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Open-Source Design of Infiltration Trenches for Sustainable Soil and Water Conservation in Rural Areas of Central Chile

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Abstract: Specific algorithms are developed to solve the equations that define the physical dimensions under various conditions. In this sense, the storm index method was incorporated for the variable precipitation intensity, expanding the number of rainfall stations with the intensity duration frequency (IDF) curves from 9 to 31 within the considered territory (the Biobio Region of Central Chile). Likewise, the infiltration values and runoff coefficients necessary for calculating the dimensions of the trenches were obtained using the Python programming language. The results show that an open-source Python solution allows high reliability and efficiency based on the tests developed. For this reason, this prototype is expected to add new mathematical expressions that may arise to better account for an efficient design of soil and water conservation works or infiltration trenches. In this way, it is concluded that it is possible to develop simulation models for the efficient design of trenches based on well-defined and limited theoretical modeling, adding to computer language tools. This allows for a virtuous synergy that can help address efficient public policies to conserve soil and water in Chile and elsewhere.

Keywords: software; design; water conservation; erosion control; aquifer recharge

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1. Introduction

One of the main environmental problems in Chile corresponds to soil erosion, mainly that caused by water (water erosion) [1–3]. In this framework, government programs have been carried out for the recovery of degraded soils for both agricultural and forestry use, through water and soil conservation works [4,5]. One of the most applied water and soil conservation works are infiltration trenches (Figure 1), which are flat channels built on slopes aimed to capture water and soil that run off, reducing surface erosion processes and enhancing water infiltration into the soil [6,7]. They are built transversely to the slope and can have a trapezoidal, quadrangular, or rectangular sections [8]. As Cantonati et al. [9] and García-Colin et al. [10] highlight, technical elements based on the site's characteristics and the climatic and edaphic environment are involved in their design, which determines the specific dimensions in a framework of water efficiency for each place considering the territorial singularities of the various areas where they can be built. Thus, the main technical elements are the depth of the rainfall in a given period

and the soil conditions reflected in terms of infiltration capacity and the runoff that it can generate [11,12]. However, this approach specificity means that there are difficulties in its design, mainly due to the availability of required information. In this sense, the government programs for the recovery of degraded soils in Chile define the dimensions of the trenches, requiring a minimum of 25 cm at the base and 40 cm in height for a large portion of the territory [13], minimizing in situ singularities of precipitation and soil infiltration.



Figure 1. Examples of infiltration trenches in central Chile, courtesy of Roberto Pizarro.

Generally speaking, in order to study the interaction of hydrogeodynamic and hydrogeothermal regimes, it is necessary to identify the qualitative certainty of the dynamic structure of the underground flow under conditions of spatial heterogeneity of the temperature field, i.e., to study thermocolmatation processes and their influence on the performance of water intake structures. Along with this, it is necessary to conduct full-scale and experimental studies in natural conditions to determine the characteristics of infiltration water intakes and develop methods for determining their main parameters, considering operation in harsh climatic and complex environmental conditions [14]. However, a fundamental element for the design of hydraulic works is the intensity duration frequency (IDF) curves, which provide the maximum annual intensity for a given duration and return period [15–17]. These curves provide valuable information for designing and planning hydrological and hydraulic infrastructures, water resource management, and risk assessment associated with intense rainfall events [18,19]. In this way, IDF curves represent a fundamental aspect of hydrology when estimating extreme rainfall events [20,21].

With technological advances, various specialized tools and software have been developed to generate and analyze IDF curves [17,22]. These programs typically incorporate advanced algorithms, climate databases, and hydrological modeling techniques to estimate precipitation intensities accurately [23]. As pointed out by Herman et al. [24], there are commercial and open-source solutions for the generation of IDF curves, tools that depend on the quality of their inputs, underlying assumptions, and the precision of the models used, in addition to the specific needs of the study and the characteristics of the area of interest. Considering the above, this work presents an open-source Python application of already validated models and accurate and current data for a region of central Chile, an area undergoing extreme water scarcity [25,26].

Python is an open-source programming language that makes writing and maintaining code easier due to its straightforward and readable syntax [27]. Python libraries and frameworks are widely available for various purposes such as PyGames for video game development, Django for web development, and TensorFlow for machine learning [28]. This integration and extensive capability makes Python a preferred choice for multidisciplinary projects that require robust and scalable solutions. The open-source nature of Python fosters an active community of developers, resulting in regular updates, technical support, and a wide range of educational resources [29]. Thus, we applied Python's advantages to the development of infiltration trench design.

