A Model for a Water Potable Distribution System and its Impacts resulting from a Water Contamination Scenario.

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A system dynamics model for a potable water distribution system is of considerable interest in understanding the potable water distribution system itself as well as in identifying the consequences and impacts on other critical infrastructures when perturbations occurs to the system. In this paper we present a system dynamics model that describes a potable water distribution system, which serves an urban area. This model is a component of the Critical Infrastructure Protection Decision Support System (CIP-DSS) project, which models the dynamics of a set of coupled individual infrastructures. We investigate the interdependencies of potable water distribution systems on other critical infrastructures merging our model with other infrastructures models developed under the CIP-DSS project. The main focus of this work is to study the consequences of a potable water distribution system disruption. For this purpose we analyze the impacts on the public health and the economic effects due to a water contamination scenario.

Introduction

The Critical Infrastructure Protection-Decision Support System (CIP/DSS) project has been implementing a risk decision support system designed to make critical infrastructure protection decisions [1,2]. The system models several critical infrastructures such as population, telecommunications, public health, economics, etc. This model takes into account also the interdependencies among these infrastructures in order to simulate impacts and effects due to possible disruptions of these infrastructures. The main goal of this model is to provide modeling capabilities for the analysis of critical infrastructures and their interdependencies. This model also assists decision makers in making policy decisions, investment and mitigation planning, and improving the robustness of national critical infrastructures.

The CIP/DSS project uses a system dynamics modeling approach. This approach allows us to model a shock on a single infrastructure and to analyze how this perturbation propagates to the other infrastructures. In addition the dynamics nature of this modeling approach also consents to represent the secondary effects due to the feedback on the original infrastructure.

In this paper we present a model for a potable water distribution system developed in support of CIP-DSS project. This model is coupled to other critical infrastructures developed in the CIP-DSS Metropolitan Model. In particular, we focus in coupling the water distribution model to the public health system and the economic model. This allows us to estimate consequences and impacts of a scenario where a contamination of the potable water system occurs.

The paper is organized as follows. First, we present the main system dynamics model, which describes a generic potable water distribution system. The coupling to other critical infrastructures is also described in this first section. Next, we explain how we improve the model in order to predict the diffusion of disease over time in a population ingesting contaminated water. Finally, we conclude with results from a drinking water contamination simulation. We especially focus on determining health and economic impacts due to such scenario. In this last section we also compare our results with the results obtained for a similar scenario using EPANET [3], well-known software developed by Environmental Protection Agency (EPA) to model water distribution systems. A brief summary and conclusions follow.

Potable Water Distribution System Model: Main Structure

In support of the CIP-DSS project we develop a system dynamics model for a potable water distribution system (*PWDS*). In this work we consider a single potable water distribution system that serves a metropolitan population of approximately 2.5 million people. The model is developed using a system dynamics modeling approach where key units are stocks and flows. Based on this modeling approach the *PWDS* is described as an ensemble of connected stocks and flows forming multiple feedback structures.

A schematic representation of the model is shown in Figure 1. There are two main modules in this model. The main module (treatment process) models the water treatment process, its supply and the clean water daily distribution. The second module (contamination process) models a generic contamination scenario. In this section of the paper we focus on describing the main module and the interdependency with other infrastructures.

