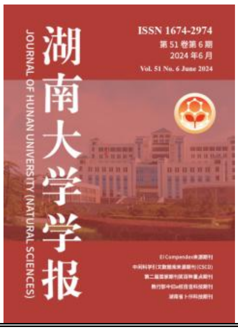

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Spatial Potential of Groundwater Recharge in Some Indonesian Rivers

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Abstract: Groundwater plays a pivotal role in hydrological systems as it is stored in an underground layer and can naturally replenish rivers, lakes, or serve as a water source. Uncontrolled groundwater pumping due to increasing clean water demand poses a threat to sustainable groundwater. Therefore, groundwater recharge capacity must be continuously maintained or even increased. Groundwater is a component of the hydrological cycle, which is replenished naturally or artificially through the infiltration of surface water, such as rainfall, into a saturated aquifer. This process of recharge has the capacity to increase the flow of discharge into rivers or lakes. The capacity of groundwater recharge in an area must be known to support integrated groundwater management. This research investigates the spatial potential of groundwater recharge. There are several techniques or methods that can be selected for estimating groundwater recharge. One such method was developed by Iwaco. This approach incorporates the principle of water balance as applicable to urban regions, having evaluated the elements of population density and land use. The formulation comprises two equations, one for examining saturated groundwater recharge and the other for unsaturated groundwater recharge. In this research, we analyzed the groundwater recharge in five areas: WS Cidanau, Ciujung, Citanduy, Indragiri, Jeneberang, and Parigi Poso. The results show that WS Parigi Poso has the highest average groundwater recharge of 619 mm/year. This is due to WS Parigi having the highest proportion of unsaturated area, which amounts to 99.3% of the total area, and only 0.7% being saturated. WS Parigi Poso, with an average percentage of yearly rainfall of 25.2%, can become the potential of groundwater recharge. Based on the results, it can be concluded that the potential of groundwater recharge depends on rainfall, saturated and unsaturated areas, and population density. The larger rainfall amounts within the region result in an expansion of the area's unsaturated zone and a decrease in population density, leading to a higher likelihood of groundwater recharge in this region.

Keywords: groundwater, recharge, river area, water balance.

印度尼西亚部分河流地下水补给的空间潜力

摘要：地下水在水文系统中起着关键作用，因为它储存在地下层，可以自然补充河流、湖泊或作为水源。由于对清洁水的需求不断增加，地下水无节制地抽取对可持续地下水构成了威胁。因此，必须持续保持甚至提高地下水补给能力。地下水是水文循环的一个组成部分，通过地表水（如雨水）渗入饱和含水层，自然或人工地补充地下水。这种补给过程能够增加流入河流或湖泊的流量。必须了解一个地区的地下水补给能力，以支持综合地下水管理。本研究调查了地下水补给的空间潜力。有几种技术或方法可供选择来估算地下水补给。其中

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一种方法是由岩古开发的。这种方法结合了适用于城市地区的水平衡原则，评估了人口密度和土地利用因素。该公式包含两个方程，一个用于考察饱和地下水补给，另一个用于考察非饱和地下水补给。在本研究中，我们分析了五个地区的地下水补给情况：西达诺、丘荣、希坦杜伊、因陀罗吉里、珍妮伯朗和波索巴黎。结果显示，WS巴黎波索的平均地下水补给量最高，为619毫米/年。这是因为WS帕里吉的不饱和面积比例最高，占总面积的99.3%，而饱和面积仅为0.7%。WS巴黎波索的年平均降雨量百分比为25.2%，可以成为地下水补给的潜力。根据结果可以得出结论，地下水补给潜力取决于降雨量、饱和和非饱和面积以及人口密度。区域内降雨量增大，导致区域非饱和区扩大，人口密度降低，从而增加了该地区地下水补给的可能性。

关键词：地下水、补给、河流面积、水量平衡。

1. Introduction

Water and water resources are divine gifts that should be managed sustainably and efficiently for the fair prosperity of the people. It is essential to utilize water resources effectively to meet the demands while ensuring their sustainability [1]. The availability of water has been adversely affected by various environmental changes, resulting in a disparity between the amount of water available and the demand for it. This gap is expected to widen as the demand for water continues to rise while the available water supply dwindles [2, 3]. This trend is further exacerbated by the increasing use of water resources [4]. To meet the demand for clean water, society explores alternative resources beyond surface water, one of which is groundwater.

