ODD+D Protocol Description

For the ODD+D protocol, see (Müller et al. 2013).

I. Overview	I.i Purpose	I.i.a What is the purpose of the study?	The purpose is to show that under specific rules for water exchanges that play out under a given set of constraints on water prediction, scheduling, and supply, actors are impacted differentially by other actors' strategies
		I.i.b For whom is the model designed?	Scientists, modelers, and water policy analysts
	I.ii Entities, state variables and scales	I.ii.a What kinds of entities are in the model?	There are two types of agents: a central management authority and subcontractors receiving water from this authority
		I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterised?	Central Management: None Subcontractors: Residential population size; water supply year-to-date; water scheduled through the end of the year; strategies for deciding to request or offer water based on predicted shortfall or surplus.
		I.ii.c What are the exogenous factors / drivers of the model?	Temperature variation by month, used to determine water demand.
		I.ii.d If applicable, how is space included in the model?	Temperature is based on real-world data that is spatially based.
		I.ii.e What are the temporal and spatial resolutions and extents of the model?	Monthly time steps, up to 1000 years
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?	Subcontractors: On October 1st declare a schedule of monthly water deliveries needed for the following calendar year. Subcontractors: Each month assess year-to-date demand vs. supply and predict a shortfall or surplus; can then offer water or request it Central Management: Apportion (each month) any offered water among any subcontractors requesting water Subcontractors: Annually (January 1st) assess last year's performance and adjust strategies for requesting and offering water.
II. Design Concepts	II.i Theoretical and Empirical Background	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?	Legal arrangements that govern how water is exchanged (e.g. preventing a water market and direct exchanges between subcontractors) can appear to be structured equitably but can lead to unexpected dynamics. Understanding these dynamics may only be possible with a dynamic ABM and could inform the design of a better system.
		II.i.b On what assumptions is/are the agents' decision model(s) based?	Agents make decisions to minimize both shortfalls and surpluses based on limited information. The Central Management apportions water based on a strict mathematical rule (allocate all offered water in proportion to requests) that is applied to all subcontractors equally.
		II.i.c Why is /are certain decision model(s) chosen?	The Central Management rule is implemented because no mechanism for exchanging water among subcontractors exists. The Subcontractors' rules were based on simple heuristics because no actual rules exist. (Real-world subcontractors would additionally have multiple water sources and hence other ways to address both shortages and surpluses.)
		II.i.d If the model / submodel (e.g. the decision model) is based on empirical data, where do the data come from?	Data on actual contractor's scheduled water supply and delivery is available from the Central Arizona Project (https://www.cap-az.com/departments/water-operations/deliveries). Temperature data is available for the study area for a set of years that were used as a baseline for stochastic fluctuations; the impact of temperature on water demand

			was based on a formula from a study context nearby and data from the study context (gallons per capita per day residential usage) (See Ozik et al. 2014).
		II.i.e At which level of aggregation were the data available?	Monthly.
	II.ii Individual Decision Making	II.ii.a What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included?	Subcontractors decide annually what their projected demand will be; they decide monthly whether they are likely to see a surplus or shortfall by the end of the year, and how much to request or offer to the Central Management. Central Management determines how to apportion water offered from surpluses to subcontractors making requests to buttress shortfalls.
		II.ii.b What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	Subcontractors are attempting to minimize shortfalls and surpluses vs. predicted water demand.
		II.ii.c How do agents make their decisions?	Subcontractors use simple algorithms, parameterized by unique strategies, to determine how they act when they forecast a shortfall or a surplus; see equations below.
		II.ii.d Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?	The subcontractors' strategies are adjusted through time based on their success or failure in minimizing shortfalls and surpluses.
		II.ii.e Do social norms or cultural values play a role in the decision-making process?	No.
		II.ii.f Do spatial aspects play a role in the decision process?	Real-world locations drive temperature, which impacts water demand, and there is some correlation between temperatures in adjacent subcontractors' locations, but otherwise space is not an element.
		II.ii.g Do temporal aspects play a role in the decision process?	Subcontractors adjust their upcoming schedules based on last year's demand and adjust their strategies incrementally through time.
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	Uncertainty is not explicitly modelled, but instead is captured in the agents' strategies, which are more or less successful based in the degree to which they ameliorate uncertainty.
	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	Subcontractors update their strategies based on the previous year's success or failure to reduce surplus/shortage.
		II.iii.b Is collective learning implemented in the model?	No.
	II.iv Individual Sensing	II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?	Subcontractors know only their own situations (their strategies, their scheduled water demands for the remainder of the year, and year-to-date water demand); these they know without error. They do not know others' situations, except through being allowed to donate surpluses and receive excesses from the Central Management.
		II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	None.
		II.iv.c What is the spatial scale of sensing?	Does not apply.
		II.iv.d Are the mechanisms by which agents obtain information modelled explicitly, or are	All other variables are just known by the agents.

