Journal of Civil and Hydraulic Engineering
https://www.acadlore.com/journals/JCHE

Evaluation of Rainwater Harvesting and Bio-pore Infiltration Holes for Flood Mitigation and Soil Conservation

Naharuddin Naharuddin[1*], Sudirman Daeng Massiri[1], Hendra Pribadi[1], Arman Maiwa[1], Muhammad Ihsan[2]

[1] Department of Forestry, Tadulako University, 94148 Palu, Central Sulawesi, Indonesia
[2] Mercy Corps Indonesia, 94231 Palu, Indonesia

[*] Correspondence: Naharuddin Naharuddin (nahar.pailing@gmail.com)

Received: 06-12-2024 **Revised:** 08-02-2024 **Accepted:** 08-08-2024

Citation: N. Naharuddin, S. D. Massiri, H. Pribadi, A. Maiwa, and M. Ihsan, "Evaluation of rainwater harvesting and bio-pore infiltration holes for flood mitigation and soil conservation," *J. Civ. Hydraul. Eng.*, vol. 2, no. 3, pp. 142–150, 2024. https://doi.org/10.56578/jche020302.

Abstract: Rainwater harvesting (RH) techniques, specifically the implementation of Bio-pore Infiltration Holes (BIH), have been investigated as cost-effective and practical methods for managing surface runoff and mitigating flood risks. This study aimed to evaluate the infiltration rates of BIH in secondary forest and agricultural moorland areas, providing a basis for sustainable soil and water conservation practices. A survey methodology was employed to assess infiltration rates using the Horton equation model applied to circular holes with a depth of 50 cm. Soil samples were collected from the vicinity of the BIH for analysis of physical properties at the Soil Science Laboratory, Faculty of Agriculture, Tadulako University. A 4-inch diameter PVC pipe, inserted 30 cm into the soil, was used to measure water infiltration, with water levels recorded up to 60 cm. The findings indicated that infiltration rates in both secondary forest and agricultural lands were moderate. The physical characteristics of the soil, including its texture and organic carbon content, were identified as suboptimal, which constrained the efficiency of waste absorption through the infiltration process. The soil texture in both land types was classified as sandy according to USDA standards, making it susceptible to erosion, which is directly related to the infiltration capacity and the potential for soil transport during erosion events. The carbon organic content was relatively low, at 2.50% in secondary forest land and 1.17% in agricultural land, indicating medium-level criteria for organic content. To enhance soil conservation and flood mitigation, it is recommended that efforts be made to increase organic material content through compost application and post-flood land rehabilitation. Expanding the use of BIH in high-risk flood areas is advocated to effectively reduce and control surface runoff.

Keywords: Rainwater harvesting (RH); Bio-pore infiltration holes (BIH); Infiltration; Soil physical properties; Flood

1 Introduction

Flood, earthquake, hurricane, storm, forest fire, volcanic eruption, and landslide are natural processes that have shaped the earth's landscape for thousands of years and are a major danger [1, 2]. These processes can cause natural disasters when they interact with human-made features such as settlements, agriculture, and infrastructure. Flooding has been recognized as one of the worst disasters [3, 4] and the most frequent natural disaster in the world [5–7], affecting hundreds of millions of people. Additionally, it causes social and physical losses and significantly influences the country's economic condition.

In the last decade, Indonesia has often faced repeated floods in many areas due to its high vulnerability compared to other countries. Flooding is often linked with forest destruction and land degradation, particularly in the upstream portion of the river basin. Furthermore, flood discharge in a river plays an essential role in designing a soil erosion control plan as well as assessing water yield potential. This also serves as a basis for determining and managing the risk of environmental damage [8].

Floods and landslides have been identified as the main environmental problem issues in Central Sulawesi Province since 2019, which have been recorded to increase annually by 41% (2015), 54% (2016), 60% (2017), and 59% (2018) [9]. During 2023, natural disasters such as floods in Central Sulawesi ranked first compared to others such as drought, tornadoes, forest and land fires, abrasion, earthquakes, and landslides. Data from the Central Sulawesi Regional Disaster Management Agency (RDMA) in 2024 shows that floods occurred 57 times more than other natural disasters. Balongga Village, Sigi Regency, is one of the recorded places concerned with incidents of flood disasters, leading to a significant decrease in agricultural productivity. This phenomenon affects the community, where rainfall patterns are not decisive, showing the need for an effective and long-term strategy. With frequently recurring flood patterns and current climate change projections, the future of food security depends on productivity and the availability of food reserves, as well as efforts to overcome the challenges posed by climate risks such as flooding [10–12].