Groundwater is a critical component of hydrological systems [5] and is stored in an underground layer, which can naturally replenish river bodies, lakes, or serve as a source of water. Approximately 1.69% of the Earth's water is in the form of groundwater, which may seem insignificant; however, it is substantial when compared to the volume of river water, which constitutes only 0.0002% of the total water on Earth. Uncontrolled extraction of groundwater due to the growing demand for potable water poses a significant challenge to the long-term sustainability of this valuable resource. As a result, it is crucial to continuously replenish the groundwater supply, even at increased levels [6].

In Water Resources Law No. 17 of 2019 [7], groundwater conservation is required so that the carrying capacity and function of groundwater recharge [8] can be well maintained. Groundwater recharge is a groundwater conservation strategy [9] that is intended to protect and maintain the availability, condition, and environment of groundwater [10].

Groundwater recharge is the process of adding groundwater from outside (rainfall) into an unsaturated aquifer naturally or artificially, directly to the aquifer or another formation [11]. This recharge has the potential to add flow discharge in the river or lake. Groundwater replenishment is a component of hydrologic processes, which encompasses the natural and artificial movement of surface water into underground reservoirs [12, 13].

The knowledge of the capacity for groundwater recharge in a particular region is crucial for implementing effective integrated groundwater management practices [14, 15]. There are many techniques or methods that can be selected for estimating groundwater recharge [16], such as measuring water absorption using a lysimeter that is installed in an unsaturated zone, analyzing catchment water budget, using remote sensing, applying numerical models, measuring groundwater level fluctuations, and applying the radio-isotope method [17]. Groundwater recharge analysis is carried out by applying the method developed by Iwaco [18] in the Jabotabek Water Resources Management Study (JWRMS). This method incorporates the principle of water balance, which can be applied to urban areas by evaluating the factors of population size and land utilization. The methodology for analyzing recharge comprises distinct formulations for saturated regions, such as densely populated areas and industrial zones, and unsaturated regions, including forests, irrigated rice areas, and plantations. It is essential to have a land use map to classify these areas. In this study, we investigate the feasibility of recharge in the WS Cidanau-Ciujung-Cidurian, WS Citanduy, WS Indragiri, WS Jeneberang, and WS Parigi Poso areas. The identification of five riverine regions that would be suitable for evaluating the annual average recharge potential was based on factors such as land cover distribution, population density, and average rainfall in a particular year.

2. Materials and Methods

Groundwater recharge analysis is carried out by applying the method developed by Iwaco [19, 20] in the JWRMS. This method incorporates the principle of water balance by evaluating the variables of population size and land utilization. The equation utilized for assessing recharge in this method is distinct for areas that are saturated (such as heavily populated regions or industrial zones) and those that are unsaturated (like forests, irrigated rice fields, or plantations); hence, a land use map is necessary for categorization. The mechanism of recharge analysis using this method is illustrated in Fig. 1.