Several authors have focused their studies on automating the design of infiltration trenches. For example, Wang et al. [30] developed a hybrid model integrating cost–benefit analyses with a stochastic approach for urban areas in Beijing (China), providing a useful tool for metropolitan water management, while Rowe et al. [31] also focused on the cost-effectiveness of infiltration trench design in urban areas of Ontario (Canada). Moreover, Campisano et al. [32] mathematically simplified the design of infiltration trenches based on rainfall–runoff process models for urban areas, while and Nieć et al. [33] focused on seepage models. Finally, Creaco and Franchini [34] developed a dimensionless mathematical procedure for the design of infiltration trenches. Despite the above, the creation of a software specifically used for the design of infiltration trenches is, to the best of our knowledge and based on scientific publications, a novel approach. Based on the above, this study presents the development and application of a computational tool to facilitate the design of infiltration trenches based on hydrological engineering criteria to be applied in central Chile, based on already existing equations and local knowledge. This software seeks to automate the design process of infiltration trenches considering territorial singularities such as precipitation intensity and infiltration rates, facilitating the implementation of these structures in restoration programs for degraded environments as well as water conservation.

2. Methodology

2.1. Study Area

The study area is located in the Biobío Region, covering the southern limit of the central zone of Chile, between 36°26′ and 38°29′ [35]. It has an area of 37,069 km^2. Its climate is mainly Mediterranean, with longitudinal variations and rainfall concentrated in winter months (Figure 2). From the geomorphological point of view, the traditional units of the Chilean topography are distinguished, such as the Andes mountain range, the intermediate depression, the Coastal mountain range, and the coastal plains [36]. These variations in climate and geomorphology translate into a variation in rainfall in the territory [37], which raises the need for computer tools to use and analyze rainfall records.

The area has 9 manual stations and 22 automated rainfall stations (Figure 2), which were used to estimate the IDF curves for the open-source solution under evaluation.