		individuals simply assumed to know these variables?	
		II.iv.e Are the costs for cognition and the costs for gathering information explicitly included in the model?	No.
	II.v Individual Prediction	II.v.a Which data do the agents use to predict future conditions?	Agents know only their own water schedules and their own performance in the previous year (year totalled surplus of scheduled vs. used or shortfall or used vs. scheduled).
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?	When forecasting the year's shortfall or surplus, the agent takes year-to-date usage and adds remaining months' scheduled water, then compares this to the total scheduled for the year. When estimating next year's demand (on October 1st), the subcontractor uses the previous 12 months' actual usage.
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	Subcontractors' predictions are erroneous because demand is stochastic, and other subcontractors' shortages or surpluses are unknown.
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?	Indirect through the exchange of water via the Central Management.
		II.vi.b On what do the interactions depend?	All subcontractors interact only with the Central Management.
		II.vi.c If the interactions involve communication, how are such communications represented?	N/A.
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	The Central Management coordinates all water exchanged in the cases of shortages and surpluses.
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect and are affected by the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?	No.
		II.vii.b How are collectives represented?	N/A.
	II.viii Heteroge-neity	II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?	Subcontractors vary in their population sizes, their water demands per capita, the way that temperature affects this demand, the temperatures that they experience during a year, and in their strategies for exchanging water.
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?	The subcontractors vary in the values that define their strategies, but the strategies are all algorithmically identical.
	II.ix Stochasticity	II.ix.a What processes (including initialisation) are modelled by assuming they are random or partly random?	Variability in water demand per month; see Temperature Impact on Water Demand submodel, below.

	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding and analysing it, and how and when are they collected?	Simulation output is collected at the end of the simulated calendar year; data collected per subcontractor include the contractor's strategy, total water demand, and total water supplied (from which surplus or shortage can be calculated).
		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)	Subcontractor strategies for proportion of surplus to offer and proportion of shortage to request move as the simulation iterates through multiple years; subcontractors of different sizes are pushed toward different ending values, resulting in a collection of subcontractors who are all pursuing different strategies, all of which are more or less successful based on the strategies of others.
III. Details	III.i Implementation Details	III.i.a. How has the model been implemented?	In the Repast platform (North et al. 2013).
		III.i.b Is the model accessible, and if so where?	Code is available at https://www.comses.net/codebase-release/25cdadab-2f13-41f1-895b-d29dc4cbc9b3 .
	III.ii Initialisation	III.ii.a What is the initial state of the model world, i.e. at time t=0 of a simulation run?	14 subcontractors are initialized with specific values for strategy: proportion of surplus to offer vs. proportion of shortage to request.
		III.ii.b Is the initialisation always the same, or is it allowed to vary among simulations?	The subcontractors' positions in strategy space (amount to request, amount to offer) can be varied to explore situations in which specific actors (or classes of actors) are pursuing specific strategies (e.g. generous offers or high requests)..
		III.ii.c Are the initial values chosen arbitrarily or based on data?	Arbitrarily.
	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?	Several real-world years of temperature data provide baseline values for temperature by month in the specific locations.
	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?	Temperature Impact on Water Demand; Strategy Adjustment
		III.iv.b What are the model parameters, their dimensions and reference values?	See text below.
		III.iv.c How were the submodels designed or chosen, and how were they parameterised and then tested?	See text below.