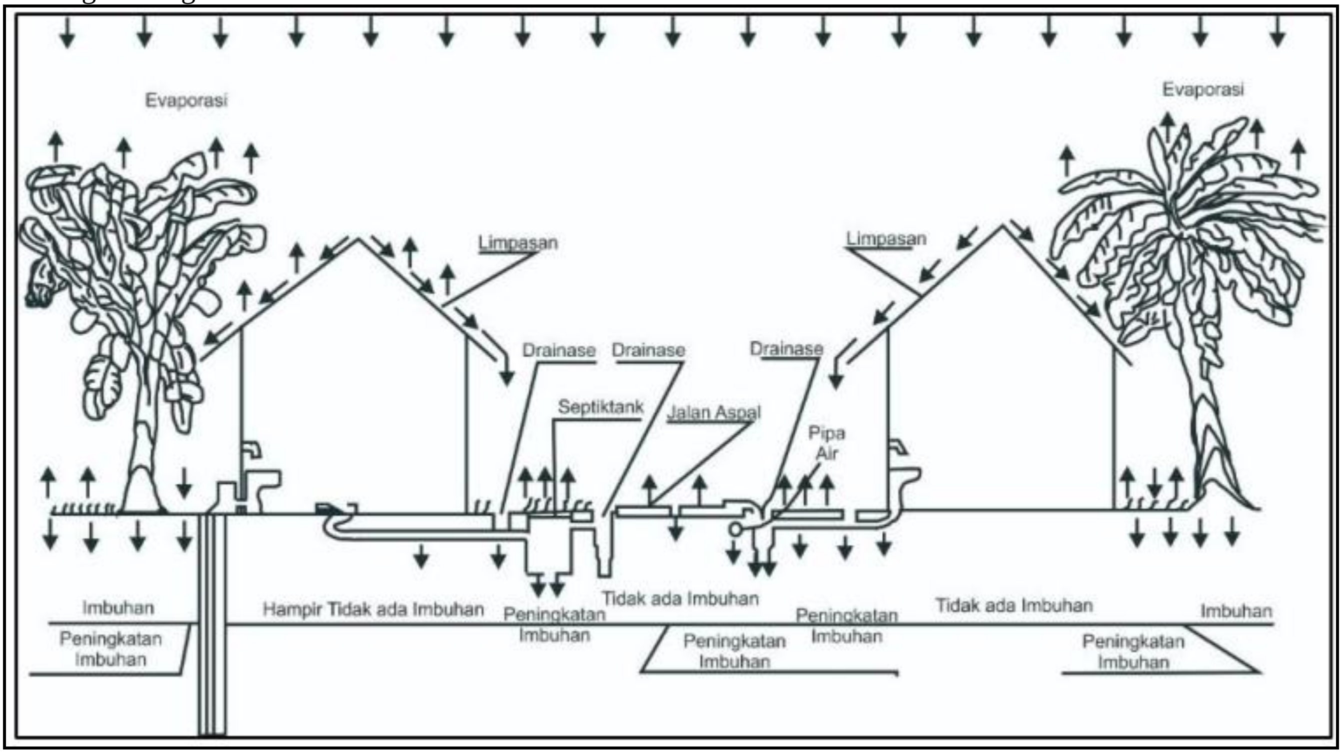

Fig. 1 Mechanism of recharge in a big city [19]

The equation is as follows [13]:

$$R_{perv} = \left(1 - f_{impv}\right) * \left(P * \left(1 - k_{dsro}\right) - E_{act}\right) \quad (1)$$

$$R_{impv} = f_{impv} * k_{impv} * \left(P - Ea_{impv}\right) \quad (2)$$

where:

R_{perv} - rainfall recharge dropped onto an unsaturated surface

R_{impv} - rainfall recharge dropped onto a saturated surface

f_{impv} - percentage of saturated surface area (in relation to population density, speed, and commercial activity)

P - rainfall

k_{dsro} - percentage of direct surface runoff from unsaturated land

k_{impv} - percentage of rainfall dropped on a saturated surface that is infiltrated into soil

E_{act} - actual evapotranspiration from an unsaturated surface

Ea_{impv} - actual evapotranspiration from a saturated surface

The percentages of surface runoff (k_{dsro}) and infiltration (k_{impv}) are arranged based on the land use map. The analysis of groundwater recharge in this research is then differentiated for saturated and unsaturated areas, as can be seen in Equations (1) and (2). Accordingly, reclassification is conducted for each type of land use into two distinct classes: saturated and unsaturated areas. Unsaturated regions encompass irrigated rice fields, plantations, mining operations, farms, and moors, among other such areas. Saturated regions include developed environments and water bodies. The value of k_{dsro} is assessed exclusively for unsaturated regions, as this parameter takes into account the fact that not all rainfall will be intercepted by the soil in these areas; portions of it will still overflow onto the surface. The value of k_{dsro} is typically estimated to be around 0.1 or 10% of the rainfall, which is considered comparable to the surface runoff in sloping grassland and sandy soil, and is commonly employed in the rational method for evaluating peak discharge in drainage systems [19]. Another parameter that is calculated based on the land use map is the percentage of infiltration from the surface in saturated surface (k_{impv}). The parameter k_{impv} is assessed exclusively for saturated areas as it takes into consideration the fact that not all rainfall will result in overflow in these areas. Despite this, there will still be a small amount of recharge into the soil, such as through drainage systems, as illustrated in Fig. 1. The four classes that make up the value of k_{impv} are illustrated in Table 1. The greater the class, the more rainfall is infiltrated in the saturated area.

Table 1 Infiltration percentages (The authors)

Infiltration class of the drainage system	**Percentage of recharge from runoff in saturated areas**
1	20%
2	25%
3	30%
4	40%

The estimation of the percentage value of the saturated surface (f_{impv}) is necessary due to the unavailability of field data related to the saturated surface. The estimation of f_{impv} is derived from the population density data for the village scale, which is obtained from the Statistical Center Institution (BPS). In the JWRMS, the estimation of f_{impv} is based on the population density, which is presented in Table 2. Areas with higher population densities are typically considered to be densely settled or developed regions, which can be classified as saturated zones. Consequently, the value of f_{impv} tends to be higher in these areas.