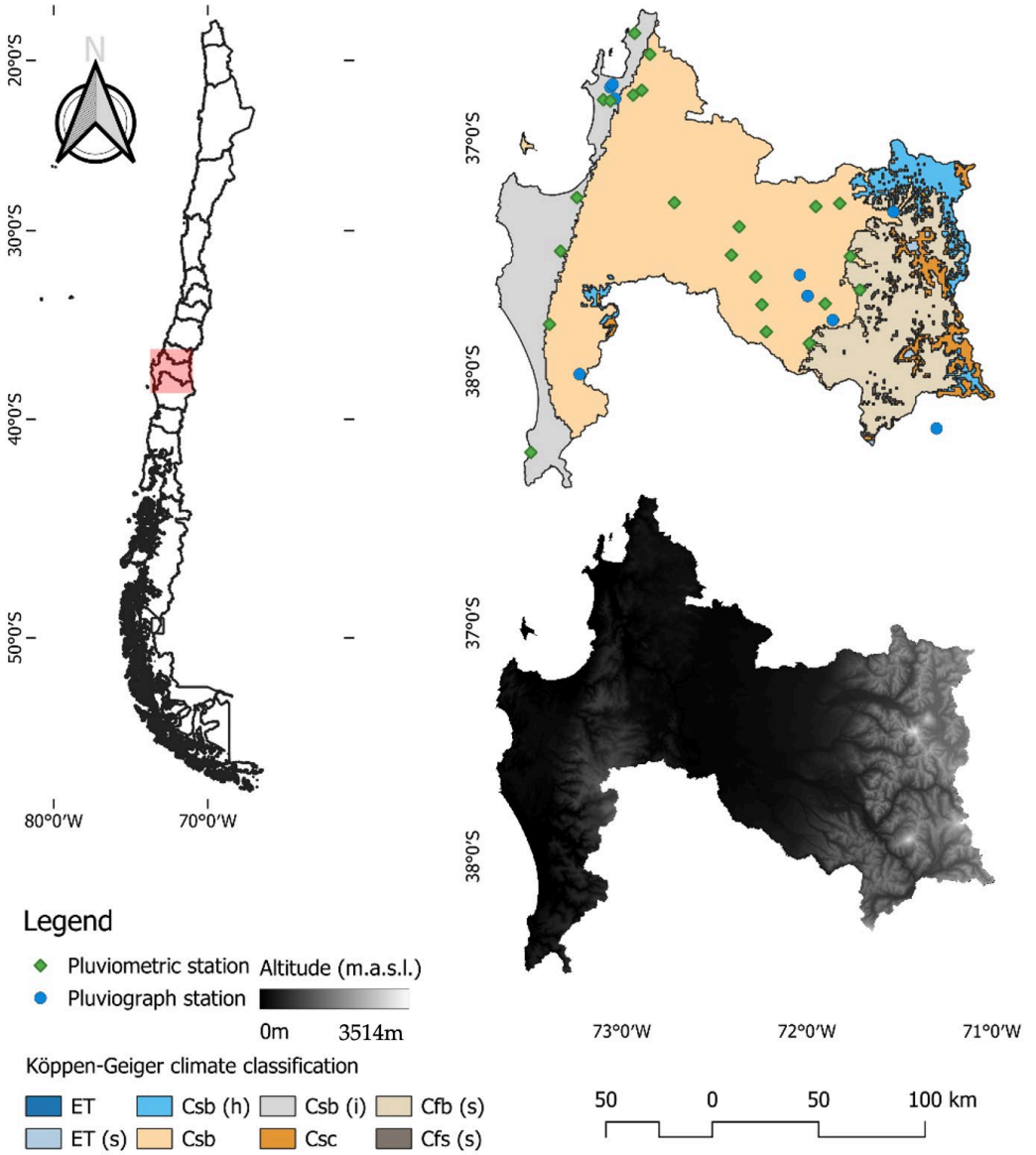


Figure 2. Location of study area within Chile, showing where each used rainfall station was installed, as well as the general topography of the area. Own work with data from Sarricolea et al. [38].

2.2. Design of Infiltration Trenches

Differently from other hydraulic structures such as dams, the design of infiltration trenches does not require advanced tools such as satellite imagery or geographic information systems. The basic principle for an efficient design of infiltration trenches is that they must be capable of capturing all of the surface runoff generated upstream of the trenches during storm events [11,39]. In other words, the volume of water contributed by the catchment area must be less than or equal to the volume captured by the trench, as illustrated in Figures 3 and 4. Equations (1) and (2) represent the mathematical expression of the previous statement [11].

$$Ve \leq Vo + Vi \quad (1)$$

$$Ve = I * Ai * e \quad (2)$$

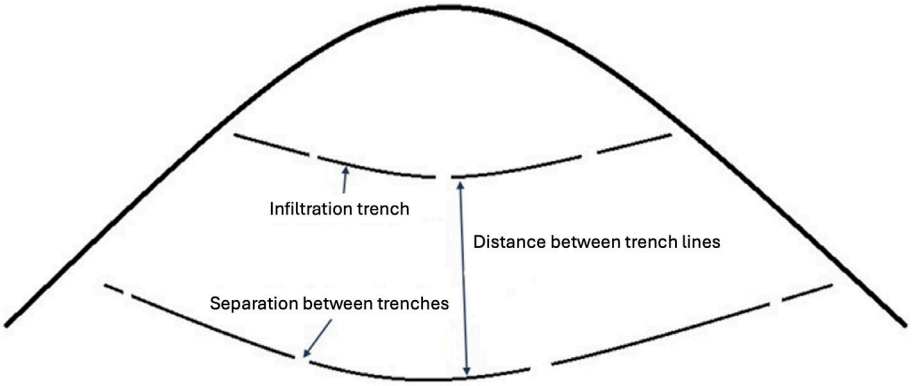
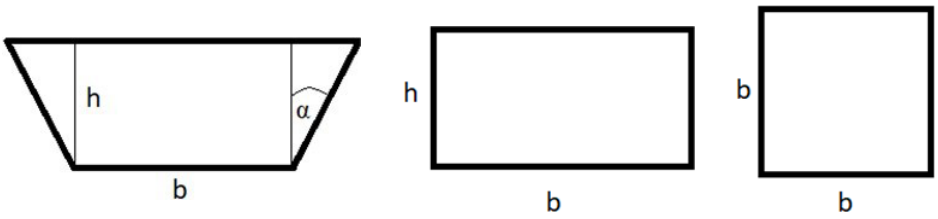


Figure 3. Scheme of the location of infiltration trenches on the slope of a hill.



(**a**) Trapezoidal (**b**) Rectangular (**c**) Square

Figure 4. Section diagram of infiltration trenches.

