Population Change	c	1	Year

Water availability, *w*, over time increases the population. The main delay in this process is incorporated in the smooth function of socioeconomic growth, *G*. It takes time for a society to perceive water availability. After this delay in perception, *e*, the population changes accordingly within a year.

Delay for Vulnerability Decline b 10 Year

When the society wants to adjust itself to drought situation, water dependency declines with a slower rate. This effect is known as stickiness in economics literature. Therefore, the rate of change in vulnerability is different when it is growing or decreasing. When $Q>V(t)$ the delay is *a* and when $Q<V(t)$ delay becomes *b*. *b* is always greater than *a*.

Delay for Vulnerability Growth a 5 Year

When the society wants to adjust itself to drought situation, water dependency declines with a slower rate. This effect is known as stickiness in economics literature. Therefore, the rate of change in vulnerability is different when it is growing or decreasing. When $Q>V(t)$ the delay is *a* and when $Q<V(t)$ delay becomes *b*. *b* is always greater than *a*.

Delay in Supply k 1 Year

Time to release supply water from storage facilities. Since we care about annual statistics, this delay is one.

Demand per Person per Year z 1385000 Liter/Person/Year

The global annual average of water consumption per capita is 1,385 cubic meters (Scientific American, 2012).

Liter to MCM u 1e-09 MCM/Liter

One liter is one billionth of a million cubic meter.

Public Pressure Multiplier p 1 Dimensionless

This multiplier shows the sensitivity of a society toward economic damages forced by water shortage. A society with higher *p* would put more pressure on government to facilitate the supply process.

Public Pressure Threshold t 0.15 Dimensionless

Public Pressure forces the government to build more reservoirs, however, it should reach a threshold to become significant in the system.

Recharging Delay	d	1	Year
Time that surface water takes to inflow into the storage facilities. Since we care about annual statistics, this delay is one.			
Socioeconomic Growth Exponent	g	0.2	Dimensionless
The rate of socioeconomic growth varies in different societies. This rate is addressed by the exponent *g*. The higher the growth exponent, the faster the society changes.			
Time to Adjust Capacity	h	5	Year
Time that a government takes to recognize that more water storage infrastructure is needed.			
Time to Perceive Availability	e	5	Year
There is an information delay between changes in water availability and changes in socioeconomic growth. It takes time for the societies to change their opinion about the overall availability of water in their region.			
Tolerable Shortage	f	0.15	Dimensionless
When water is abundant the *G* will be positive and during severe water shortages *G* will be negative. The economy grows even during small tolerable water shortage, *f*.			
Vulnerability Multiplier	v	1	Dimensionless
When water becomes abundant people become more dependent on water. This rate of vulnerability change, v, varies in different societies. The greater the vulnerability multiplier, v, the higher the rate of changes in vulnerability.			