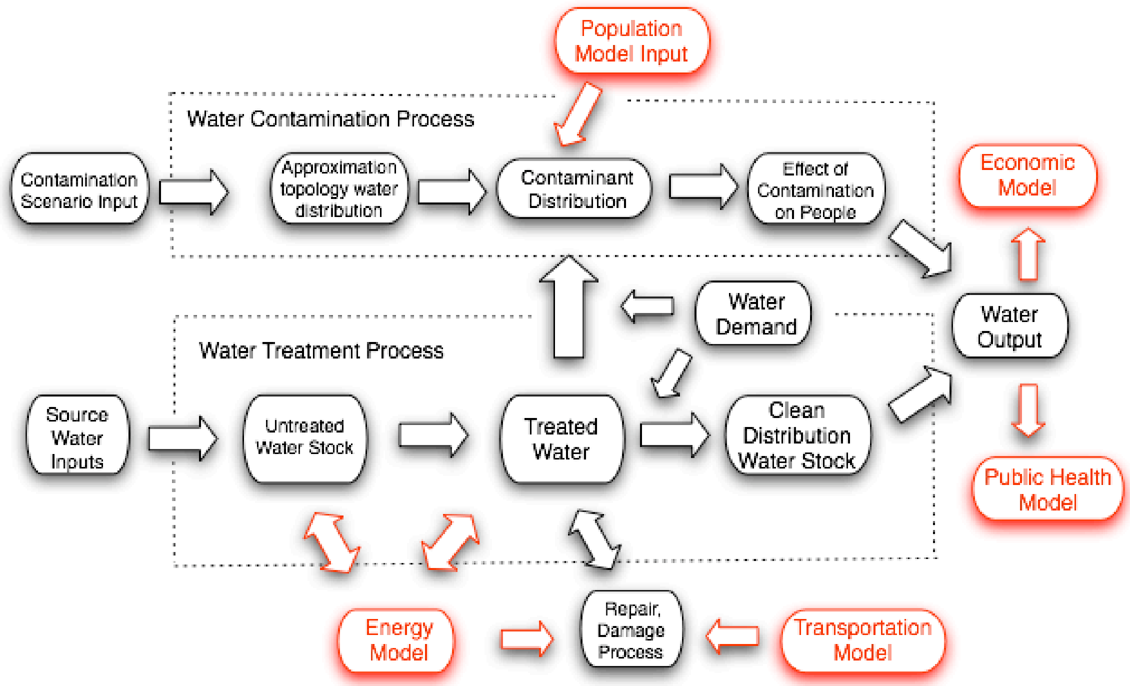


Figure 1: Schematic representation of the potable distribution system model. The model is formed by two parts: main structure and the contamination process structure. The main structure describes the water treatment process where the water is treated and ready to be consumed. In this first structure the demand rates subscripted for different user-type consumers is also calculated. The second structure describes the contamination process and the impacts on the population. The water model is coupled to other critical infrastructures models (red units): population, transportation, energy, public health, and economic model.

Due to the system dynamics modeling approach of our model the detailed network topology of a real metropolitan potable water system is not explicitly represented. The main structure of the model consists of a water flow, which starts from the raw water source, primary stock, and ends in a stock of processed water ready to be distributed to the urban area (see Figure 2). During this flow the water is treated and stored in a treated water stock. In the treated process the model takes into account the damage and repair processes that affect the levels of the water capacity stock. The water source stock represents the total available raw water. It takes into account the percentages of raw water from different water sources: reservoirs, rivers, groundwater, pipelines, and other sources. The overall storage capacity of source water stocks for our model is determined by estimating reservoir capacity from Arizona Department of Water Resources Phoenix Active Management Area 2000 [4].

The processed water is distributed to different end-users through consumption flows. The end-users are divided (subscripted) into five different classes: residential, commercial, industrial, public health, and other users. Each class has a specific consumption flow that is estimated using the specific daily demand profiles. Figure 3 shows the demands profiles for residential and commercial end-users over 24 hours consistent with end-user studies published [5].