In order to overcome climate risk challenges such as flood control, this is in line with sustainable development goals. Sustainable development goals have been discussed by the United Nations (UN), which proposed 17 Sustainable Development Goals for 2030 [13, 14]. These include access to clean water (Goal 6), affordable energy and clean (Goal 7), sustainable cities and communities (Goal 11), and action to avoid the impacts of climate change (Goal 13). RHS are promising technologies that can contribute to achieving this goal. Moreover, rainwater can be used for drinking and non-potable purposes, resulting in the conservation of raw and treated water as well as saving resources used in water processing and distribution.

In an effort to mitigate floods and conserve soil, the technology for making BIH has been implemented. BIHs are holes made perpendicularly (vertically) into the ground, with a diameter of between 10 and 25 cm and a depth of around 100 cm, or not exceeding the depth of the ground water table. RH through BIH has proven to be a simple process (simple technology) used to save rainwater by collecting, storing, channeling, and purifying rainwater flowing from open land. Sustainable water management through RH covers several aspects, such as decentralizing public water supply systems and providing assistance in flood protection [15]. This serves as a method of diversifying water sources and providing better water security [16]. The increase in water security has demonstrated rainwater sustainability to reduce climate change impact, causing heavy rain for a longer duration [17]. Prolonged days without rain can affect water supply services. It shows the need for RH to reduce the impact of climate change and minimize the environmental effects of buildings and cities to enhance sustainability. BIH is one of the concepts of water conservation that involves storing some of the surface runoff or rainwater into the ground (infiltration), especially during the rainy season [18]. This concept can be called part of a flood control system because it aims to reduce the amount of runoff that has the potential to increase flood discharge [19].

Water conservation efforts are carried out by supplementing soil through infiltration processes, such as making BIH to prevent water scarcity [20]. Additionally, BIH is an appropriate technology that is easily implemented, cheap, and useful in minimizing surface runoff rates. Apart from functioning in water conservation, it can also control flooding. Infiltration measurements were carried out using the Horton model. The Horton model has been widely used to simulate infiltration under waterlogging conditions. The Horton model is good for handling unstable rainfall events by calculating infiltration capacity and waterlogging time based on cumulative infiltration. However, the Horton method has weaknesses in the continuous infiltration simulation process. The working principle of BIH is to improve environmental conditions, particularly the hydrological characteristics and ecosystems of river basins.

Based on the background, the aim of this research is to determine the soil infiltration rate based on the Horton model in secondary forest and agricultural land as a solution to reduce flooding and the basis for sustainable soil as well as water conservation.

2 Methodology

2.1 Research Area and Time

This research was carried out from May to July 2024 in the administrative area of Balongga Village, South Dolo Sub-district, Sigi Regency, located in the Wisolo sub-river basin area, Palu river basin, with coordinate positions 1°2' - 1°3' South Latitude and between 119°50' - 119°51' East Longitude. However, secondary data collection was carried out from January to April 2024 in the Kulawi Forest Management Unit area. The geographical location is in a disaster-prone area: South Dolo District, Sigi Regency, Central Sulawesi. The research area is climate type B, with topographic conditions generally having a steep to very steep slope level. There is a narrow valley, which is the flow of the Ombi River, which divides Balongga Village, which is flanked by steep hills and has a height of 131 m above sea level. This research was conducted in two steps, namely, the first was the collection of soil samples on agricultural land and secondary forest land to analyze the physical properties. The second step was taking infiltration data on agricultural and secondary forest land. The Wisolo sub-river basin is classified as climate type B, with topographic conditions generally characterized by steep to very steep slopes. Additionally, there is a narrow valley where the Wisolo River flows, which divides Balongga Village and is flanked by a steep hill at 150 m above sea level.

2.2 Procedures for Implementing and Measuring Infiltration Rates

Infiltration measurements were carried out through RH at BIH made with a circular hole pattern applied at a depth of 50 cm, as shown in Figure 1. BIH was installed in as many as 25 pieces each for secondary forest land and agricultural land, with a distance between one BIH hole and another of 1 m, so that the total number of BIH was 50 pieces. Environmental variables of soil physical properties measured were C-organic, soil texture, content weight, and soil porosity. Soil samples were collected near the hole for physical property analysis in the Soil Science Laboratory, Faculty of Agriculture, Tadulako University. This research used a 4-inch-diameter PVC pipe as a BIH pipe. Water droplets were also measured using a PVC pipe with a diameter of 4 inches and a length of 100 cm. The pipe is inserted 30 cm into the ground and filled with water to a height of 60 cm.

Figure 1. Installation of BIH to determine infiltration coefficient

Infiltration measurements were carried out using the Horton equation model. According to the model, infiltration capacity decreases with time until a constant value is achieved. In this research, the factors influencing the infiltration capacity were observed at the soil surface rather than flow in the soil. Moreover, several surveys measuring infiltration rates, land development, land type, or compaction level have been used to calculate the influence of shrinkage.