Table 2 Values of f_{impv} based on the population density (The authors)

Population density	f_{impv}	
	Percentage	**Value**
<50	10%	0.1
50-100	25%	0.25
100-150	40%	0.4
150-200	50%	0.5
200-250	57%	0.57
250-300	65%	0.65
300-350	70%	0.7
350-400	75%	0.75
400-500	80%	0.8
>500	85%	0.85

The annual average rainfall at each rainfall station is calculated by analyzing the daily rainfall in the data series. This analysis is conducted using the Isohyet method, which involves creating lines that connect points with the same rainfall depth. The Isohyet method assumes that the rainfall in the area between two Isohyet lines is equal to the average of the two lines. The resulting line represents the distribution of rainfall in the area, taking into account the spatial variation.

The analysis of evapotranspiration utilized is the Penman-Monteith method. This method needs four climate parameters, and the equation is as follows [20, 21]:

$$ET_p = \frac{0{,}408\Delta(R_n - G) + \gamma \frac{900}{T_{mean}+273} u(e_s - e_a)}{\Delta + \gamma(1+0{,}34u)} \quad (3)$$

where:
ET_p - potential evapotranspiration (mm/day)
Δ - gradient curve of the vapor pressure (kPa/°C)
G - hot flux of soil (MJ/m^2/day)
E_a - saturated vapor pressure (kPa)

The following equation is employed to evaluate the worth of Δ:

$$\Delta = \frac{4098(0{,}6108)\exp\left(\frac{17{,}27 T_{mean}}{T_{mean}+237{,}3}\right)}{(T_{mean}+273{,}3)^2} \quad (4)$$

The midday G value is estimated as follows:

$$G = 0{,}1R_n \quad (5)$$

At night, the equation for G may be approximated as follows:

$$G = 0{,}5R_n \quad (6)$$

The value of e_s is evaluated using the following equation:

$$e_s = \frac{e^{\circ}(T_{max}) + e^{\circ}(T_{min})}{2} \quad (7)$$

The examination of recharge in areas with impermeable and permeable surfaces involves the application of Equations (1) and (2), which is facilitated by the raster calculator toolbox in ArcGIS.

3. Results and Discussion

The study of the recharge potential in the five river regions revealed that land cover and population density significantly impact the distribution of recharge potential. In particular, areas with high population density and saturated conditions tend to have lower recharge potential compared to regions with low population density and unsaturated conditions. Furthermore, the average rainfall depth plays a crucial role in determining the annual average recharge potential as it is the primary source of recharge water. The findings are illustrated in Fig. 2.