As Pizarro-Tapia et al. [11] describe, *Ve* is the runoff volume (m^3) from a given rainfall depth based on the contributing area (m); *Vo* is the collected volume within the structure (m^3); *Vi* is the infiltrated volume (m^3); *I* is the maximum rainfall intensity for one hour with a specific return period (mh^{-1}); *Ai* is the drainage area (m^2); and *e* is the runoff coefficient. This work assumes that the dimensions of the infiltration trenches are previously defined, so the unknown variable to be calculated is the horizontal distance (dh, m) between trench lines. Then, from the described equations and solving and reducing terms, mathematical expressions are obtained (see [11]) to define the dh for trenches with trapezoidal section (Equation (3)), rectangular section (Equation (4)), and quadrangular section (Equation (5)).

$$dht = \frac{b * (h + Vin) + h^2 tg\alpha}{I * e} \quad (3)$$

$$dhr = \frac{b * (h + Vin)}{I * e} \quad (4)$$

$$dhc = \frac{b^2 + b * Vin}{I * e} \quad (5)$$

where *dht* is the horizontal distance between trapezoidal trench rows (m); *dhr* is the horizontal distance between rectangular trench rows (m); *dhc* is the horizontal distance between square trench rows (m); *b* is the trench's base (m); *h* is the trench's height (m); α is the slope angle (°); and *Vin* is the infiltration rate ($m\ s^{-1}$).

A limitation of this mathematical hydrological analysis is that it only considers the liquid flow and not the solid flow (sediments). This determines that these types of works must be periodically maintained so that they do not become filled with sediments, which leads to collapses. Thus, the dimensions reached by the respective equations will be able to respond to the physical reality of the place.

2.2.1. Design Rainfall

The IDF curves developed for the Biobío Region [40] were used to obtain the design rainfall. This study incorporated nine automatic rain gauges (stations with continuous recordings). The storm index tables corresponding to each station were also used (see [16]).

In the territory under study, there are also 22 manual rain gauges (see Figure 2), that is, stations with one record every 24 h, in which the storm index (IT) method was used [16,40]. This method allows the construction of IDF curves based on maximum intensity information in 24 h. To do this, it is assumed that each rainfall station can be associated with a rainfall station with similar behavior in terms of maximum 24 h intensities [16].

2.2.2. Infiltration Rate

The infiltration rate is defined as the velocity with which water penetrates the soil, generally expressed in mm h^{-1} or cm h^{-1}, and depends on the soil's physical properties and its moisture content [41,42]. For this work, tabulated values from Horton's method were used for different types of soil and types of vegetation cover [43] (see Table 1).

Table 1. Maximum average infiltration capacity according to the soil and vegetation present using Horton's method [43].

Floor	Little Vegetation (cm h^{-1})	Dense Vegetation (cm h^{-1})
Dry sandy	12.7	25.4
Silty dry	7.6	15.2
Clayey dry	2.5	5.0
Sandy wet	4.2	8.5
Silty wet	2.5	5.0
Clayey humid	0.8	3.6

2.2.3. Runoff Coefficient

The runoff coefficient is defined as the proportion of rainfall that generates surface runoff [44]. The magnitude of the runoff coefficient varies between 0 and 1 and depends on factors such as storm intensity, soil and vegetation cover characteristics, slope, and basin area [45,46]. These estimates respond to empirical frameworks developed in Chile [47], which have been tested in various water and soil conservation projects, experimentally. However, their application is low, a consequence that requires new technical knowledge for those who work in these areas, as is the case of IDF curves and water infiltration into the soil. Hence, it is important to input these estimates into a mathematical simulator, which allows them to be operationalized, with a view to their widespread use in various areas within the national territory and even in other countries. For the design of infiltration trenches, it is preferable to use values close to 1 (0.8 or 0.9) as runoff coefficient to avoid unfavorable situations [48].

2.3. Python Application

The simulator was built based on the Python language, an open-source, freely accessible, and very versatile programming language, with the aim being to create a web and desktop software application [49,50]. Python has an extensive publicly available library. For the app's graphical development, PyQT5 was used, which is a binding of the QT graphical library for the Python programming language [51]. PyQT5 allows the quick and easy creation of graphical interfaces with Python. As previously mentioned, the readability of the Python code makes it an easy task to create graphical interfaces. For instance, the classic 'Hello World!' example in Python is simply written as 'print("*Hello World*! \n");' (note that it contains only one line of coding).

Another of the libraries that was used in this study for the development of the simulator application is OpenPyXL [52]. This Python library is used to read/write Excel 2010 files with the xlsx/xlsm/xltx/xltm extensions. It was born from the lack of an existing library to natively read/write the Office Open XLM format from Python. This library can be used in the PyCharm program Community Edition 2022.1.3 [53]. Using this module allows the designer to control Excel without opening the application. It is used to perform Excel tasks like reading data from an Excel file, writing data to the Excel file, drawing some charts,

accessing the Excel sheet, changing the name of the sheet, modifying (adding and deleting) data in the Excel sheet, formatting and designing the sheet, and any other related task.