Complete soil samples measure physical properties, including carbon organic (c-organic), texture, porosity, and bulk density. This measurement is carried out by cleaning the occupied grass to take samples and leveling the land. During this process, the sample ring is placed perpendicular to the pointed part in the lower position. The ring is hit until it is embedded using another pressure ring, which is placed on top of the first and covered with a board, thereby preventing tilting. The surrounding soil is excavated using a crowbar, and the ring is lifted. Subsequently, the ring filled with soil is sliced with a cutter until evenness is achieved, covered with a plastic bag, tied using rubber, and given a label.

Incomplete soil sampling for texture analysis and c-organic analysis is carried out by collecting samples using a shovel and drill at a depth of 20–30 cm. Approximately 1 kg of soil sample is collected around the sample ring at the point specified, which is previously determined. Subsequently, the sample is put in a plastic bag, tied, and labeled.

2.3 Data Analysis

Infiltration coefficient can be calculated using the formula according to the instructions of the studies [20–22]:

$$f(t) = fc + (f0 - fc)e^{-kt} \tag{1}$$

where,

$f(t)$: infiltration rate at time tth (cm/minute)

fc: constant infiltration rate (cm/minute)

$f0$: initial infiltration rate (cm/minute)

e: exponential number (2.718)

k: constant (-1/(m log 2, 718))

t: time (minutes)

The infiltration rate has a specific classification (Table 1), which is determined according to the US Soil Conservation Act [23, 24].

Based on Table 2, analysis of soil physical properties was carried out at the Soil Science Laboratory, Faculty of Agriculture, Tadulako University.

Table 1. Classification of infiltration rates

Criteria	Infiltration Rates (cm/hour)
Very fast	> 25.4
Fast	$12.7 - 25.4$
Somewhat Fast	$6.3 - 12.7$
Moderate	$2 - 6.3$
Somewhat slow	$0.5 - 2$
Slow	$0.1 - 0.5$
Very slow	< 0.1

Table 2. Observation variables of soil physical properties and analysis method

Observation Variables	Analysis Method	Reference
C-organic	Walkley and black	[25]
Soil Texture	Pipette	[26]
Content Weight	Gravimetry	[27]
Porosity	Gravimetry	[28]

3 Results and Discussion

3.1 Characteristics and Physical Properties of Soil

Soil physical properties are related to the shape or condition, including texture, bulk density, porosity, particle density, and C-organic. These properties play a significant role in plant root activity, absorbing nutrients, water, and oxygen as well as limiting plant root movement. One of the most widely used definitions of soil quality is the capacity of the physical properties that function within the boundaries of an ecosystem to maintain biological productivity and environmental quality, as well as improve the health of plants and animals [29]. Soil physical properties and characteristics are based on observation results in the field and analysis in the laboratory, as presented in Table 3.

Table 3. Results of soil physical properties analysis

Land Use	Content Weight (gr/cm^3)	Porosity (%)	C-organic (%)	Soil Texture			USDA Texture Grade
				Sand (%)	Dust (%)	Clay (%)	
Secondary Forest Land	1.39	43.02	2.50	91.6	4.7	3.8	Sandy
Agricultural land	1.48	39.47	1.17	87.2	12.4	0.4	Sandy

Source: Results of Soil Physical Properties Analysis from Tadulako University at Soil Science Laboratory in 2024

The results of soil texture analysis show that secondary forest land is dominated by 91.6% sand, 4.7% dust, and 3.8% clay. The agricultural land is dominated by 87.2% sand, 12.4% dust, and 0.4% clay. Texture classes in secondary forests and agricultural land are according to the USDA sandy texture classification. Based on the texture class, this soil type is classified as sandy and prone to erosion. Stated that sandy land had low productivity due to the loose structure. Therefore, texture is related to infiltration capacity and the ease of transporting soil during erosion [30].

Based on the analysis results in Table 3, the bulk weight of secondary forest land is 1.39 gr/cm^3, and agricultural land is 1.48 gr/cm^3. This shows that secondary forest has a lower bulk density than agricultural land in all soil layers. Similarly, the study [31] stated that natural characteristics could be maintained in the environment through the influence of root action, forest litter production, and soil fauna.

Soil bulk weight from low to medium is influenced by the texture, which is dominated by sand, leading to the formation of a small number of soil pores. Due to soil compaction, the bulk density value will increase further, resulting in a slow infiltration rate. This is in line with the statement by the study [32], where higher unit weight corresponds to denser soil, thereby lower porosity.

The analysis of soil porosity shows that secondary forest and agricultural land have porosities of 43.02% and 39.47%, respectively. The highest value is found on secondary forest land; thereby, water enters the ground more quickly, causing an increase in the infiltration rate. Meanwhile, the lowest value is found in agricultural land, showing that small soil porosity reduces the infiltration rate.