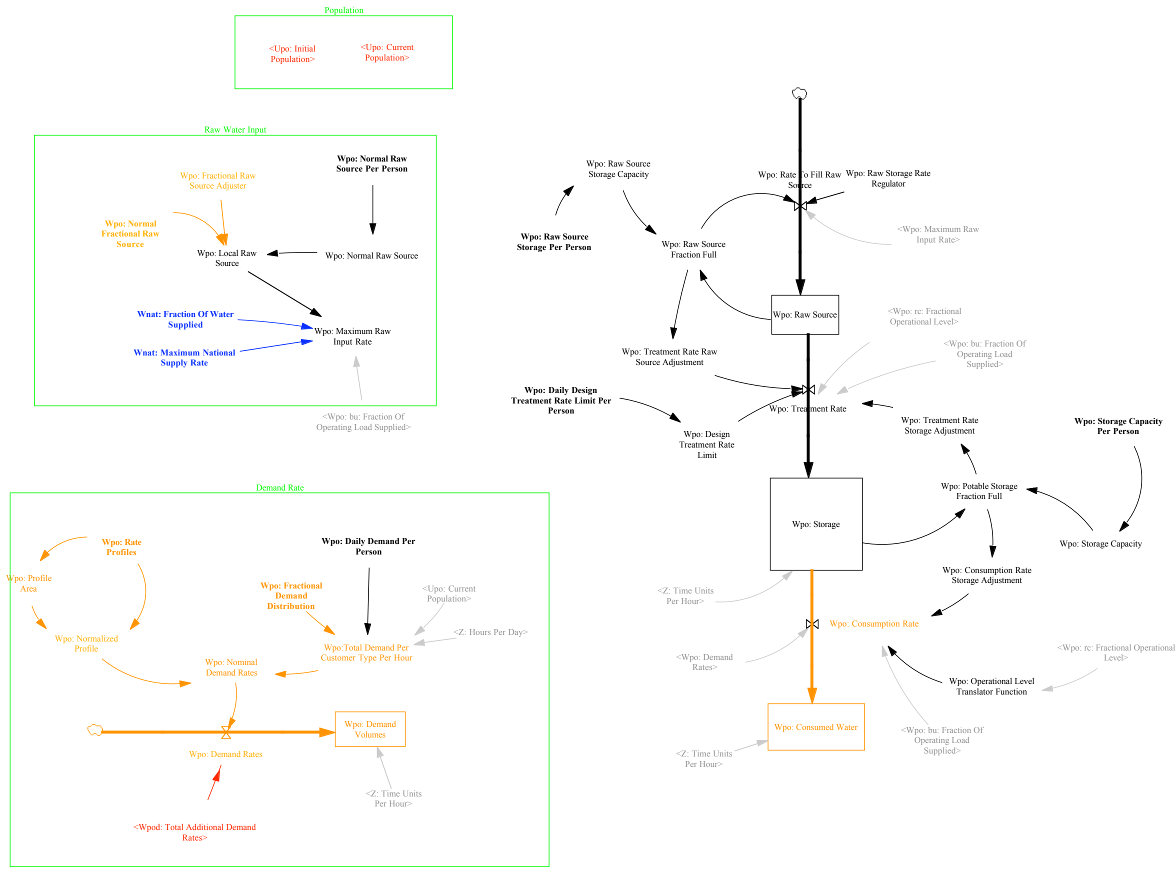


Figure 2: Main influence diagram for a metropolitan potable water distribution system.

There are a number of interdependencies between the potable water infrastructure and other infrastructures. The *PWDS* model is coupled with other infrastructure such as metropolitan energy, transportation, and economic. For example, the ability to repair a damaged water system depends on the availability of transportation, energy, and labor force; the treated process also depends on the availability of energy. In the case of a scenario the interdependency between *PWDS* and public health also needs to be considered, as we will describe in the following section. In Figure 1 the red units describe these interdependences.

Summarizing, the main model structure represents

- raw water sources
- water treatment process
- storage of treated water
- damage of the *PWDS*
- repair to the *PWDS*