Once intensity information was available for the different areas of the Biobio region, with infiltration data and runoff coefficients, it was now possible to build a simulator to design infiltration trenches [11,54]. The resulting simulator was a desktop application developed in Python. The computer expression is established based on the algorithms proposed by the mathematical design of infiltration trenches. A parameter input module was considered, and two cases were differentiated: a standard section, independent of the shape of the trench section, and the second specific to the type of trenches considered. Table 2 shows the input variables for the program based on the kind of trench considered.

Table 2. Input variables for the program according to the shape of the infiltration trench.

Input Variables	Trapezoidal Trench	Rectangular Trench	Square Trench
Common variables			
Intensity (m h^{-1})	x	x	x
Runoff coefficient	x	x	x
Infiltration speed (m h^{-1})	x	x	x
Trench base (m)	x	x	x
Specific variables			
Height (m)	x	x	
Slope angle (°)	x		

Finally, the open-source solution was validated by means of the mean absolute error (MAE, Equation (6)) between the horizontal distances calculated by the open-source solution and those obtained using an Excel spreadsheet.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (6)$$

where y is the horizontal distance (dh) calculated in the Excel spreadsheet; $\hat{y}$ is the estimated dh in the open-source solution; and n is the number of observations. In addition, the time taken to estimate the dh was evaluated using both methods, for various types of trenches.

3. Results

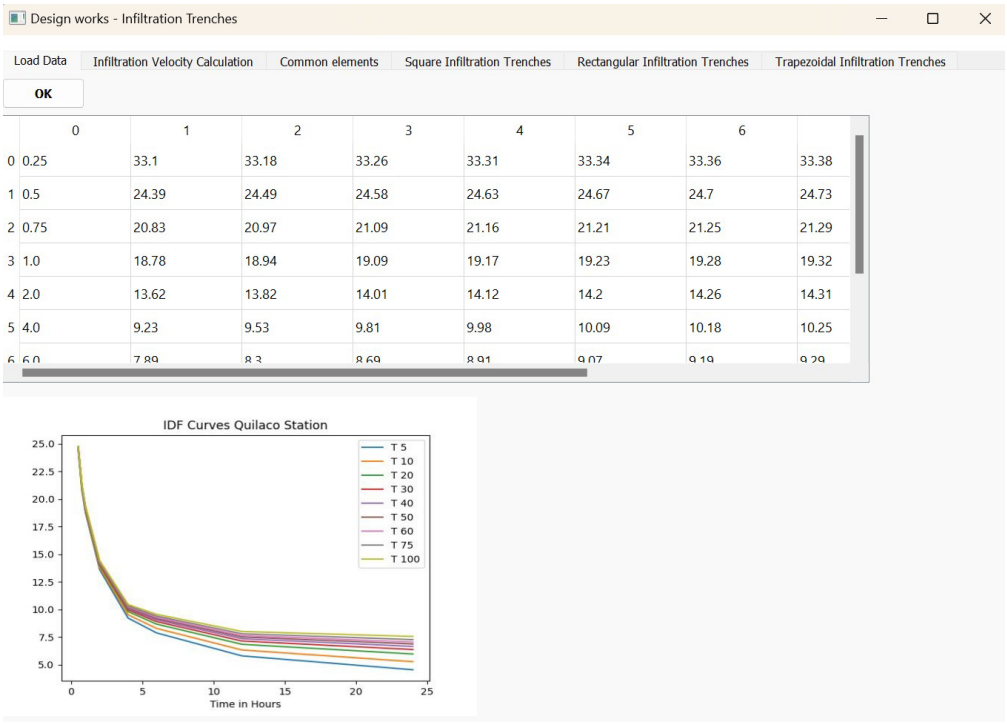
The main result of this study is the open-source solution. To show its operation, a case analysis was carried out for the "Quilaco" rainfall station. Figure 5 shows the precipitation intensities and IDF curves created for this station. In this tab, the user can select the duration and return period, thus obtaining the intensity of precipitation for the area where the trenches will be designed.

In addition, the open-source solution provides tabulated values to estimate the infiltration rates based on the previously mentioned Horton's formula (Figure 6). In this tab, the user can obtain the infiltration rate by entering the type of soil and vegetation in the area. Additionally, if the user has measured or estimated infiltration values, these can be included in the software or modified (Figure 7), in order to calculate dh.

In the common elements tab, it is also possible to modify the rainfall intensity (I in mh^{-1}), the runoff coefficient (e, although it is recommended to leave high values as a safety factor), and the base (b in m) used for trench design. In the case of trapezoidal trenches, the trench's cross-sectional angle must be included in the Trapezoidal Infiltration Trenches tab (Figure 7).

