Irrigation Efficiency using a Systems Dynamics Model: A Case Study of a Pepper Crop in La Merced - Peru

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Abstract. This paper presents a system dynamics simulation model for an irrigation system applied to bell pepper crops, integrating various components of a cropping system, including water usage and plant growth. The study focuses on Latin American regions with limited irrigation facilities, highlighting the importance of simulation techniques to analyze different levels of analysis for irrigation components, including water wastage. The increasing global population, food security, and water management concerns require innovative approaches to overcome difficulties and paradigms in crop irrigation. The simulation model proposed in this study provides insights into the irrigation system's behavior and explores various scenarios to optimize crop yield while minimizing water wastage. Results obtained through simulation demonstrate the dynamics between irrigation time and water discarded in a crop, considering the complex behavior of living systems. The paper's contribution highlights the value of simulation models as a powerful tool for analyzing and improving crop irrigation systems, ultimately contributing to sustainable agriculture and water management practices.

Keywords: Irrigation Model, Pepper Crop, System Dynamic, Waste Management.

1 Introduction

1.1 The role of agriculture

Agriculture plays a crucial role in feeding the world's growing population and contributing to economic development [1]. However, water scarcity and inefficient use in agriculture have become significant challenges globally, particularly in arid and semiarid regions [2]. Irrigation is an essential component of agricultural production and has contributed to improving productivity and profitability [3]. Nevertheless, it also faces challenges such as unequal water distribution and inadequate irrigation methods [4]. According to the International Atomic Energy Agency [5], improving water use efficiency in agriculture is critical to meeting growing food demand while also preserving water resources. System dynamics modeling has been used to analyze the interactions and feedbacks between water, agriculture, and other factors, providing insights into the system's behavior and identifying potential solutions [6].

1.2 Irrigated agriculture

Irrigated agriculture has played a critical role in enhancing agricultural productivity in Latin America. It accounts for more than 60% of the region's agricultural production [7]. However, it also faces various challenges, including inefficient water use, inadequate infrastructure, and poor management practices [8]. Efforts to improve irrigation efficiency in Latin America have focused on adopting best management practices, including modernizing irrigation infrastructure, using precision irrigation systems, and promoting water-saving technologies. Such practices have been shown to increase water use efficiency and reduce water waste [9].

The use of system dynamics modeling can help identify the potential impacts of different management scenarios on the system and can inform decision-making processes. For example, modeling can be used to simulate the impact of climate change on water availability and crop production, and to assess the effectiveness of different adaptation strategies [10]. Efficient irrigation practices and the adoption of best management practices can also contribute to more sustainable and resilient agriculture systems, which can enhance their productivity, economic viability, and environmental sustainability. In turn, this can contribute to the development of more vibrant rural economies, including increased job opportunities and income generation.

Types of irrigation. Irrigation can be classified into several types based on the method of water delivery to the crops [11]. According to the FAO report [12] , irrigation efficiency is defined as the ratio of water beneficially used in crops and the total water used in irrigation practice. The following Table 1 gives a summary of some of the most common types, and the percentage of efficiency in each type of irrigation.

Table 1. Type of irrigation and efficiency.

Irrigation Type	Cost	Efficiency in water use	Use of technology	Crop yield	Percentage of efficiency
Flooding	Very Low	Very Low	Null	Low / Medium	40 – 50%
Furrow	Low	Low	Low	Medium	50 – 70%
Sprinkler	Medium	Medium	Medium	Medium / High	70 – 80%
Drip or underground	Very High	Very High	Very High	High	90 – 95%