- distribution of water, and end-user demand

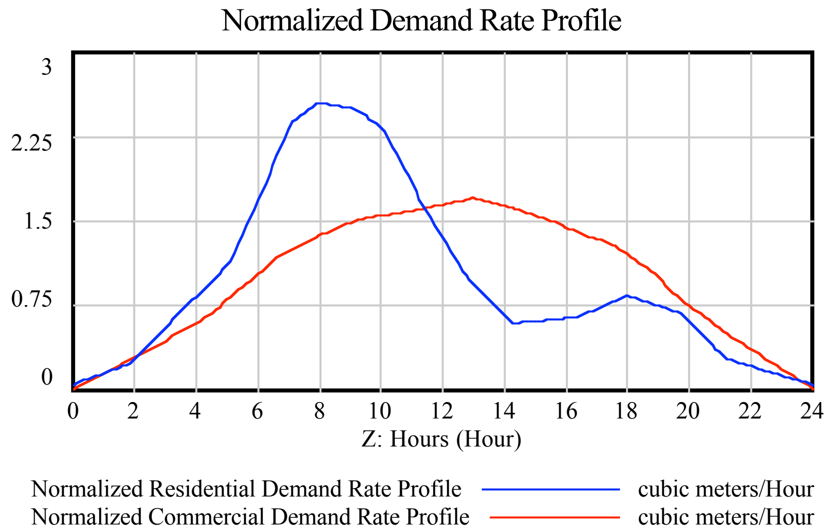


Figure 3: Daily demand rate for residential and commercial consumers. The demand rates are normalized to the area.

Water Contamination Scenario Model: Second Structure and Results

The *PWDS* model allows exploring a number of use-case scenarios, including the case where a contaminant is introduced into the treated water supply. We focus on an application where we want to predict the spread of disease due to the contamination of drinking water. The main goal is to quantify the risk associated with consuming contaminated water.
We analyze a specific scenario where a quantity (1320gr) of a non-specific contaminant is injected for one hour in the treated water supply at 7:30am. The lethality of this contaminant is characterized by a LD50 (Lethal Dose 50 [6]) of 10 μgr/Kg. The contaminant cannot be seen in water, thus it is hypothesized for this reason the public health community is not likely to consider water as the source within the fist 24 hours. The onset of symptoms has a range of 2 hours after the injection to 8 days after the injection, with majority of cases presenting within 72 hours.
In order to study the effects on the population of an accidental injection of a contaminant in the water distribution system in a city, we need to addresses three main issues:

- how to approximate the structure (topology) of the water distribution system
- how the contaminant diffuses in the system and reaches the end-users (hydraulic behavior)
- how the contaminant affects the afflicted population

The water distribution system is a complex network of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. In a "realistic" model one should model the hydraulic behavior within pipe networks tracking the flow of water in each pipe, the pressure at each node, the height of water in each tank, and turbulence in the pipes, like simulations performed in EPANET (Environment Protection Agency's software) [3]. EPANET software, developed by the Environmental Protection Agency (EPA), is widely used to models the hydraulic behavior of water distribution systems making many assumptions about flow in distribution systems. Unlike EPANET, in a system dynamics model these physical details cannot be modeled. In order to solve the lack of a physical component, we make simple approximations about the topology and the diffusion of the contaminant. In this model we approximate the water distribution network as a tree topology network with 2 children nodes (see Figure 4). Giving the level of the node where the contaminant injection occurs and the number of the total population, this approximation allows calculating the total number of exposed people. For the case analyzed, the number of exposed people results to be 8586.

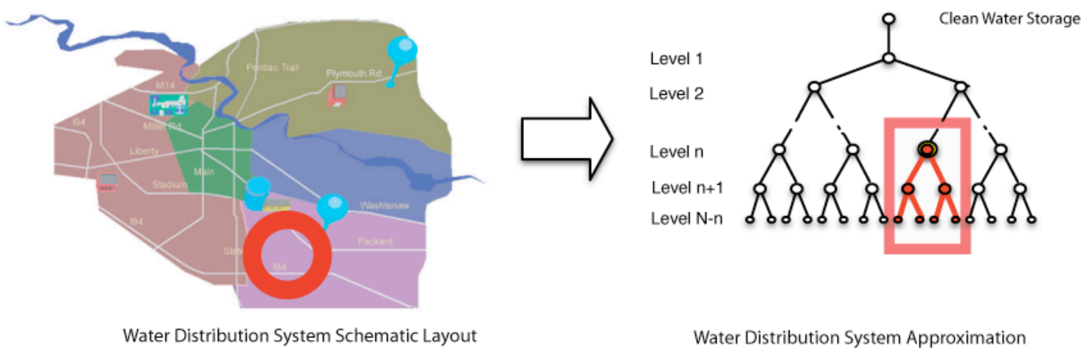


Figure 4 Approximation of a water distribution system network. The water distribution system schematic layout (fist graphic in this figure) does not represent an actual water distribution system and it is used only for illustration purposes.