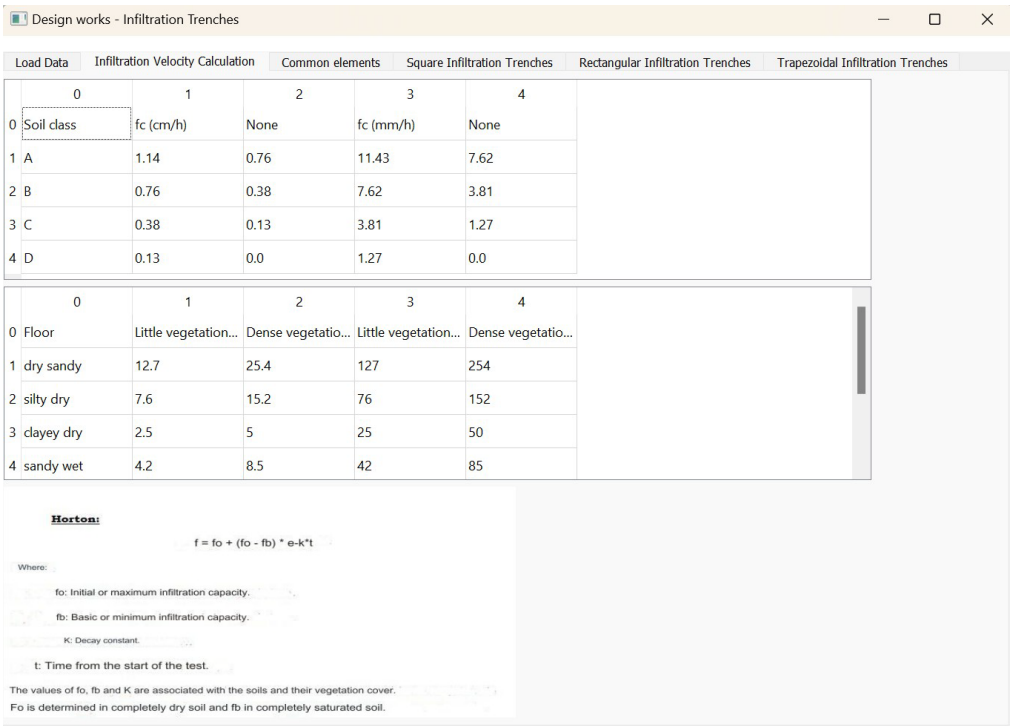
The open-source solution was validated to corroborate that the estimates made coincide with the traditional method, using a calculation spreadsheet (Excel). For this, 40 cases were considered and MAE was estimated, with no differences found in the estimates (MAE = 0). It is important to note that the open-source solution is an automation of the

method used in the Excel spreadsheet, and therefore, the MAE must be 0 (i.e., the results should be the same).



	0	1	2	3	4	5	6	
0	0.25	33.1	33.18	33.26	33.31	33.34	33.36	33.38
1	0.5	24.39	24.49	24.58	24.63	24.67	24.7	24.73
2	0.75	20.83	20.97	21.09	21.16	21.21	21.25	21.29
3	1.0	18.78	18.94	19.09	19.17	19.23	19.28	19.32
4	2.0	13.62	13.82	14.01	14.12	14.2	14.26	14.31
5	4.0	9.23	9.53	9.81	9.98	10.09	10.18	10.25
6	6.0	7.89	8.3	8.69	8.91	9.07	9.19	9.29

Figure 5. Intensities at different return periods and durations with their respective IDF Curve. The values of the IDF curves come from previous work carried out in the study area (see [40]).



	0	1	2	3	4
0	Soil class	fc (cm/h)	None	fc (mm/h)	None
1	A	1.14	0.76	11.43	7.62
2	B	0.76	0.38	7.62	3.81
3	C	0.38	0.13	3.81	1.27
4	D	0.13	0.0	1.27	0.0

	0	1	2	3	4
0	Floor	Little vegetation...	Dense vegetatio...	Little vegetation...	Dense vegetatio...
1	dry sandy	12.7	25.4	127	254
2	silty dry	7.6	15.2	76	152
3	clayey dry	2.5	5	25	50
4	sandy wet	4.2	8.5	42	85

Figure 6. Calculation of infiltration velocity in the simulator. The values in the Horton table were obtained from Cao et al. [43].