Irrigation efficiency. Irrigation efficiency refers to the amount of water applied to crops that is used by the plants for growth and development. A high irrigation efficiency means that more water is being used for crop growth and less is being lost to non-productive sources, leading to higher crop yields and less water waste [13]. Improving irrigation efficiency is crucial for sustainable water management and food security,

especially in regions with limited water resources. The irrigation system is complex. On the one hand, it is necessary to use less water for the crop in a shorter time but, on the other hand, the farmer seeks to maximize crop productivity with the available water and losses from the irrigation system. To solve this dilemma, the use of a system dynamics approach and determination of the optimal amount of water for the crop is proposed.
Consequently, the main problem is the failure to use water resources and the amount of water needed for agricultural use. The purpose of this study is to apply a dynamic water management model to a bell pepper crop to determine the amount of water available for the crop in La Merced and the future trend under conditions of climate change and a growing demand for water. The contribution of this article is to highlight the value of simulation models as a powerful tool to analyze and improve crop irrigation systems, ultimately contributing to farmer decision making and efficient water use with sustainable management.

2 Literature review

System dynamics is a methodology that uses computer simulation models to analyze and understand complex systems over time [14]. It can be applied to irrigation systems to identify key variables and feedback loops, and to test different scenarios and interventions for improving system performance. Table 2 shows the literature reviewed, detailing the approach evaluated in each case.

Table 2. Reviewed literature on irrigation efficiency with a system dynamics approach.

Reviewed papers	Summary
Dynamic Simulation of Irrigation Efficiency in Surface Irrigation Systems [15]	This article presents a dynamic simulation model for irrigation efficiency in surface irrigation systems. The model uses a system dynamics approach and considers factors such as soil infiltration, crop water uptake, and irrigation system design. The model is tested on a hypothetical field and results show that it can accurately predict irrigation efficiency under various conditions.
Modeling Irrigation Efficiency with a System Dynamics Approach [16]	This article presents a system dynamics model for analyzing irrigation efficiency in agricultural systems. The model incorporates factors such as weather conditions, soil characteristics, crop water requirements, and irrigation system design. The authors apply the model to a case study in the Texas High Plains and show that it can accurately predict irrigation efficiency under different conditions.
Using System Dynamics to Improve Water Use Efficiency in Irrigated Agriculture [17]	This article presents a system dynamics model for improving water use efficiency in irrigated agriculture. The model considers factors such as soil characteristics, crop water requirements, and irrigation system design. The authors apply the model to a case study in Iran and show that it can be used to identify opportunities for improving water use efficiency in the region.

The classical causal model is a type of system dynamics model that uses causal loops to represent the feedback relationships between variables in a system [18]. In the context of irrigation, the classical causal model can be used to identify the factors that affect irrigation efficiency, such as irrigation scheduling, crop water requirements, soil type and moisture, and irrigation system design. Based on these reviews and the models used, we propose the use of the system dynamics approach with different scenarios, varying the discard fraction and irrigation time.

The objective of this article is to value simulation models as a powerful tool to analyze and improve crop irrigation systems, ultimately contributing to farmer decision making and sustainable water management in agriculture.

3 Methodology

The case study will be based on the systems thinking methodology [18]; there are four stages involved with the execution of the system dynamics model. It begins with the identification and definition of the problem; followed by system conceptualization, model formulation, model testing, and evaluation, model use, implementation and dissemination, and learning/strategy/infrastructure design. The steps required to model and simulate the complex system based on systems thinking in the case study are detailed in Fig. 1.

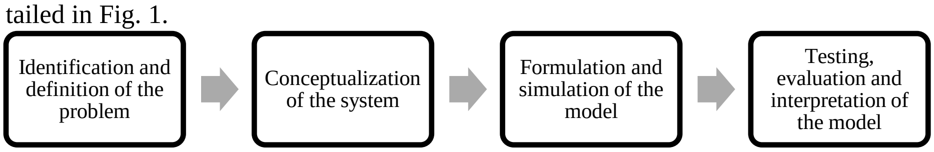

Fig. 1. Systems thinking methodology.

4 Case study

For the identification and definition of the problem, a Randomized Complete Block Design (RBLD) was used to observe and analyze plant behavior and water consumption in localized irrigation for a small plant (less than 30 days, before flowering) and a large plant (more than 30 days, after flowering until fruit development) versus flood irrigation in a bell pepper crop in La Merced-Peru (Fig. 2).