The contaminant's diffusion in the potable water system is approximated by a flow with several delays in order to calculate the total delay between the injection and the consumption due to several hydrologic effects, like for example contaminant diffusion in the pipe, flow drift, and pipe length. Figure 5 shows the diffusion of the contaminant in the water system.

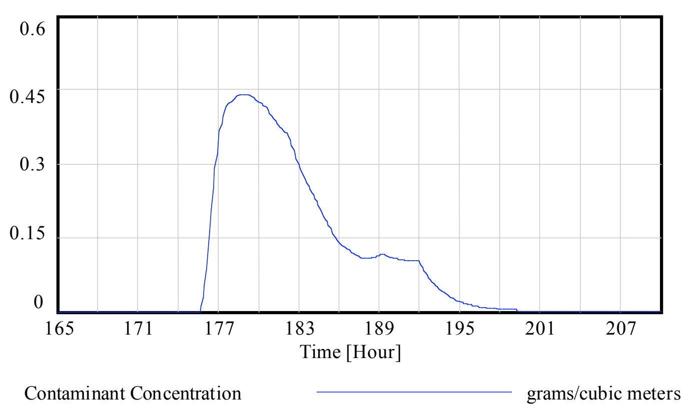


Figure 5 Contaminant concentration in the water system at the end-users level.