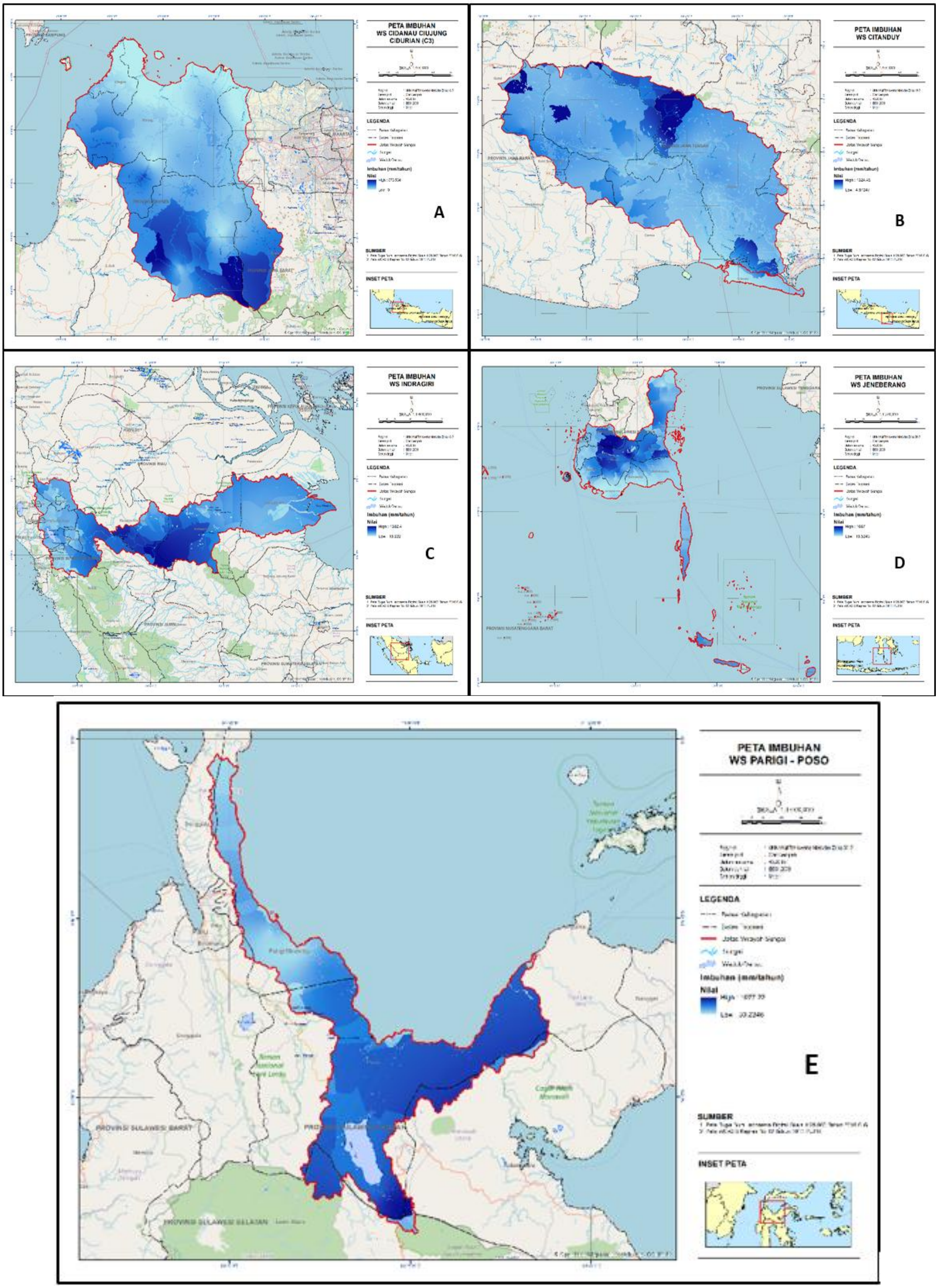

Fig. 2 Map of recharge potential in the river regions: (A) C3, (B) Citanduy, (C) Indragiri, (D) Jeneberang, and (E) Parigi Poso (The authors)

The data outlining the average recharge potential per year for the five river regions is presented in Table 3.

Table 3 Recharge potential in the five river regions (The authors)

No	Lokasi	Luas (km2)		Total	%Area		Kimpv	Rata-Rata Imbuhan			Rata-Rata Hujan			% Rata-Rata Imbuhan		
		Kedap	Tidak Kedap		Kedap	Tidak Kedap		Kedap	Tidak Kedap	Semua Area	Kedap	Tidak Kedap	Semua Area	Kedap	Tidak Kedap	Semua Area
1	WS C3	318.3873	3807.144	4125.5	7.7%	92.3%	0.2	104	152	128	1788	2180	1984	5.84%	6.95%	6.45%
2	WS Citanduy	378.972	4104.5983	4483.6	8.5%	91.5%	0.2	140	252	196	2744	2717	2730	5.10%	9.27%	7.18%
3	WS Indragiri	453.3735	21793.98994	22247.4	2.0%	98.0%	0.2	142	631	387	2182	2250	2216	6.51%	28.05%	17.45%
4	WS Jeneberang	629.9018	8820.5612	9450.5	6.7%	93.3%	0.2	179	553	366	2287	2467	2377	7.84%	22.42%	15.41%
5	WS Parigi Poso	56.991	8558.1243	8615.1	0.7%	99.3%	0.2	162	1076	619	2318	2598	2458	6.99%	41.42%	25.18%

The following is a summary of the recharge potential:

The average annual recharge in the saturated area of WS C3 measures 104 mm, while the yearly average rainfall in this region is 1,788 mm. It is estimated that approximately 5.8% of the yearly rainfall has the potential to become recharge in the saturated area of WS C3. In contrast, the average annual recharge in the unsaturated area is 152 mm, whereas the yearly average rainfall in this area is 2,180 mm. It is approximated that roughly 7% of the annual rainfall in the WS C3 unsaturated zone has the potential to recharge. Taking into account the entire WS C3 area, the average annual recharge is 128 mm. Considering the yearly rainfall in the WS C3 area, which amounts to 1,984 mm, the average percentage of rainfall that becomes recharge potential is approximately 6.5%. The WS C3 area remains relatively unsaturated, with almost 92.3% of the zone classified as unsaturated and only 7.7% as saturated.