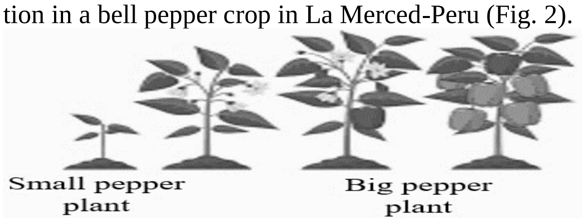

Fig. 2. Bell pepper plant growth.

The system dynamics simulation model was applied to the data obtained in the experiment. The significant variables for the simulation were: irrigation time, amount of water used, irrigation area, and plant behavior.

The bell pepper (Capsicum annum L.) is a fruit vegetable. It is very important from a commercial and nutritional point of view, as it is used both fresh and processed and is rich in vitamin C [19]. It represents an essential source of income for family farming in Peru. Furthermore, as its cultivation, production and trade rises, the demand for it also increases.
The simulation model applied to the problem considering different amounts of water and the available time for irrigation is analyzed using system dynamics methodology. During the experiment, we observed that the irrigation time for small pepper plants can be divided into specific intervals: quarter, half, and no more than an hour. However, for big pepper plants, we estimated that the irrigation time should vary between 30 minutes, one hour, and one and a half hours based on our observations during the experiment. It is important to note that these observations were made during the real experiment. Sections 4.1 to 4.3 present the general description of the irrigation system. Then, Sections from 4.4 to 4.7 present the verification and validation of the applied model simulation. Finally, the results are shown in section 5. The following sections present the models for analyzing an irrigation system and the simulation results.

4.1 The classical causal loop diagram for irrigation systems

In system dynamics, a Causal Loop Diagram is used to represent a conceptual model for a particular system. Modelling an irrigation system using this approach allows us to start with basic variables and simulate behaviors to study dynamics. The Causal Loop Diagram (CLD) for an irrigation system is based on six interrelated variables.
The variable **Irrigated Area** is considered a stock variable that accumulates all behaviors. The **Increase Rate** and **Discard Rate** variables impact how the irrigated area behaves. The irrigation system is controlled by limiting elements, including the **Planned Irrigated Area**, **Irrigated Area Adjustment Time**, and **Discard Fraction**, which can be established or determined by the analyst. In Section 4.3, we provide more context on the related variables. For the irrigation system studied in this work, the variables in the Classic Irrigation System Causal Loop represent the following elements.

- **Stock variable:** The irrigated area accumulates the dynamics for the increase rate and discard rate showing the main goal of the conceptual model [18].
- **Secondary variables:** The increase rate is a function of the planned irrigated area and irrigated area adjustment time that could be deterministic or not. The behavior of the discard rate is limited by the discard fraction that represents how much water can be discarded in the system and depends on the area being irrigated at the time.
- **Limiting variables:** Planned irrigated area is the specific value that is going to be irrigated. Irrigated area adjustment time is related to the time that we expect to have for irrigating the planned irrigated area. Discard fraction represents the fraction of water that is allowed to spend during the irrigation.

Both feedbacks in the conceptual model correspond to balancing loops because the model is seeking a specific goal which is to irrigate the planned area within a specific time (Fig. 3).

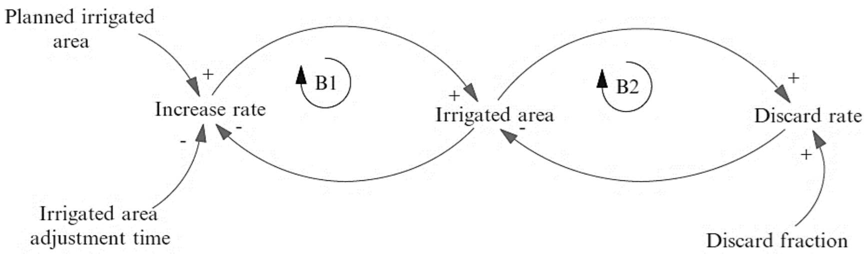

Fig. 3. Causal Loop Diagram from a classic irrigation system.