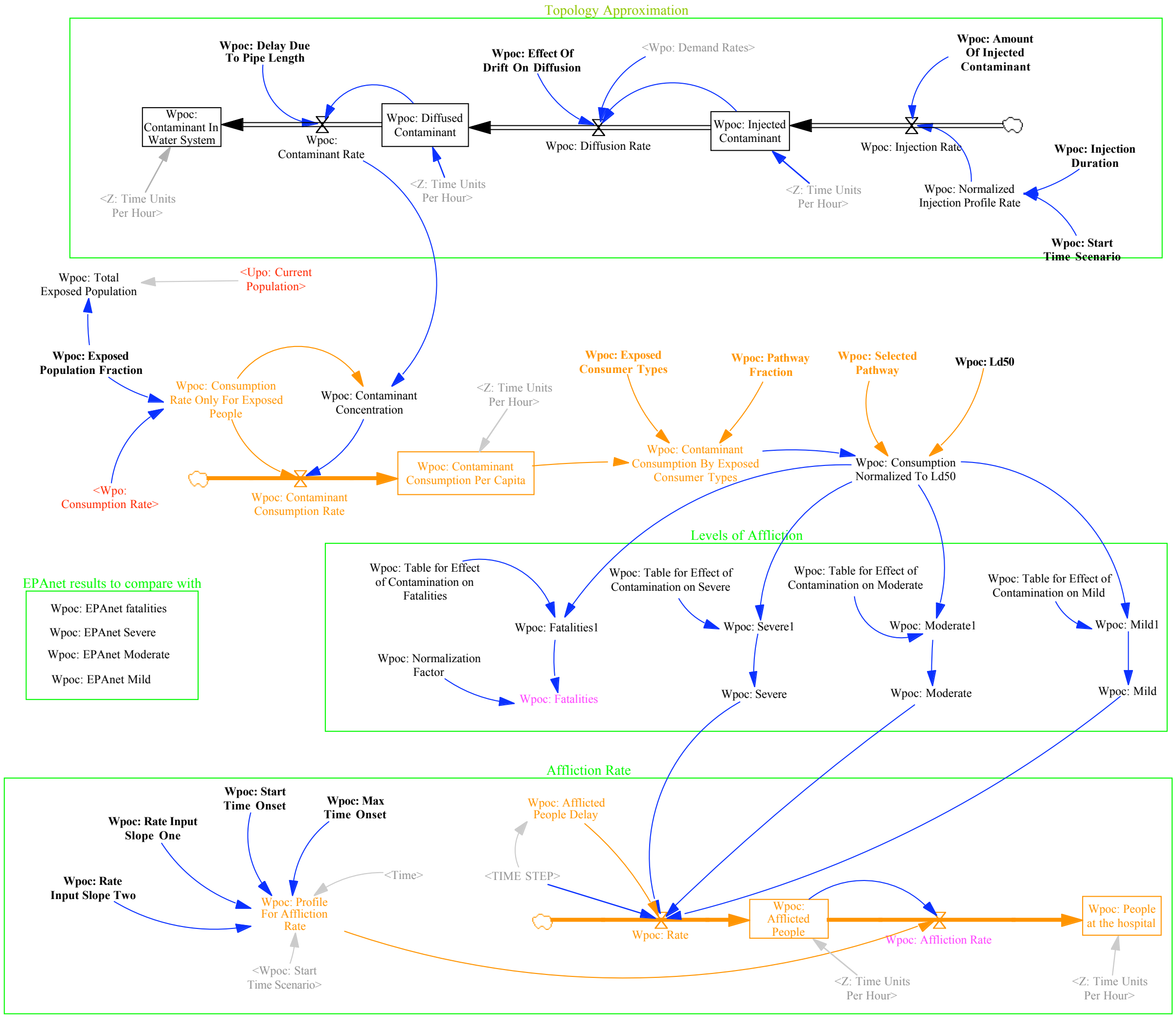


Figure 6 Influence diagram for the drinking water contamination scenario.

Once the concentration of the contaminant in the water system is known, the model calculates the effects of the contamination on the afflicted population We divide the afflicted population into four classes: mild, moderate, severe and fatality. The afflicted people in the mild class don't need hospitalization, the ones in the moderate class need hospitalization for 3 weeks and the ones in the severe class need hospitalization for 6 weeks. The main criteria used to determine health impacts are the dose and the dose response curve that are the amount of contaminated water consumed and the probability of a given health response respectively. In particular, the level of illness severity depends on the concentration consumed by the users through a dose-response curve. In this scenario we just assume that the end-user types afflicted are only residential and commercial and the contaminant can be consumed only through ingestion (drinking). Using a specific dose-curve for each class of affliction the model determines the rate of affliction for the four different classes. The cumulative number of afflicted people in each class is shown in Figure 7.

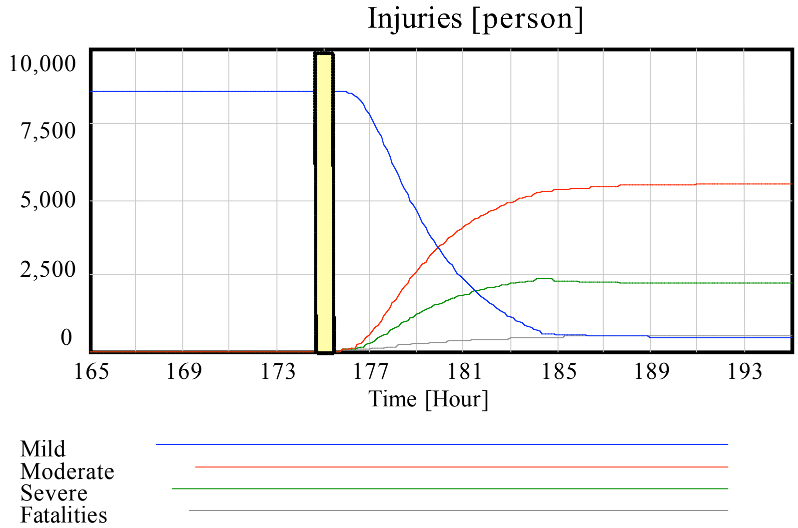
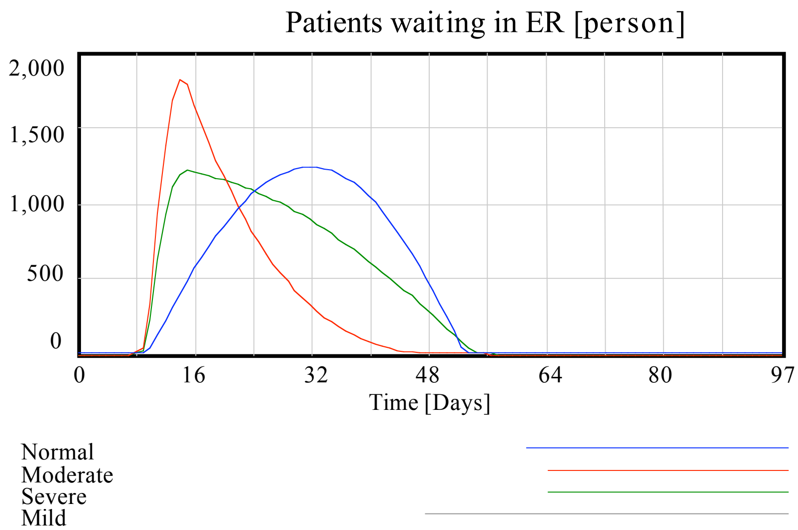