The results of the c-organic analysis show values of 2.50% and 1.17% for secondary forest and agricultural, respectively. The highest c-organic value is in secondary forest land and the lowest in agricultural land. An increase in c-organic content corresponds to a higher porosity value and reduced soil bulk density. Moreover, this low bulk density and the high porosity will benefit the infiltration process. Soil that contains a lot of organic matter has good physical soil properties and has the ability to infiltrate water several times so that it can reduce the risk of flooding.

The degradation of physical properties is the main process that causes soil quality loss. The changes are more obvious on land used intensively, such as agricultural, which significantly influences soil structure. This form of degradation increases soil compaction and resistance to root growth but reduces pore volume and distribution, water infiltration, aggregate stability, and development.

The input of organic matter into the soil is considered capable of providing an opportunity to improve soil properties, which then affect the rate of soil infiltration. The application of organic matter to the soil is usually specifically intended to create gaps or pore spaces in the soil so that water can enter so that it can support the balancing of soil aggregates.

In increasing the content of soil organic matter, it is necessary to provide and maintain cover crops and carry out crop rotation as 'green manure'. Cover crops and crop rotation are beneficial for overall soil health because they are planted during periods when the soil is bare, thus protecting the soil from degradation and increasing soil resilience to threats of damage to its physical and biological properties.

3.2 Infiltration on Secondary Forest Land

The analysis results of infiltration rates on secondary forest land are presented in Table 4.

Table 4. Infiltration rate on secondary forest land

Time (t) (hours)	Infiltration Rate (f) (cm/hour)
0.00	14
0.16	9.2
0.33	7.3
0.50	6.2
0.66	5.1
0.83	2.7
1.00	2.5

Table 4 shows that the decrease in infiltration rate in the 10th minute was 9.2 cm, the 20th minute = 7.3 cm, the 30th minute = 6.2 cm, the 40th minute = 5.1 cm, the 50th minute = 2.7 cm and 60th minute = 2.5 cm (values have been constant). The decrease in infiltration rate on secondary forest land was influenced by soil texture.

Figure 2 and Figure 3 show that the initial infiltration capacity was significantly faster due to soil conditions in agricultural and secondary forest land. Furthermore, contractions associated with compaction on agricultural land adversely influenced soil infiltration rates. These results are in line with the study [33], where the infiltration rate varies between compacted and non-compacted areas. Construction activities or compaction actions reduce the infiltration rate by 70% to 99%.

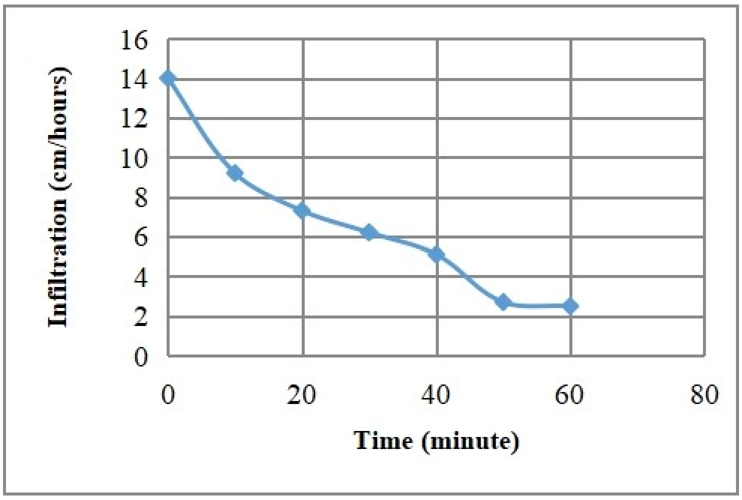

Figure 2. Infiltration rate on secondary forest land

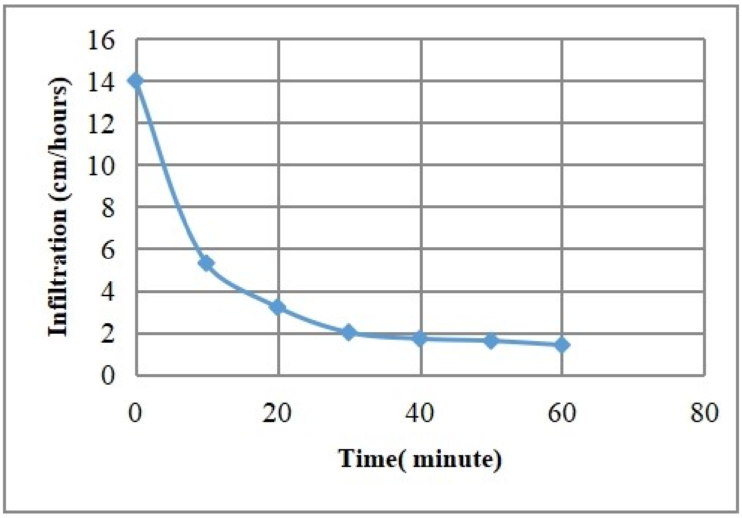

Figure 3. Graph of infiltration rate on agricultural land

The infiltration rate in secondary forest land is included in the medium criteria, as shown in Figure 2. This categorization is based on the presence of several types of vegetation and soil physical properties. It was stated that the infiltration rate in secondary forest was considered fast because the vegetation, comprising many species, contributed to water inflow. Soil density in agricultural land use areas is more significant than in agroforestry, but the porosity is lower. In comparison, the bulk density of secondary forest is smaller, while the porosity of secondary forest is greater [22]. The large number of cavities in soil facilitates the infiltration process.