The Irrigation CLD explains how an irrigated area depends on different variables and can stress other behaviors. Nowadays it is important to grow different crops but considering that not too much water should be discarded. This literature model can be transformed and applied to a real crop, as we propose in this paper.

4.2 The mathematical model for the irrigation system

The classic CLD for irrigation systems is defined by a mathematical model that represents the irrigation system dynamics using the main variables. Equations from 1 to 5 explain the mathematical relations for the classical irrigation model.

$$Irrigated\ area = A = \int \frac{A}{t_0} dt' = \frac{A}{t_0} t' \Big|_0^t = A \frac{t}{t_0} \tag{1}$$

$$A = \int_0^t increase\ rate(dt) - \int_0^t discard\ rate(dt) \tag{2}$$

$$t_0 = irrigated\ area\ adjustment\ time(time\ units) \tag{3}$$

$$Increase\ rate = \frac{(Planned\ area - Irrigated\ area)}{t_0} = \frac{A}{t_0} \tag{4}$$

$$Discard\ rate = Irrigated\ area * Discard\ fraction \tag{5}$$

4.3 Stock and flow diagram for irrigation system

Fig. 4 shows the Stock and Flow Diagram (SFD) for the irrigation system that we analyzed. This model is the interpretation of the theoretical CLD for an irrigation system and is programmed into the Vensim simulator. The SFD or the system of the differential equations represents the feedback structure about the CLD for irrigation systems [18]. For the verification and validation conceptual model, we propose general data just to obtain the behaviors and use them with the real parameters of the crop. There are three main variables: irrigated area, irrigated area increases rate and irrigation area discard rate. The stock variables area limited by the condition of irrigation, the inflow-increasing rate and decreased-by-one outflow discard rate [18]. Also, irrigated area adjustment time and discard fraction are variables that limit the irrigation system. In this section, we present the results of the verification process. We programmed two irrigation models: the first is a General Model based on SFD (Fig. 4), which uses general data for verification and validation.

The time units used for the model were years and hours (h), and areas were measured in square meters (m^2). Table 3 presents the parameters for each variable of the Irrigation Models.

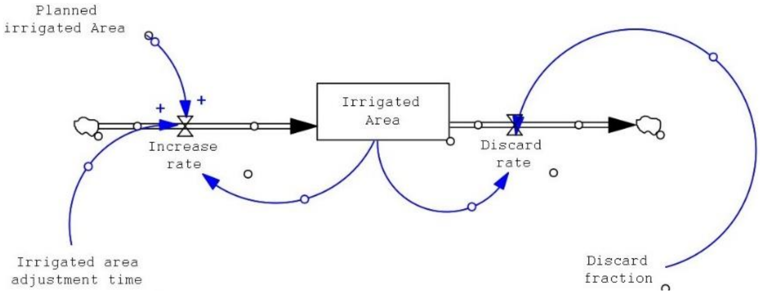

Fig. 4. Vensim Lay-Out of Stock and Flow Diagram for Irrigation Model.

An ongoing simulation has been developed using the six classical variables defined by experimental parameters. A study on the cultivation of real pepper crops is being conducted in Peru. Simulation is an optional way of obtaining valuable data in a shorter time. It also allows us to observe the different behaviors when testing various water percentages, depending on the irrigation technique being studied. In this paper, a General Irrigation Model was established to verify and validate the simulation. With appropriate data from the real crop and literature, we programmed the Applied Irrigation Model. Following simulation methodologies from the literature [20], we propose to verify and validate a general conceptual model and its application. Sections 4.4 and 4.5 present the verification and validation tests of the irrigation system simulation. To verify the simulation model, we conducted structural and behavioral verification tests, parameter verifications, and simulations under extreme conditions based on Kleijnen [21] y Sargent [22]. Additionally, for model validation, we planned the irrigation area and set the simulation time to run the experiments. To validate the simulation results of the applied simulation model, we presented the results to a pepper crop expert.