Figure 7 Cumulative number of afflicted people in each class. The simulation starts 7 days before the scenario (the contaminant injection starts after 175.5 hours) to allow the reader to see the "normal" case without scenario. The yellow box represents the contaminant injection event.

Once the rate of affliction for each injury levels is calculated, the model is coupled to the public health infrastructure. The availability to model this interdependency between the potable water infrastructure and the public health allows us to investigate and to understand the real impact of the scenario. Coupling the two infrastructures we calculate different variables that allow us to understand and estimate the consequences of this scenario (Figure 8).
We also couple our model to the economic model developed for CIP/DSS project [7]. This allows us to estimate the total cost of this scenario (Figure 9). The number of the total exposed people and the number of afflicted people for each class are also compared with the results obtained using EPANET. In Figure 10 time-dependent behavior of the number of fatality, mild, moderate and severe afflicted people are compared with the steady-state values obtained using EPANET simulations [8]. Figure 10 shows that with the right calibration of the system dynamics model's parameters, the agreement with EPANET results is good.



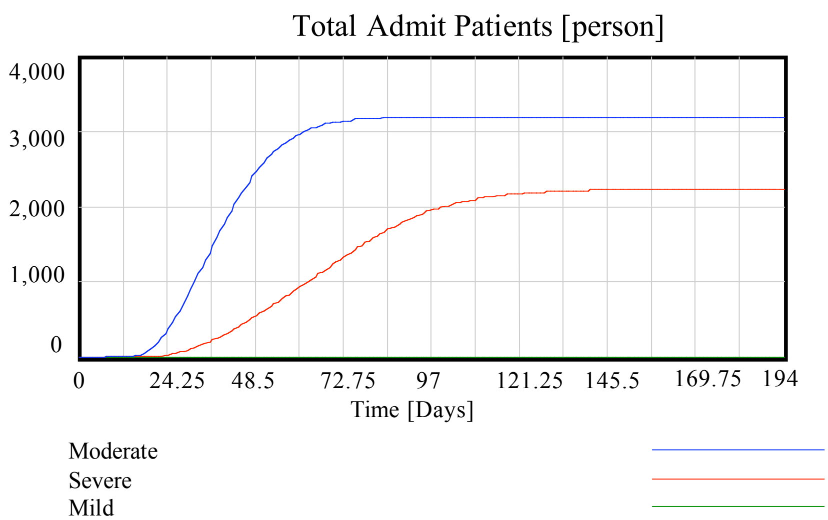


Figure 8 Results for coupling the water model to the public health mode. First plot shows the number of people waiting in the emergency room. Normal refers to the people that go to the hospital not because they drank contaminated water but for other reasons. The second plot represents the total accumulative number of patients in bed at the hospital.

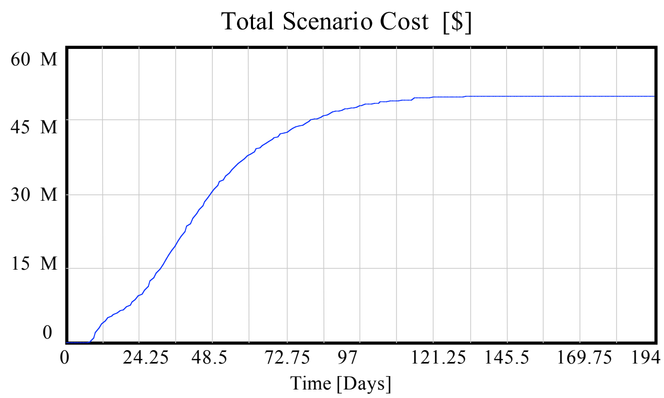


Figure 9 Total cost for this specific scenario.