3.3 Infiltration Rate on Agricultural Land

The analysis results of infiltration rates on agricultural land are presented in Table 5.

Table 5. Infiltration rate on agricultural land

Time (t) (hours)	Infiltration Rate (f) (cm/hour)
0.00	14
0.16	5.3
0.33	3.2
0.50	2
0.66	1.7
0.83	1.6
1.00	1.4

Table 5 shows that the decrease in infiltration rate in the 10th minute was 5.3 cm, the 20th minute = 3.2 cm, the 30th minute = 2 cm, the 40th minute = 1.7 cm, the 50th minute = 1.6 cm and the 60th minute = 1.4 cm (values have been constant).

Infiltration on agricultural land presented in Figure 3 is lower compared to secondary forest with medium criteria. This is due to higher activity or frequency of soil processing on agricultural land, resulting in greater bulk density, which also causes very low soil porosity. Similarly, the study [34] stated that water infiltration in forest areas tended to be superior to that in agricultural areas. Removing natural vegetation and introducing cultivated plants or animals for grazing causes a significant reduction in the water infiltration capacity of agricultural land.

Vegetation and litter layers protect the soil surface from direct hits from raindrops, which can destroy aggregates, leading to compaction and blockage of soil pores, inhibiting infiltration, and resulting in increased surface runoff. On agricultural land, vegetation, particularly trees, as a producer of organic material, is very lacking. The dominant vegetation is observed to be seedlings and undergrowth, which have short roots and are incapable of absorbing water compared to secondary forest land, with a higher organic matter content of 2.60%. The study [35] stated that the diversity of vegetation types positively influenced infiltration in both dry and saturated soil conditions through the plant root system and organic matter in the soil. The organic matter formed by the roots of forest species is deep and facilitates infiltration. However, in food and pasture crops, the roots are shallow as well as smaller in length and diameter. Secondary forests have higher levels of c-organic in the soil; thereby, the quality can also increase infiltration rates, which is essential for forming and stabilizing aggregates.

Water infiltration into soil is considered the best parameter to evaluate the physical condition of soil because the quality and structural stability influence the pore size distribution, determining the water infiltration capacity. On secondary forest land, soil generally has greater porosity because there are more macropores, which serve as the main places for water entry, distribution, and supply from the water surface. Forms of land use that increase water infiltration rates are essential when the land is to be recharged by underground reservoirs. However, river flows should be controlled during the dry season, and the impacts of flood, runoff, and water erosion require mitigation.

Land cover in secondary forests with various growth strata at tree level, root influence, and litter on the soil surface is essential in controlling land degradation because it helps maintain structure quality. The studies [36–38] reported that soil surface compaction on agricultural land caused by agricultural cultivation and machine traffic affected the shape and distribution of pore spaces, particularly bio-pores. According to the studies [39–41], biological attributes are more sensitive to changes in soil quality caused by land use and management changes than other variables.

4 Conclusions

The infiltration rate carried out using the Horton model on secondary forest and agricultural land was classified as medium. Therefore, the research area was found to be prone to flooding during high-intensity rain. This was because soil could not absorb water properly due to changes in land use, leading to prolonged water absorption.

Infiltration rate was used to describe changes in the magnitude of soil storage capacity influenced by construction activities or compaction actions. Based on the results, the high groundwater level affected the infiltration rate; thereby, each soil property had a different infiltration rate. When the ratio of rain intensity was smaller than the infiltration rate, all rainwater seeped into the ground.

Infiltration capacity was more effective on land with many plants due to their ability to facilitate water absorption. Additionally, c-organic content was relatively low, with 2.50% and 1.17% in secondary forest land and agricultural land (medium criteria), respectively. This influenced low infiltration; thereby, steps were recommended to increase the organic material content by adding organic fertilizer-based compost and post-flood land rehabilitation activities. Specific methods to increase organic matter content include composting, adding mulch, using green manure, crop rotation and crop rotation systems, using biochar, integrating animal waste and organic fertilizer, and covering crops, as well as implementing sustainable agroforestry techniques.