4.4 Verification of Irrigation Models

In this section, we present the results of the verification process. We programmed two irrigation models: the first is a General Model based on SFD (Fig. 4), which uses general data for verification and validation.

The second model, named the Applied Irrigation model, uses data from the real crop and literature. To verify the models, we applied four different tests based on the Verification and Validation process (V&V process) mentioned by Sargent [22] and Kleijnen [21]. Firstly, we verified the structure of the conceptual model in Vensim Layout, followed by reviewing the equations and parameters proposed in the programmed model. Then, we observed the behavior of partial and final outputs, such as the increase rate and irrigated area. We started with a simplified model using general data, and the General Irrigation Model was simulated using the same variables and relations programmed in Vensim software from the Stock and Flow Diagram. However, the set parameters were general data for testing the final simulation time for the real parameters (see Table

3). The following table shows the data programmed for this simulation model. Finally, we used the animation of the behavior to observe the operation of the irrigation simulation model [22]. To determine if the model is sensitive to the simulation time, we found that this parameter cannot be excluded from verification because the results need a particular simulation time to be consistent. Thus, the simulation time will be validated for the Applied Irrigation Model in section 4.5.

Table 3. Reviewed literature on irrigation efficiency with a system dynamics approach.

Variable	Units	General Irrigation Model	Applied Irrigation Model (Results)	Units
Planned Irrigated Area	Hectare (ha)	1000	205	(m^2)
Irrigated Area	(ha)	0.25	-	(m^2)
Discard fraction	(1/year)	0.1	0.35	(1/year)
Discard rate	(ha/year)	Max (Irrigated Area * discard fraction, 0)		(m^2/h)
Increase rate	(ha/year)	Max (Planned Irrigated Area - Irrigated Area / Irrigated area adjustment time, 0)		(m^2/h)
Irrigated Area adjustment time	(year)	0.20	(h)	(h)
Final Time	(year)	1	3	(year)

4.5 Validation of Irrigation Models

Based on the V&V process, we conducted several tests to validate the Irrigation Model, including graphical comparisons of data, animation, and expert opinion, following the guidelines suggested by Sargent [22] and Kleijnen [21]. In Peru, the irrigated area for pepper crops is typically around 180 m^2. To ensure the validity of our simulation results, we validated the parameter for this variable. Table 3 presents the values programmed in Vensim, and we compared the obtained irrigated area with the objective of the simulation (180 m^2), as shown in Fig. 5a. We used 205 m^2 as the parameter for the simulation model and observed how the discard rate changed during different simulation times (Fig. 5b; Table 4). We found that a simulation time of three years was acceptable for the experiments. Furthermore, the general irrigation model also resulted in a simulation time of three years (Fig. 5c).

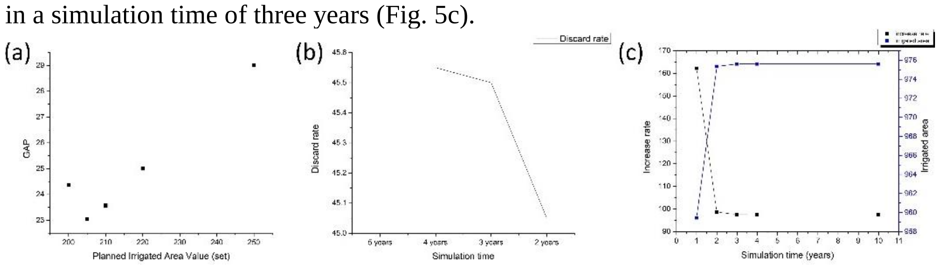

Fig. 5. Validation results from Irrigation Models. (a) represents the gap between the set planned irrigation area and the simulation value. (b) shows the consistency of discard

rate value obtained in different simulations. (c) compares the simulation time programmed into Vensim.

Table 4. Validation results of planned irrigation and for simulation time.