1 Overview

1.1 Purpose

The purpose of the simulation is to understand the dynamics of an exchange system among water managers facing uncertain demand under requirements of advanced scheduling of water supply. More specifically, an exchange system in which a superficially equitable system is used to allocate surplus water to those with a shortage is examined for its differential effects on managers with different demand requirements. The model is designed as a demonstration to illustrate how a dynamic agent-based model can be used to explore the impacts of a specific non-market system of water allocation.

1.2 Entities, State Variables, and Scales

The model consists of two types of agents: a central management agent, which plays a role as arbiter of water exchanges but has no elements other than automatically enforcing the rules of exchange, and subcontractor agents who interact with the management agent to request, receive, and offer water over an annual schedule during the course of the simulation. Subcontractors have specific residential population sizes that do not change during the simulation; the values used are:

Carefree	2,445
Cave Creek	5,063
Goodyear	42,495
Surprise	43,484
Apache Junction	55,162
Avondale	76,980
Peoria	138,185
Tempe	168,339
Scottsdale	220,002
Glendale	227,190
Gilbert	234,968
Chandler	246,136
Mesa	476,118
Phoenix	1,471,900

Table 1: Subcontractors' names and population sorted by size.

Monthly water demand for a subcontractor is a function of population size, temperature, and a stochastic element such that demand fluctuates within and between years. See discussion of "Temperature Impact on Water Demand" submodel.

Water managers construct monthly water schedules in advance, track their actual water usage throughout the year, and create a subsequent year's schedule based on the previous year's usage. Space is implicitly included by different temperature values for each contractor (these are drawn from real-world climate data), but otherwise the simulation is aspatial, in that there is no sense of proximity or spatial connection among managers.

Water managers also have a set of variables that define their strategies for water exchanges. These are:

Strategy Value	Meaning
x	Fraction over projected demand that scheduled supply must exceed to trigger an offer of water to other managers
z	Fraction under projected demand that scheduled supply must exceed to trigger a request of water from other managers
s	Fraction of projected surplus that will be offered, if offer is made
r	Fraction of projected shortfall that will be requested, if request is made

Table 2: Variables defining a subcontractor's strategy.

1.3 Process Overview and Scheduling

Subcontractors are asked to provide a schedule for a calendar year (January through December); they provide this on October 1st. The schedule includes estimates of residential water usage by month. As the year progresses, actual usage, driven by population, temperature, and stochasticity, can diverge from what was estimated. On the 1st of each month, subcontractors can assess whether they are under or over their estimated water usage. If they are outside of acceptable ranges the subcontractor can offer surplus water, or request additional water, from the central management. The central management can move water from subcontractors with surpluses to those with shortages in the subsequent month. At the end of the year (December 31st) subcontractors can assess whether they had surpluses or shortfalls, and can adjust their strategies accordingly for the next year.

2 Design Concepts

2.1 Theoretical and Empirical Background

The model is based loosely on the system managed by the Central Arizona Project (CAP) in and around Phoenix, Arizona. The calendrical schedule and the fact that water is scheduled in advance with estimates of monthly usage is drawn from actual CAP management practices. Sales and direct exchanges of water among subcontractors are not permitted. Water shortages are problematic because supply may not meet demand; water surpluses, however, are also problematic because the subcontractor may be charged a fee for water scheduled even if it is not delivered. The simulation takes these facts and explores a hypothetical solution to the problem created by advanced scheduling and uncertain demand. The system employed in the simulation is chosen by the modelers as representative of a system in which all subcontractors are treated equally.

2.2 Individual Decision-Making

Subcontractor agents make two decisions throughout simulation time. Annually on October 1st they provide the next calendar year's schedule; the schedule they provide is the actual water demand from the 12 months prior to that date (October 1st through September 30th). This is true despite the fact that the preceding year's usage is unlikely to match the subsequent year's demand: other algorithms (e.g. rolling averages over the past N years) could be employed.

Each month subcontractors also decide whether to request water (if a shortfall) or offer it (if a surplus). When making this decision, the subcontractor calculates a projection of the water remaining to be received vs. the expected demand through the end of the year. Any overage is considered against a threshold, x; if the overage will exceed this threshold, the manager will elect to offer back a fraction s of the projected surplus. Conversely, if the manager projects a shortfall, this will be considered against a threshold z, and if the shortfall will exceed this level, the manager will elect to request a fraction r of the shortfall from the CAP management. Both the request and the offer can be larger than the respective shortfall or surplus; nothing prohibits a manager from requesting more than is immediately needed or offering more than is currently available.