An integrated approach involving education, policy, partnerships, and community-based adaptation, biopore infiltration hole technology, can be widely accepted and implemented for the benefits of water management and flood risk reduction. In addition, in order to increase and accelerate rainwater infiltration into the soil, reduce the risk of puddles, improve soil quality, and increase organic matter, it is necessary to carry out targeted and sustainable development. To further support the flood mitigation aspect and the basis for sustainable soil conservation, the technical approach is not only limited to that, but community education is important to be carried out continuously.

Author Contributions

Drafting the manuscript, N.N. and M.I.; methodology, S.D.M.; validation, H.P. and A.M.; formal analysis, N.N.; resources, M.I.; data curation,S.D.M.; writing—original draft preparation, H.P.; writing, review and editing, N.N.; visualization, A.M.; supervision, S.D.M.; project administration, M.I.; funding acquisition, A.M.

Funding

The authors are grateful to Mercy Corps Indonesia for support with research funding for Contract No. 009/YMCI/SSC/PLW0025/V/24.

Data Availability

The data used to support the research findings are available from the corresponding author on request.

Acknowledgements

The authors are grateful to the Dean of the Faculty of Forestry, Tadulako University, and the MBKM students of the Faculty of Forestry, Tadulako University, who assisted in collecting primary and secondary data.

Conflicts of Interest

All authors declare no conflict of interest.

References

[1] V. Oladokun and D. Proverbs, "Flood risk management in Nigeria: A review of the challenges and opportunities," *Flood Risk Manag. Response*, vol. 6, no. 3, pp. 485–497, 2016. https://doi.org/10.2495/SAFE-V6-N3-485-497

[2] M. T. Chaudhary and A. Piracha, "Natural disasters—origins, impacts, management," *Encycl.*, vol. 1, no. 4, pp. 1101–1131, 2021. https://doi.org/10.3390/encyclopedia1040084

[3] B. Merz, G. Blöschl, S. Vorogushyn, F. Dottori, J. C. Aerts, P. Bates, and E. Macdonald, "Causes, impacts and patterns of disastrous river floods," *Nat. Rev. Earth Environ.*, vol. 2, no. 9, pp. 592–609, 2021. https://doi.org/10.1038/s43017-021-00195-3

[4] T. A. Khan, M. M. Alam, Z. Shahid, and M. M. Su'Ud, "Investigation of flash floods on early basis: A factual comprehensive review," *IEEE Access*, vol. 8, pp. 19 364–19 380, 2020. https://doi.org/10.1109/ACCESS.2020.2967496

[5] S. Wu and Y. Lei, "Multiscale flood disaster risk assessment in the Lancang-Mekong River basin: A focus on watershed and community levels," *Atmos.*, vol. 14, no. 4, p. 657, 2023. https://doi.org/10.3390/atmos14040657

[6] G. Nearing, D. Cohen, V. Dube, M. Gauch, O. Gilon, S. Harrigan, and Y. Matias, "Global prediction of extreme floods in ungauged watersheds," *Nature*, vol. 627, no. 8004, pp. 559–563, 2024. https://doi.org/10.1038/s41586-024-07145-1

[7] R. Joseph, D. Proverbs, and J. Lamond, "Homeowners' perceptions of Property-Level Flood Risk Adaptation (PLFRA) measures: The case of the summer 2007 flood event in England," *Secur. Saf. Eng.*, vol. 5, no. 3, pp. 251–265, 2015. https://doi.org/10.2495/SAFE-V5-N3-251-265

[8] S. D. Massiri, B. Toknok, and I. N. Korja, "Estimation of peak current as a basis for sustainable watershed conservation using the number-curve land conservation," *Glob. J. Environ. Sci. Manag.*, vol. 10, no. 3, pp. 1017–1028, 2024. https://doi.org/10.22034/gjesm.2024.03.06

[9] N. N. Naharuddin, S. M. M. Sadeghi, A. Malik, A. Rosyid, and A. Ahyauddin, "Peak discharge estimation to evaluate and monitor the gumbasa watershed performance, central sulawesi, Indonesia," *Agric. Eng. Int.: CIGR J.*, vol. 23, no. 3, pp. 31–41, 2021.

[10] B. H. Narendra, C. A. Siregar, I. W. S. Dharmawan, A. Sukmana, Pratiwi, and I. B. Pramono, "A review on sustainability of watershed management in Indonesia," *Sustainability*, vol. 13, no. 19, p. 11125, 2021. https://doi.org/10.3390/su131911125

[11] M. R. H, E. Warni, R. Angriawan, M. Hariadi, Y. M. Arif, and D. Maulina, "Design of flood early detection based on the internet of things and decision support system," *Ing. Syst. Inform.*, vol. 19, no. 3, pp. 1183–1193, 2024. https://doi.org/10.18280/isi.290335