	Validation results of planned irrigation area		Validation results for simulation time	
Set planned irrigation area (m^2)	Simulation value (m^2)	Discard rate	Simulation time (years)	Discard rate
200	175.63	43.91	5	45.55
250	221.00	55.49	4	45.55
220	195.00	48.00	3	45.50
210	186.43	46.60	2	45.05
205	181.96	45.49	-	-

The behavior presented in the CLD is validated by the SFD simulation, as shown in Fig. 6. This indicates that the structure of the model is consistent with the behavior of the system. To verify the parameter for an irrigated area of 205 m^2, we conducted a simulation of the model and obtained the irrigation time required for this area. The verification process included comparing the simulated results with real-world data, as well as analyzing the sensitivity of the model to different input parameters. To ensure the accuracy of the model, a warm-up simulation time of three years was required, which is consistent with the simulation results.

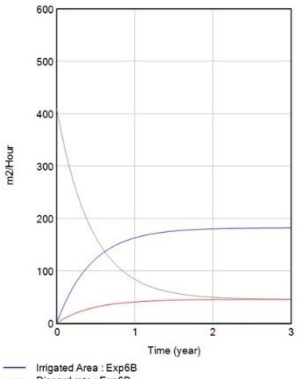

Fig. 6. Behaviors obtained from validation.

4.6 Application of an irrigation simulation model for a crop

The following behaviors correspond to the results of a simulation for a pepper crop cultivated in Peru. For about four months, the simulation used parameters obtained by means of real experimental design under ambient conditions. To find the answers to the above questions, we proposed different scenarios that estimated the possible behavior of one plant in a crop. We decided to run the model with parameters that belong to one plant. We designed two main scenarios for the simulation:

- **Scenario 1**. What are the system dynamics for a small pepper plant from crop A?
- **Scenario 2**. What are the system dynamics for a big pepper plant from crop A?

With both scenarios, we propose 30 different simulation experiments, considering the combination of the different possible values of the time setting for an irrigation area and the discard fraction depending on irrigation technique by zones. The simulation was performed using the following model assumptions:

- A small plant has a shorter irrigation time than a bigger one.
- The discard fraction is higher when the plant is smaller because they have smaller roots.
- The crops can be irrigated by different techniques, such as flooding and localization. The value of the water discarded by crop facilities is reflected by the percentage of water wasted. And more, these values are different between a global parameter than Latin America or Peru areas.
- The irrigation time for a pepper plant is from 10 to 60 minutes depending on the size.

4.7 Data for the model

To ensure the simulation model achieves its objectives, two types of data were used and are listed in Table 3. The use of both data sets ensures that the water volumes discarded from irrigating the crop at various times are accurately determined (see Table 3, Table 4 and Table 5). The specific data set for the pepper crop simulation was used to simulate and study the behavior of different irrigation scenarios. These parameters were based on the literature recommendations for irrigation efficiency in pepper crops (see Table 5). For global behavior, 0.10 is the value presented in the literature for the localization technique and 0.25 for the flood irrigation technique. In the case of Peru, records show that 45% of the water is wasted by flood irrigation and 35% of the water is wasted in the case of the rest of Latin America. The simulation model allows us to explore different discard fractions to waste less water in the cultivation of a crop. Furthermore, we use this data to propose different experiments to study different discard fractions and irrigation times for the crop. In summary, using both the generic and specific data sets allowed for accurate determination of water volumes discarded from irrigating the crop at various times, and helped achieve the objectives of the simulation model. As outlined in Section 4, we derived the variation of irrigation time from our observations during the real experiment. The values tested in the Irrigation Model were obtained through a combination of various parameters, and the details of each experiment are available in a publicly accessible repository called “Irrigation Efficiency_EUROSIM2023” [23] . We represented the discrete values for irrigation time and discard fraction based on the relevant literature and the real experiment as follows:

- Irrigation time: discrete values from 0.25 to 1.5 hours
- Discard fraction: from 0.10 to 0.45 depending on the crop irrigation technique and the geography (see Table 5).