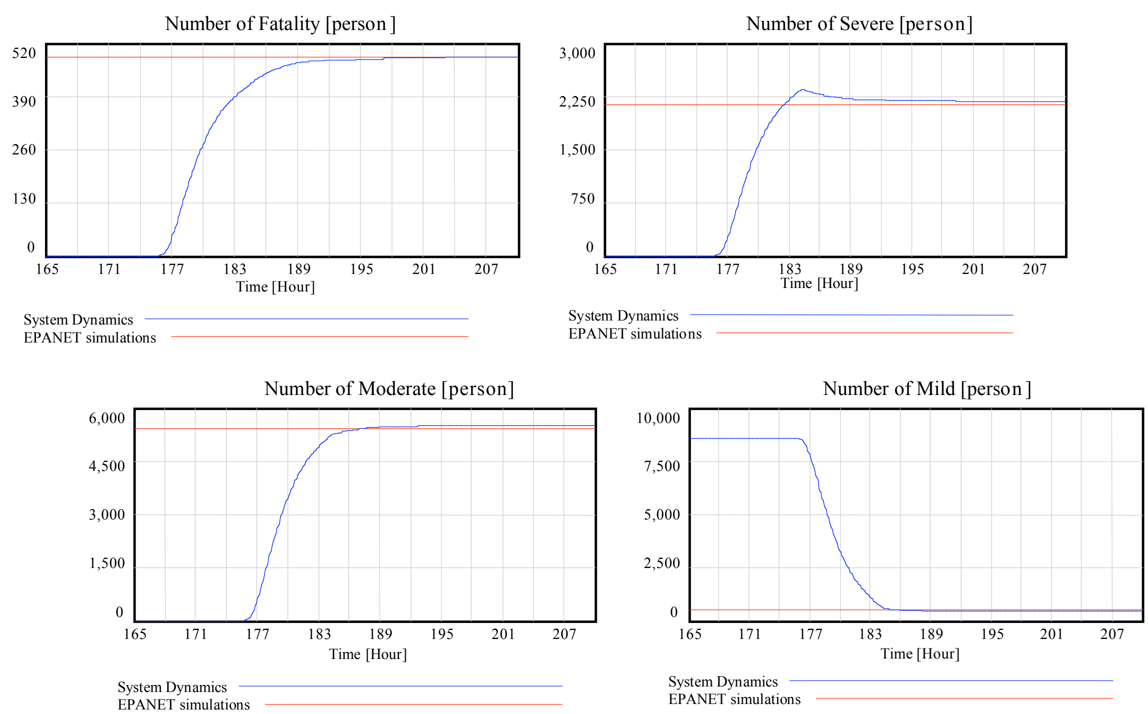


Figure 10 Comparison with the results obtained by EPANET simulations.

Conclusions

This paper describes a system dynamics model to understand the consequences of disruptions to potable water distributions systems. In particular we present a specific scenario of consumption of contaminated drinking water. The coupling with other models such as the public health and economic models provide information about the temporal distribution of the water infrastructure.

This system dynamics model allows predicting the diffusion of disease in a population consuming contaminated water and as consequence the health impacts of the contamination. Some of our results are also compared with the results obtained using a more sophisticated hydrologic model. The comparison shows a good agreement at least for this specific scenario. Further research is necessary to better understand the relationship between the input parameters of our system dynamics model and the physical parameters used in EPANET simulations. That will allow us to improve our model in order to be used in more general scenarios.

Acknowledgements
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[6] LD50 or semi lethal dose of a particular substance is a measure of how much constitutes a lethal dose. The dose administered that kills half the test population is referred to as the LD_{50}, for "Lethal Dose, 50%".

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[8] The EPANET simulations are performed by Luke Bartlein and Tim McPherson at Los Alamos National Laboratory.