[12] S. Rusadi, R. Mulyawan, U. Suwaryo, and N. Y. Yuningsih, "Implementing good environmental governance to manage coastal abrasion in Bengkalis Regency, Indonesia," *Int. J. Sustainable Dev. Plan.*, vol. 19, no. 5, pp. 1911–1919, 2024. https://doi.org/10.18280/ijsdp.190529

[13] S. Weiland, T. Hickmann, M. Lederer, J. Marquardt, and S. Schwindenhammer, "The 2030 agenda for sustainable development: Transformative change through the sustainable development goals?" *Polit. Gov.*, vol. 9, no. 1, pp. 90–95, 2021. https://doi.org/10.17645/pag.v9i1.4191

[14] W. Leal Filho, L. V. Trevisan, I. S. Rampasso, R. Anholon, M. A. P. Dinis, and L. L. Brandli, "When the alarm bells ring: Why the UN sustainable development goals may not be achieved by 2030," *J. Clean. Prod.*, vol. 407, p. 137108, 2023. https://doi.org/10.1016/j.jclepro.2023.137108

[15] Z. Huang, E. L. Nya, M. A. Rahman, T. B. Mwamila, V. Cao, W. Gwenzi, and C. Noubactep, "Integrated water resource management: Rethinking the contribution of rainwater harvesting," *Sustainability*, vol. 13, no. 15, p. 8338, 2021. https://doi.org/10.3390/su13158338

[16] C. Cook and K. Bakker, "Water security: Debating an emerging paradigm," *Global Environ. Change*, vol. 22, no. 1, pp. 94–102, 2012. https://doi.org/10.1016/j.gloenvcha.2011.10.011

[17] J. P. Eekhout, J. E. Hunink, W. Terink, and J. de Vente, "Why increased extreme precipitation under climate change negatively affects water security," *Hydrol. Earth Syst. Sci.*, vol. 22, no. 11, pp. 5935–5946, 2018. https://doi.org/10.5194/hess-22-5935-2018

[18] F. Abdulla, C. Abdulla, and S. Eslamian, "Concept and technology of rainwater harvesting," in *Handbook of Water Harvesting and Conservation: Basic Concepts and Fundamentals*, 2021, pp. 1–16. https://doi.org/10.1002/9781119478911.ch1

[19] A. Z. Jiang and E. A. McBean, "Sponge City: Using the 'One Water' concept to improve understanding of flood management effectiveness," *Water*, vol. 13, no. 5, p. 583, 2021. https://doi.org/10.3390/w13050583

[20] N. I. Khusna, S. Amin, and C. E. Sekarrini, "The effect of using biopore on flood reduction in district of Besuki, Tulungagung Regency," *Sumatra J. Disaster, Geogr. and Geogr. Educ.*, vol. 4, no. 1, pp. 100–104, 2020.

[21] K. Fan, W. Zou, P. Zhang, X. Wang, and Y. Shen, "Laboratory investigation and theoretical analysis of lateral pressure exerted by expansive soils on retaining walls with expanded polystyrene geofoam block upon water infiltration," *Geotext. Geomembr.*, vol. 52, no. 3, pp. 332–341, 2024. https://doi.org/10.1016/j.geotexmem.2023.11.005

[22] B. Qi, P. Xu, and C. Wu, "Analysis of the infiltration and water storage performance of recycled brick mix

aggregates in sponge city construction," *Water*, vol. 15, no. 2, p. 363, 2023. https://doi.org/10.3390/w15020363

[23] N. Naharuddin, A. Wahid, G. Golar, I. Rachman, A. Akhbar, and S. D. Massiri, "Soil infiltration in various areas as a basis for hydrological alterations in the Toboli Watershed, Central Sulawesi, Indonesia," *Water Conserv. & Manag.*, vol. 6, no. 2, pp. 76–80, 2022. http://doi.org/10.26480/wcm.02.2022.76.80

[24] F. Fathurrahman, I. F. Radam, and N. Novitasari, "Testing the infiltration rate of Datar Ajab Village, Hulu Sungai District," *SSRG Int. J. Civ. Eng.*, vol. 10, no. 2, pp. 25–31, 2023. https://doi.org/10.14445/23488352/IJCE-V10I2P103

[25] W. Djauhari, A. G. Koto, R. Jaya, S. R. Ayuba, A. S. Rijal, and T. Tisen, "Analysis of infiltration in various land use in the Alo River Sub-Region," *J. Geografika (Geografi Lingkungan Lahan Basah)*, vol. 4, no. 1, pp. 9–22, 2023. https://doi.org/10.20527/jgp.v4i1.8060

[26] A. Zeyede, "Optimization of the analytical method for the determination of organic matter," *J. Soil Sci. Environ. Manage.*, vol. 11, no. 1, pp. 1–5, 2020. https://doi.org/10.5897/JSSEM2019.0784