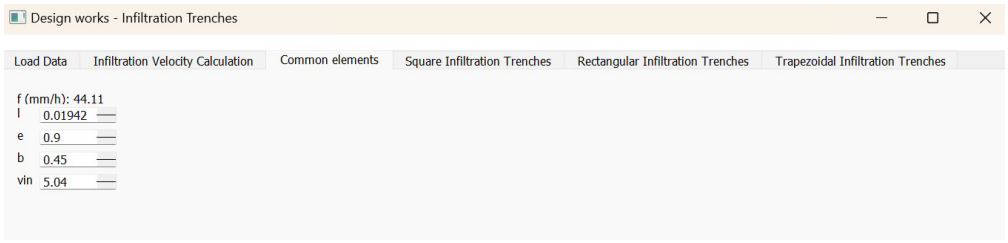


Figure 7. Input variables of common elements to be used in the design of the different types of trenches. Precipitation intensity values come from the Quilaco station (I); the runoff coefficient (e) is close to 1 (recommendation by Pizarro et al. [48]); the base was made according to values recommended by Carrasco et al. [55]. Likewise, the tabs Trapezoidal Infiltration Trenches, Rectangular Infiltration Trenches, and Square Infiltration Trenches estimate dh using equations 3, 4, and 5, respectively.

The performance of the open-source solution was assessed in comparison with the traditional design method. One criterion used was the feasibility of using both tools (execution), another was the execution time, and a third was the precision of the results. In the first criterion, it was considered that the probability that a user has a spreadsheet application is 100%, but not everyone has Python to run this software. However, a self-executing version can be created to improve access to the program. In the case of the second criterion, the software is between 107 and 200% faster than the traditional method (Table 3). Considering the criterion related to the precision of the obtained results, there is no difference between the two tools. Table 3 summarizes the comparison based on the defined criteria.

Table 3. Software efficiency analysis compared to calculation on an electronic spreadsheet.

Criterion/Type of Trench	Execution Time (%) *	Precision
Trapezoidal	150	1
Rectangular	107	1
Square	200	1

* Percentage value when comparing the time of the traditional method versus the open-source solution.

As an example, the results of the open-source solution are presented in three conditions for the Biobío region, namely, (a) coastal (Carriel Sur), (b) intermediate depression (Los Ángeles), and (c) foothills (Quilaco), represented by their respective rainfall stations. For this, the dimensions of the trenches recommended by the Degraded Soil Recovery Program [19] were entered, and the horizontal distance between the rows of infiltration trenches was estimated for each situation (Table 4).

Table 4. Calculation of the design parameters for infiltration trenches on the three analyzed stations.

Variable	Carriel Sur	Quilaco	Los Ángeles
I (mm h^{-1})	28.9	19.1	19.8
Infiltration velocity (mm h^{-1})	44.1	44.1	44.1
Base (cm)	35	35	35
Height (cm)	40	40	40
Distance dh (m)	7.1	10.8	10.4
Volume (m^3 ha^{-1})	238.5	157.5	163.5

The results of this test show that for higher rainfall intensities, the software decreases the spacing between the trenches. That is, the software optimizes the layout of the trenches based on the rainfall and infiltration information of the study area (i.e., the distance between the infiltration trenches is optimal when considering the volume precipitated in the rainfall area). Nevertheless, the variation in parameters is wide depending on what mathematical

expressions allow for each case. In reality, however, this variation is limited, meaning that it is not possible to think in practical terms about trenches with height or base dimensions greater than one meter (they are normally much smaller, for cost limitations).

4. Discussion

The results from the open-source solution are the same as those obtained from the traditional method. However, the open-source solution minimizes human error, since it automates solving equations, achieving reliable results equivalent to the traditionally used method. Likewise, the open-source solution increases efficiency in the design of infiltration trenches, allowing one worker to design up to three trapezoidal trenches at the same time it takes to create one using the traditional method. The open-source solution can also be used with the storm index, thus estimating the horizontal distance in areas devoid of rain intensity information.

Finally, the validation of the model was a success; it was carried out by contrasting the computing efficiency and precision of obtained software solution's results versus the use of an Excel spreadsheet for the design of various infiltration trenches. There were no significant differences, but in terms of computing time, our application was more efficient. Our software application was developed in consideration of user requirements.

The use of infiltration trenches for soil and water conservation, as well as favoring the infiltration of water into the soil, has a very ancient origin [56]. However, in Chile, their construction has always obeyed previously defined values that do not incorporate aspects of hydrologic precision to reduce costs, on the one hand, and to make the process of water infiltration into the soil more efficient, on the other. In this sense, the methodology used by the open-source solution for the design of infiltration trenches, by equating the volume of the stormwater area with the volume captured by the structures, allows the estimation of the optimal horizontal distance between trenches so that their capacity is not exceeded. Furthermore, by using runoff coefficient values close to unity, an additional safety factor is generated [48].