The CAP management responds by allocating any offered water among any subcontractors making requests. If water offered exactly equals water requested, then all requests are filled. However, this is unlikely, and more common are the cases in which requests exceed offers or vice versa. In the case of requests exceeding offers, the total water offered is distributed to the requesting subcontractors proportionally to the sizes of their original requests, such that if the total water offered is some percentage of the total requested, each requestor will receive that percentage of the original request. In the case of offers exceeding requests, all requests are filled, and the excess amount is shared among all offering subcontractors in proportion to their offers, such that each keeps the same percentage of the original offer.

2.3 Learning

Learning in this simulation is defined as the agents' revisions to their strategies. At the end of each year, each manager assesses its success or failure in meeting the actual demand, and adjusts strategies based on this. Four possibilities are considered:

1) Demand was not met even though water was requested
2) Demand was not met and water was offered back to the exchange
3) Demand was exceeded by scheduled supply and water was requested from the exchange
4) Demand was exceeded by scheduled supply and water was offered back to the exchange.

Cases 2 and 4 represent unusual circumstances: a manager at some point during the year perceived an anticipated surplus or shortfall and attempted to correct for this; by the end of the year the situation had reversed. In all cases, the manager will adjust the appropriate fraction(s) s and r to either increase or decrease the water received to match the actual demand. See the Strategy Adjustment submodel, described below.

2.4 Individual Sensing

Subcontractors are aware only of their own water demands, their annual scheduled water amounts available, and their water received from the management. They do not directly sense other agents' water supplies or shortfalls.

2.5 Individual Prediction

Subcontractors are predictive in their scheduling, on October 1st, of water supply for the subsequent calendar year. Within the year the decision determined by their strategies is a form of prediction, anticipating an annual surplus or shortfall based on the water demand up to that point in the year and the scheduled deliveries for the rest of the year. If actual demand has exceeded or fallen short of scheduled demand by a fraction of the total year's scheduled demand, an action is triggered that is intended to address the actual water need through the remainder of the year.

2.6 Interaction

Subcontractors interact directly only with the central management; they do not interact with each other except insofar as a request to give or receive water is only successful if other subcontractors have made complementary requests. They are not permitted to exchange water directly among themselves.

2.7 Collectives

Subcontractor agents do not form collectives.

2.8 Heterogeneity

Subcontractor agents differ in their current strategies and their water demands (by virtue of different populations, temperature, and stochastic noise). All subcontractors, however, are subject to the same rules, schedule, and treatment by the central management.

2.9 Stochasticity

Stochasticity in water demand is introduced by a simple noise variable that raises or lowers demand away from what it would otherwise be strictly based on temperature, and population.

2.10 Observation

The outcomes of the model are the strategies of the subcontractors through time and their water received vs. actual water demand.

3 Details

3.1 Implementation Details

The simulation is implemented in Repast Simphony (Java). It is available at https://www.comses.net/codebase-release/25cdadab-2f13-41f1-895b-d29dc4cbc9b3 .

3.2 Initialization

The simulation is typically initialized with subcontractors endowed with a baseline schedule for the upcoming year's water and a specific strategy (amount to offer, amount to request). Commonly all subcontractors may be given the same initial strategy; alternatively, subcontractors with large vs. small populations may be given a specific kind of strategy (e.g. offer very little, request a lot).

3.3 Parameters

Most of the values in the simulation are driven by data (e.g. temperature, impact on per-capita water demand). Only four parameters are employed: *Kx*, *Kz*, *Ks*, and *Kr* are constants that determine the rates at which change takes place during strategy adjustment (see Strategy Adjustment submodel). Two values used for changing the thresholds at which offers or requests take place (*Kx, Kz*) are commonly zero; if this is the case, no changes in the thresholds are performed. The most common value for the adjustment of request proportion, *Kr,* is 2, while the equivalent value for the adjustment of surplus offered, *Ks,* is 1; changes to the shortage requests are twice the magnitude of changes to the surplus offers.