Table 5. Parameters of different discard fractions used in the model.

Discard fractions used for the simulation model	Parameter
Discard fraction for small plants	0.25
Discard fraction for big plants	0.18
	0.15
Discard fraction in Peru	0.45
Discard fraction in Latin America	0.35
Sustainable Discard fraction (by localization)	0.10

The values of 0.10 and 0.25 for the localization and flood irrigation techniques, respectively, are commonly reported in the literature for the global behavior. However, in Peru, empirical records demonstrate that as much as 45% of water is wasted through flood irrigation, while the rest of Latin America experiences a 35% waste rate. To address this challenge, the simulation model is used to explore different discard fractions that may help to reduce water wastage during crop cultivation. Based on this data, several experiments are designed to study the impact of different discard fractions and irrigation times on the crop. Table 5 provides five distinct values for the discard fraction that are used in the simulation experiments. To determine the parameters for larger pepper plants, we rely on real-world experiments conducted over four months. To evaluate the efficiency of the proposed irrigation system, we simulated the above parameters using the developed model. The obtained results are presented and analyzed in detail in the following sections.

5 Results

5.1 Analysis of discard rate results

The results of the simulation experiments are classified under these different criteria: not obtain adequate parameters for an effective irrigation system, the time setting for an irrigation the discard rate, and sustainable irrigation options. Moreover, the experiment results are given for small and bigger pepper plants. In this first step of the analysis of the experiment results, only the behavior of the discard rate is considered.
Fig. 7 shows that not every experiment is adequate for an effective irrigation system. The results classified as sustainable show that a long irrigation time and low water discard fraction mean less water wastage. The details about the simulation parameters for each experiment can be found in repository presents the details about the simulation parameter for each experiment [23] (Irrigation Efficiency_EUROSIM2023). The simulation results indicate that the irrigation system is more sensitive for small pepper plants than for bigger ones. Moreover, if the goal is to determine better conditions for

less water waste, the irrigation time should not be rushed. Thus, the efficiency of the irrigation system and the water wasted in the zones can radically decrease. Based on the simulation results, we propose to analyze the results from its dynamics rather than just focusing on how much water can be discarded. The next section presents the second step of the experiment analysis.

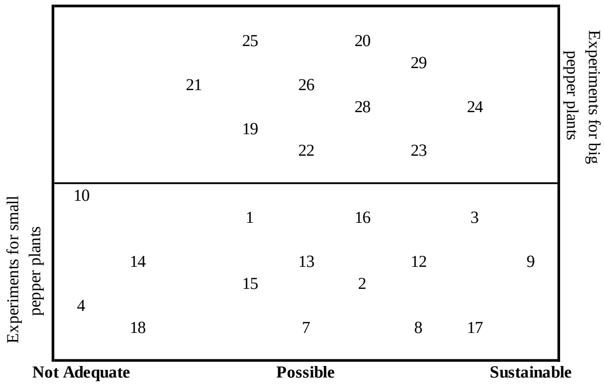

Fig. 7. Classification of simulation experiments results for small and big pepper plants.

5.2 Analysis of irrigation system results

The second step of the analysis of the experimental design is to study the dynamics that happen when different amounts of water can be used during many irrigation times. The simulation results allowed us to investigate the effects of shortening or lengthening irrigation time on small and big pepper plants. Table 6 presents the feasible experiments for the Irrigation Model experiment design based on parameter combinations.

Table 6. Classification of the experiments for an efficient irrigation system.