At a global level, there are other techniques to design infiltration trenches such as the method used by Pruski et al. [57]. Although this technique is easy and quick to apply, it requires having precipitation intensity values and inputs and knowledge of the curve number methodology for its application. Another way to estimate the dh between trenches was used by Chinchilla-Ureña et al. [58], defining the distance based on the surface runoff calculated with the curve number; although this way of calculating the distance is simple to apply, not using the precipitation intensity for the design of the trenches represents a risk for overflows to occur. Moreover, Flores Villanelo [59] implemented three trench design models in his doctoral thesis, programming the models in Matlab to simplify their application. However, since they are programmed in Matlab, their application is limited since the license is prohibitive for most consultants and requires knowledge of Matlab language. The application presented herein is programmed in Python and self-contained, can be widely distributed and free of charge; thus, it allows the technology to be democratized, especially in consultancies focused on the restoration of degraded soils as well as water conservation.

The open-source solution provided, which assumes the conceptual and mathematical frameworks already described, and makes them freely available, in a powerful computer language that reduces processing times and ensures dimensions based on hydrological science. This is important in a country where precipitation falls in winter and large volumes of water are used during summer [60]. Therefore, promoting the infiltration of water into the soil to recharge the aquifers and use them as natural reservoirs is an objective that must be achieved and done so in areas where infiltration trenches are a very appropriate tool [61,62]. However, resources must be used in the most efficient way possible, and this software points to a need for rational use and strengthening nature-based solutions.

Using hydrology software enables the simplifying of calculations for modeling hydrological processes in watersheds [63], thus yielding reliable results for watershed management [64]. However, to the authors' knowledge, no specific open-source software packages

are available to address the design of infiltration trenches. One Excel spreadsheet, CUBHIC 2.0 [65], and an online platform developed by the Engineering Standards for Water and Soil Center (EIAS) at the University of Talca were found. However, the latter has been discontinued and is offline. Although there are paid software applications for designing works (e.g., DC-infilt, MicroDrainage, Flores Villanelo, 2016 [59]), their licenses are expensive, limiting their use. This restriction on access to software for trench design prevents their overcrowding, and for this reason, spreadsheets or simply calculators are still used to estimate the spacing between trenches. However, the use of these tools is prone to error, since the formulas must be entered manually, increasing the possibility of a typing error, and if the formula was not built considering future modifications (i.e., intensity values, base, height, and infiltration were left fixed in the formulas), the formula must be modified, increasing the possibility of errors.

In this context, this open-source solution simplifies the trench design process. The above allows structures to be designed that, on the one hand, capture the volume of surface runoff during storms and, on the other hand, reduce costs and implementation time, a derivative that optimizes the spacing between the trenches. Additionally, while being open-sourced, it can be easily updated and avoids the risk of going offline, as is the case with the EIAS platform.

Despite all the above, a limitation of the proposed software is that it only has the IDF curves of the Biobío region, making its application and use specific to the local area. However, the code will be published so that it can be updated to different regions or countries in the future.

5. Conclusions

The simulator obtained based on the Python language has shown high flexibility and efficiency, so this prototype is expected to be used recurrently. New mathematical expressions can be added to better account for an efficient design of soil and water conservation works such as infiltration trenches.

In conclusion, it is possible to develop simulation models for the efficient design of infiltration trenches based on well-defined and limited theoretical modeling and considering computer language tools available in a broad spectrum, in a virtuous conjunction that can help address efficient public policies to conserve soil and water.

The construction of this software and its application recommendations makes it possible to fill the gaps in knowledge, on the one hand, and tends toward greater economic and structural efficiency of the resources, pointing to the reduction in erosive processes and the recharge of aquifers, on the other hand. In this framework, the software represents a great step toward facilitating the efficient design of infiltration trenches.

However, in the future, more specific parametric values should be established for the various territories, especially those related to the infiltration of water into the soil, given that in a country such as Chile this is a value that differs in only meters due to soils with high textural variability and composition, which conditions the infiltration rate over close distances.

Finally, it is recommended that this simulation model be extended to works with various design characteristics and based on other considerations such as including vegetation variables that could guide the afforestation of these areas, expanding the framework of action from hydrotechnics to biotechnics. Similarly, and needless to say, it is recommended for this valuable experience to be replicated in other parts of Chile and the world.

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