4 Submodels

4.1 Temperature Impact on Water Demand

Using earlier work in this area (Ozik et al. 2014) we apply a formula (derived from (Balling and Gober 2007)) that converts the monthly average of daily temperatures into overall water demand, such that summer months have higher demand than winter months. The formula is:

$$W = (I_{mc} + T_{mac} * S_{mc}) * n \qquad (1)$$

where I_{mc} is a constant derived from data (representing a Y-intercept for the linear portion of the equation) that is unique to that contractor and represents its baseline usage in a typical month; T_{mac} is the monthly average temperature for that contractor; S_{mc} is the slope of a line derived from data that represents that contractor's response to temperature changes; and n is a 'noise' factor to introduce stochasticity.

4.2 Strategy Adjustment

The algorithm by which agents adjust their strategies at the end of a year is:

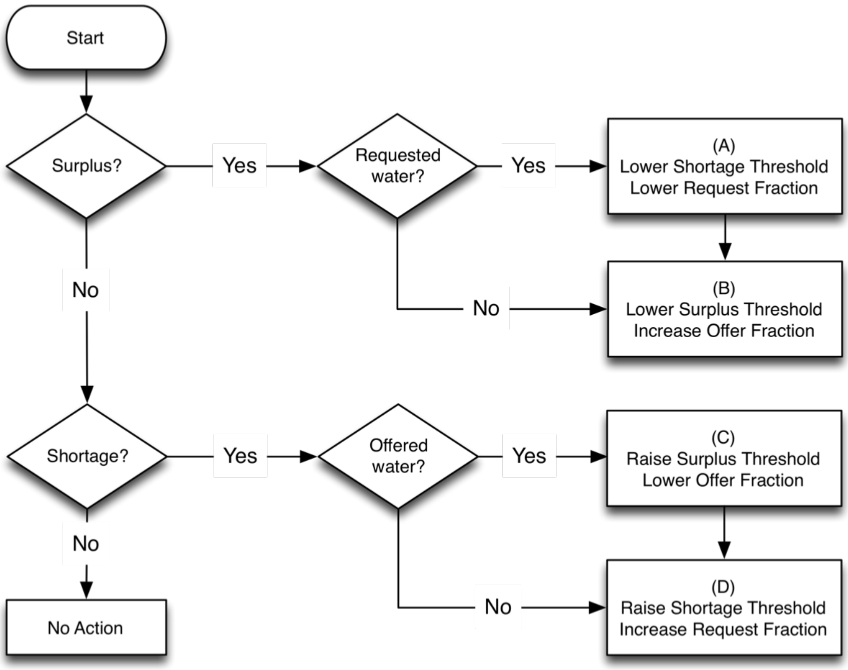

Figure 1: Actions that can be taken by individual subcontractors.

The actions taken are:

A: Lower the shortage threshold *z* and lower the request fraction:

$$\Delta z = \frac{-1 * w * Kz * WaterScheduled}{WaterDelivered} \quad (2)$$

$$\Delta r = \frac{-1 * (1-w) * Kr * WaterScheduled}{WaterDelivered} \quad (3)$$

B: Lower the surplus threshold and increase the offer fraction:

$$\Delta x = \frac{-1 * w * Kx * WaterScheduled}{WaterDelivered} \quad (4)$$

$$\Delta s = \frac{(1-w) * Ks * WaterScheduled}{WaterDelivered} \quad (5)$$

C: Raise the surplus threshold and decrease the offer fraction:

$$\Delta x = \frac{w * Kx * WaterScheduled}{WaterDelivered} \quad (6)$$

$$\Delta s = \frac{-1 * (1-w) * Ks * WaterScheduled}{WaterDelivered} \quad (7)$$

D: Lower the shortage threshold *z* and lower the request fraction:

$$\Delta z = \frac{w * Kz * WaterScheduled}{WaterDelivered} \quad (8)$$

$$\Delta r = \frac{(1-w) * Kr * WaterScheduled}{WaterDelivered} \quad (9)$$

where *w* is a random value selected from a uniform distribution between .25 and .75 that weights which form of adjustment will be stronger.

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