In the study area of WS Citanduy, the annual recharge in the saturated zone is approximately 140 mm/year, which corresponds to an average yearly rainfall of 2,744 mm/year. It is estimated that approximately 5.1% of the yearly rainfall in the saturated zone has the potential to become recharge. In contrast, the average recharge in the unsaturated zone is approximately 252 mm/year, with an average yearly rainfall of 2,717 mm/year in the same area. It is estimated that around 9.3% of the yearly rainfall in the unsaturated zone has the potential to become recharge. Taking both zones into account, the overall average recharge in WS Citanduy is approximately 196 mm/year, with an average yearly rainfall of 2,730 mm/year. Based on these findings, it is estimated that approximately 7.2% of the yearly rainfall in WS Citanduy has the potential to become recharge. The wide extent of the unsaturated zone, accounting for about 91.5% of the total area in WS Citanduy, is a contributing factor to this result.

In the WS Indragiri region, the annual recharge in the saturated area is approximately 142 mm/year, which is significantly lower than the yearly average rainfall of 2,182 mm/year in the same area. It is estimated that about 6.5% of the annual rainfall in the saturated area has the potential to become recharge. In contrast, the average recharge in the unsaturated area is 631 mm/year, with a yearly average rainfall of 2,250 mm/year. It is estimated that approximately 28.1% of the annual rainfall in the unsaturated area has the potential to become recharge. Overall, the average recharge in WS Indragiri is 387 mm/year, with a yearly rainfall of 2,216 mm/year. It is estimated that roughly 17.5% of the annual rainfall in WS Indragiri has the potential to become recharge. This is because the unsaturated area in WS Indragiri covers a significant portion of the region, approximately 98%, while the saturated area accounts for only 2% of the total area in WS Indragiri.

In the study area of WS Jeneberang, the annual recharge rate in the saturated zone is estimated to be 179 mm/year, which is significantly lower than the annual average rainfall of 2,287 mm/year in the same zone. It is estimated that approximately 7.8% of the annual rainfall in the saturated zone has the potential to become recharge. In contrast, the unsaturated zone in WS Jeneberang has an average recharge rate of 553 mm/year, which is lower than the annual average rainfall of 2,467 mm/year in the same zone. It is estimated that about 22.4% of the annual rainfall in the unsaturated zone has the potential to become recharge. Overall, the average annual recharge rate in WS Jeneberang is 366 mm/year, which is lower than the annual average rainfall of 2,377 mm/year in the area. It is estimated that approximately 15.4% of the annual rainfall in WS Jeneberang has the potential to become recharge due to the relatively high proportion of the unsaturated zone in the area, which is about 93.3%, and the saturated zone, which is about 6.7%.

The average annual recharge in the saturated zone of WS Parigi Poso is 162 mm/year, which is significantly lower than the yearly average rainfall of 2,318 mm/year in the same area. It is estimated that approximately 7% of the yearly rainfall in the saturated zone has the potential to become recharge. In contrast, the average annual recharge in the unsaturated zone is 1,076 mm/year, which is nearly half of the yearly average rainfall of 2,598 mm/year. It is estimated that approximately 41.4% of the yearly rainfall in the unsaturated zone has the potential to become recharge. Overall, the average annual recharge in WS Parigi Poso is 619 mm/year, which is significantly lower than the yearly average rainfall of 2,458 mm/year. It is estimated that approximately 25.2% of the yearly rainfall in WS Parigi Poso has the potential to become recharge. This is because the unsaturated zone in WS Parigi Poso covers nearly all of the area, at 99.3%, while the saturated zone covers only a small fraction, at 0.7%.