[27] D. Igaz, E. Aydin, M. Šinkovičová, V. Šimanský, A. Tall, and J. Horák, "Laser diffraction as an innovative alternative to standard pipette method for determination of soil texture classes in Central Europe," *Water*, vol. 12, no. 5, p. 1232, 2020. https://doi.org/10.3390/w12051232

[28] X. Qiu, J. Hou, N. Guo, Z. Wang, and C. Wang, "Seasonal variations and influencing factors of gross nitrification rate in desert steppe soil," *Sustainability*, vol. 14, no. 8, p. 4787, 2022. https://doi.org/10.3390/su14084787

[29] Z. Chen, P. Li, R. Anderson, X. Wang, X. Zhang, L. Robison, and O. K. Farha, "Balancing volumetric and gravimetric uptake in highly porous materials for clean energy," *Science*, vol. 368, no. 6488, pp. 297–303, 2020. https://doi.org/10.1126/science.aaz8881

[30] A. Delgado and J. A. Gómez, "The soil. Physical, chemical and biological properties," in *Principles of Agronomy for Sustainable Agriculture*, 2016, pp. 15–26. https://doi.org/10.1007/978-3-319-46116-8_2

[31] P. C. Oguike, B. M. Onwuka, and S. E. Obalum, "Soil organic matter control of water transmission properties of coarse-textured soils under contrasting land-use types in tropical rainforest," *Int. J. Hydrol. Sci. Technol.*, vol. 16, no. 1, pp. 93–106, 2023. https://doi.org/10.1504/IJHST.2023.131833

[32] V. S. Lopes, I. M. Cardoso, O. R. Fernandes, G. C. Rocha, F. N. B. Simas, W. de Melo Moura, and J. M. R. da Luz, "The establishment of a secondary forest in a degraded pasture to improve hydraulic properties of the soil," *Soil Till. Res.*, vol. 198, p. 104538, 2020. https://doi.org/10.1016/j.still.2019.104538

[33] H. C. Scheuermann Filho and N. C. Consoli, "Effect of porosity/cement index on behavior of a cemented soil: The role of dosage change," *Geotech. Geol. Eng.*, vol. 42, no. 1, pp. 351–368, 2024. https://doi.org/10.1007/s10706-023-02577-4

[34] J. H. Gregory, M. D. Dukes, P. H. Jones, and G. L. Miller, "Effect of urban soil compaction on infiltration rate," *J. Soil Water Conserv.*, vol. 61, no. 3, pp. 117–124, 2006.

[35] K. F. d. Santos, F. T. Barbosa, I. Bertol, R. de Souza Werner, N. H. Wolschick, and J. M. Mota, "Study of soil physical properties and water infiltration rates in different types of land use," *Semina: Ciências Agrárias*, vol. 39, no. 1, pp. 87–97, 2018. https://doi.org/10.5433/1679-0359.2018v39n1p87

[36] D. Wang, C. Liu, Y. Yang, P. Liu, W. Hu, H. Song, and Y. Miao, "Clipping decreases plant cover, litter mass, and water infiltration rate in soil across six plant community sites in a semiarid grassland," *Sci. Total Environ.*, vol. 861, p. 160692, 2023. https://doi.org/10.1016/j.scitotenv.2022.160692

[37] M. Tian, W. R. Whalley, H. Zhou, T. Ren, and W. Gao, "Does no-tillage mitigate the negative effects of harvest compaction on soil pore characteristics in Northeast China?" *Soil Till. Res.*, vol. 233, p. 105787, 2023. https://doi.org/10.1002/ldr.5144

[38] B. Zhang, Y. Jia, H. Fan, C. Guo, J. Fu, S. Li, and R. Ma, "Soil compaction due to agricultural machinery impact: A systematic review," *Land Degrad. Dev.*, vol. 35, no. 10, pp. 3256–3273, 2024. https://doi.org/10.1002/ldr.5144

[39] A. Maini, V. Sharma, and S. Sharma, "Assessment of soil carbon and biochemical indicators of soil quality under rainfed land use systems in North Eastern region of Punjab, India," *Carbon Manage.*, vol. 11, no. 2, pp. 169–182, 2020. https://doi.org/10.1080/17583004.2020.1721976

[40] Y. Kooch, N. Ghorbanzadeh, K. Haghverdi, and R. Francaviglia, "Soil quality cannot be improved after thirty years of land use change from forest to rangeland," *Sci. Total Environ.*, vol. 856, p. 159132, 2023. https://doi.org/10.1016/j.scitotenv.2022.159132

[41] T. A. Feitosa de Souza, S. Kormann, L. K. Laurindo, and L. J. R. da Silva, "Land use and soil properties shifts soil fauna community complexity in subtropical ecosystems," *Arch. Agron. Soil Sci.*, vol. 69, no. 11, pp. 2081–2091, 2023. https://doi.org/10.1080/03650340.2022.2135176