Discard fractions parameter	Experiments for small pepper plants			Experiments for big pepper plants		
Real experimental value	1	2	3	19	20	21
Sustainable discard fraction	7	8	9	22	23	24
Peru discard fraction	11	12	13	25	26	27
LA discard fraction	15	16	17	28	29	30

The results were divided into feasible and non-feasible categories based on irrigation time, discard rate behavior, and irrigation area achievement. The feasible experiments are shown in white cells, indicating that the parameters used in those experiments can produce an efficient irrigation system. For small pepper plants, experiments 1, 2, 7, 8, 11, and 15 provided information about water discard during crop irrigation. For big pepper plants, experiments 19, 22, 23, 25, and 28 yielded results about water volumes and irrigation time. Experiments 4, 10, 14, and 18 were found to be non-feasible for an effective irrigation system as they did not reach the planned irrigation area in the

expected time. More details about the results can be found in repository [23] (Irrigation Efficiency_EUROSIM2023). Experiments 5 and 6 served as a starting point for combining certain parameters to validate the simulation models.
The simulation results indicate that increasing irrigation time does not always result in complete coverage of the irrigation area. Besides, not all the irrigated adjustment time parameters are feasible for every discard fraction. For example, if the system allows more water (0.45 or 0.35) to be discarded, then the irrigation area could not be completed, even if the irrigation time is increased. In other words, the increment of time is just for the wasted water and does not mean that the irrigation system is more efficient. Contrary to expectations, the simulation results indicate that increasing irrigation time may not always lead to greater efficiency in the irrigation system. Experiments 25 and 26 demonstrate that insufficient increments in irrigation time can result in inadequate water usage for the crops. That strategy only allows for wasting a higher amount of water. This happens because the irrigated adjustment time is not a variable that enhances the efficiency of an irrigation system, using a high discard fraction. Rather, according to experiment 23, a lower value of the discard fraction can improve efficiency. These results propose changes in irrigation techniques to achieve an effective irrigation system and sustainability. Every modification implies costs, infrastructure, and agricultural labor. The crop used for this simulation is cultivated in Latin America, where financial resources are limited. It is worth noting that the irrigation system can be sustained without relying on crop technification, as demonstrated by Experiment 19 which achieved a lower discard fraction than the current value used in Peru. About the possible amount of water that can be used in the real crop, the following Table 7 present the water quantities that can be discarded depending on the irrigation time and the discard fraction.

Table 7. Feasible values for the crop.

	Experiments for small pep-per plants (For an irrigation time of 15 and 30 minutes)		Experiments for big pep-per plants (For an irrigation time of 30 and 60 minutes)	
	Location Irrigation	Flood Irrigation	Location Irrigation	Flood Irrigation
Real experimental value	2.50 L	5.50 L	2.20 L	3.80 L
Sustainable discard fraction	1.00 L	2.20 L	1.15 L	2.16 L
Peru discard fraction	4.50 L	9.90 L	5.18 L	10.8 L
LA discard fraction	3.50 L	7.70 L	4.00 L	7.56 L

Through simulation, we verified that the only result of increasing irrigation time is more water being wasted. It also allowed us to test different discard fractions to evaluate irrigation systems. This would be very complicated to carry out in real life as it would require the farmers to have the necessary time, funds, know-how and re-sources.

6 Discussion and conclusion

In conclusion, irrigated agriculture in Latin America requires careful management and optimization for its sustainability and productivity. System dynamics modeling and best management practices can enhance the efficiency of water use, improve crop yields, and increase the economic and social benefits for farmers and rural communities. Our results demonstrate that the implementation of a state-of-the-art irrigation system, managed by a skilled technician, is necessary to achieve a sustainable discard rate and an appropriate discard fraction. This will ultimately help to minimize water waste in crops, promoting sustainable agriculture. However, an irrigation system's efficiency cannot be based solely on the discard fraction, as the time required to irrigate the entire crop area also plays a crucial role. Our simulation results show that increasing irrigation time results in more water wastage, making it challenging to evaluate different irrigation systems in real life. Non-conventional techniques such as system dynamics provide information about water efficiency and pave the way for future studies to help Latin American crop production, including finding the proper irrigation times for different zones and adapting irrigation systems to crop conditions, climate, and economic possibilities. Future work can also focus on analyzing water availability, amounts, and budget using different techniques. Ultimately, our study highlights the importance of investing in infrastructure and adopting innovative approaches to improve the sustainability and productivity of irrigated agriculture in Latin America.

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