The condition of recharge potential in the five WSs is indirectly influenced by saturated and unsaturated area conditions in each river region. The saturated region comprises the water body area and developed areas that are unable to absorb rainfall. The comparison of each river region is shown in Fig. 3. Of the five river regions, WS Indragiri has the biggest area at 22,247.4 km^2, while WS C3 has the smallest area at 4,125.5 km^2. According to the comparison of the saturated area to the river region area, WS Citanduy possesses the largest saturated area at 8.5%, with WS C3 coming in second at 7.7%. It is because both of the river regions are situated on Java Island, which boasts a high population density, resulting in numerous developed areas. However, the river regions with the smallest saturated areas are WS Indragiri (2%) and WS Parigi Poso (0.7%).

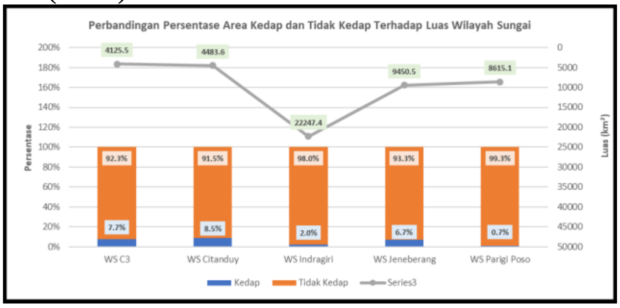

Fig. 3 Comparison of the saturated and unsaturated areas in the five WSs (The authors)

Based on Fig. 4, WS Citanduy has the highest average annual rainfall of 2,730 mm/year, while WS C3 has the lowest average annual rainfall of 1,984 mm/year. Despite this, WS Parigi Poso boasts the highest proportion of impermeable space, accounting for 99.3% of the total area, and only 0.7% is permeable (Fig. 3). Furthermore, it has an average annual rainfall recharge potential of 25.2% (Fig. 5).

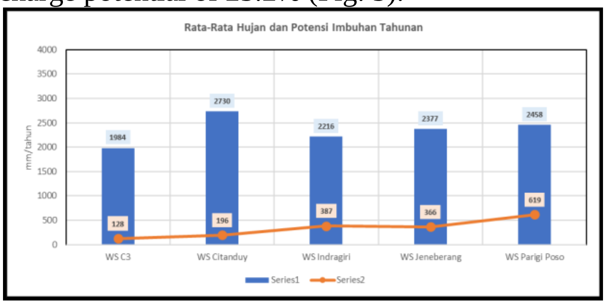

Fig. 4 Average annual rainfall and recharge potential in the five WSs (The authors)

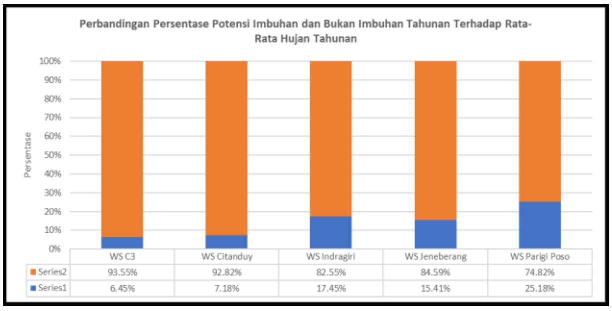

Fig. 5 Percentage comparison between the recharge potential and non-recharge potential in relation to the average annual rainfall (The authors)

4. Conclusion

Based on the analysis above, WS Citanduy has the highest average annual rainfall of 2,730 mm/year, while WS C3 has the lowest average annual rainfall of 1,984 mm/year. Despite this, WS Parigi Poso possesses the highest proportion of impermeable area, amounting to 99.3% of the total area, and only 0.7% is permeable. The average percentage of the yearly rainfall that can potentially recharge the area is 25.2%.

The analysis of recharge potential in the five river regions indicates that it is highly contingent upon rainfall, the presence of permeable and impermeable areas, and population density. It is evident that areas with higher rainfall, larger impermeable areas, and lower population density will exhibit greater recharge potential. Conversely, regions with lower rainfall, smaller impermeable areas, and higher population density will have less recharge potential.

Analysis of recharge potential in the five river regions yields several inconclusive results. This is because the analysis of recharge potential using the method developed by Iwaco [19] has some shortcomings. The method entails the calculation of three parameters, which are subjective and qualitative in nature as they are based on ranges of values determined for f_{impv}, k_{dsro}, and k_{impv}. f_{impv} is dependent on population density, while k_{dsro} is assumed to be 0.1 for impermeable surfaces, and k_{impv} is based on the estimation of the rainfall percentage in permeable surfaces that is infiltrated into soil. However, this method can be used to spatially analyze and illustrate recharge potential in an area.

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