

Chapter 2

Spatio-Seasonal Variation Assessment of Water Quality Based on GIS Techniques to Identify Pollution Sources in Mantaro Basin



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Abstract To generate sustainable management of water resources, it is necessary to know the state of water quality and promote its efficient use. This study was carried out in the Middle Mantaro Sub-basin, an important area in Peru due to its agricultural activity, which provides food to the country's capital. The objective is to explore the spatial-seasonal variation of 10 water quality parameters and analyze their pollution sources. The Geographic Information System (GIS) was used through Inverse Distance Weighted (IDW) interpolation for mapping and obtaining values at the sub-basin level. The results indicate that the high concentrations of physical–chemical, microbiological and heavy metal parameters affect 10, 33, and 27 subcatchments, respectively, out of the 39 that exist. The wet season presents higher concentrations in all parameters except for Mn, NO_3^- and TP and the primary polluting sources are municipal, domestic wastewater, and mining passives.

Keywords Water quality · Spatio-seasonal distribution · Mantaro basin

2.1 Introduction

Peru is the eighth country with the largest amount of water in the world, a reality that puts it in a privileged position; the main uses of this resource are agriculture, energy, population, mining, fishing and industrial activities (National Water Authority 2012); however, there is no adequate management of its quality. Among all its hydrographic units, less than 62% have monitoring stations and among these, more than 40% are classified as areas with poor water quality (National Water Authority 2015).

Within these hydrographic units there is the Mantaro Basin, located in the center of the country and subdivided into the Upper Sub-basin, where mining is the main activity; Middle Sub-basin with great importance due to the presence of the Mantaro Valley, which is the main food supplier of the country's capital (Correa et al. 2016);

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and the Lower Sub-basin. The Basin's water sources are used for consumptive and non-consumptive purposes, with agriculture (47%), population (30%) and mining (14%) in the first category; and in the second, energy use (98%) and aquaculture (2%) (National Water Authority 2020). This very diverse classification of water use has led to conflicts, especially between mining, population and agricultural activities, since there is not enough control in the treatment of the effluents generated, causing the concentrations of many control parameters in the water to increase.

Water quality studies in the wet season in the 7 main rivers of the Mantaro Basin show values of Cu, Pb, Zn, Fe and As below the Peruvian environmental quality standards (PEQS) for irrigation, except in the Upper Sub-basin (Custodio et al. 2020). Custodio et al. (2021a) evaluated the water quality after the cessation of activities caused by the pandemic worldwide, concluding that the mean values of Cu, As, Fe, Pb and Zn did not exceed the PEQS for human consumption, with the exception of Pb, Fe and As in the Mantaro River of the Upper Sub-basin, and As in the Middle Sub-basin. In 2014, the National Water Authority (NWA) identified 436 sources of water contamination in the Basin, including domestic, municipal, mining wastewater, mining passives, hot springs, fish farming, hydroelectric plants and slaughterhouses (National Water Authority 2015), and despite the years and strategies that have been carried out to control the problem, there are no reports on the change in water quality as a result of these projects at the hydrographic region level.

Due to this, the present study aimed to explore the spatial-seasonal variation of 10 physical-chemical, inorganic and biological parameters of surface water quality in the Middle Mantaro Sub-basin between the period 2015 and 2021 using GIS, and to analyze their pollution sources. The Middle Sub-basin was selected as our study area due to its importance in agriculture and the absence of adequate awareness and regulations for sustainable management.

This study is the first to analyze NWA's annual monitoring data in the Mantaro Valley and would serve as input to improve existing water management policies.

2.2 Materials and Methods

2.2.1 Study Site

The study area corresponds to the Middle Sub-basin that includes 3 Hydrographic Units: Cunas, Middle Alto Mantaro and Hydrographic Unit 499,691, presented in Fig. 2.1.

It is located between 11°30' and 12° 30'S latitude and 75°00' and 75° 50'W longitude. The altitude varies from 2,963 to 5,501 m above sea level, the total area is 4,723 km², and the provinces of Jauja, Chupaca, Concepcion and Huancayo belonging to the Junin region are located in this sector. The climate is characterized by two quite marked seasons: wet and dry, the first from September to April and the second from May to August (Silva and Takahashi 2008), with average annual precipitation and

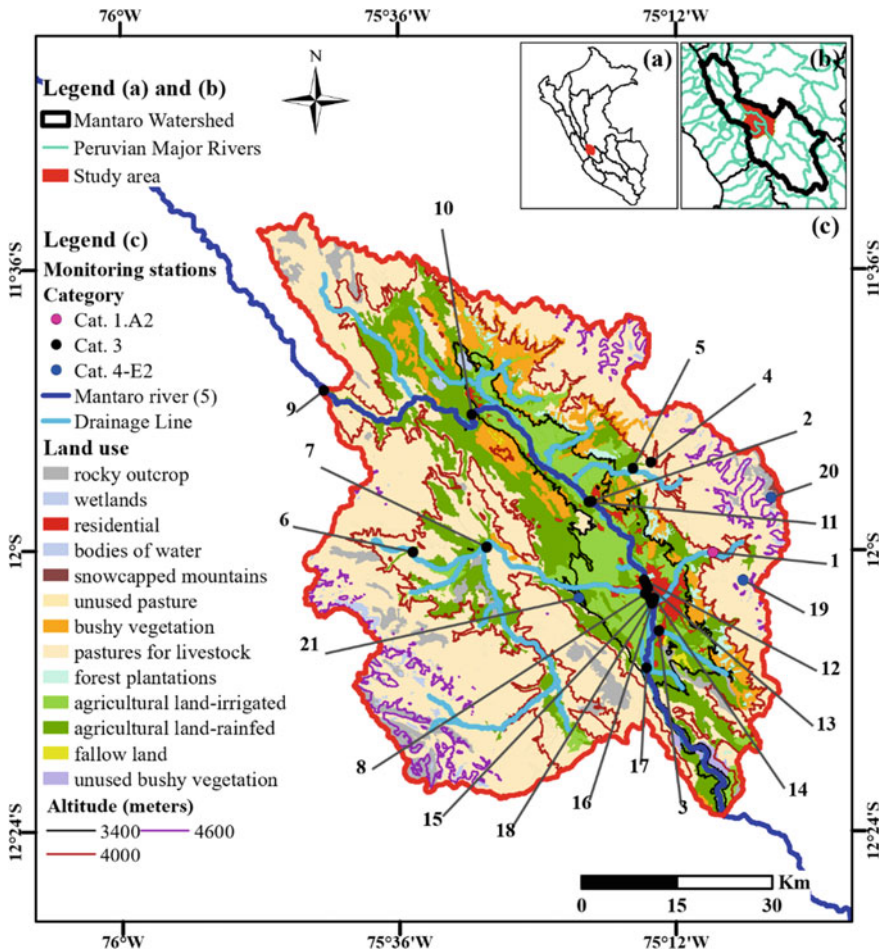


Fig. 2.1 Location of the monitoring stations, land use and hypsometry in the study area

temperature of 700 to 800 mm and 8 to 12 °C, respectively. The area is occupied by pastures for livestock (56%), mainly in the higher areas, and by agricultural land-rainfed (18%) and irrigated (9%) in the lower areas near the Mantaro River. There are metallic and non-metallic mineral deposits that have fostered mining activities in the area; especially in the sectors closest to the main river.

2.2.2 Water Quality Monitoring Data

Water quality data were obtained from the Portal of the NWA of Peru (National Water Authority 2022). The time series included 13 seasonal monitoring campaigns

between 2015 and 2021, 21 points were analyzed, located at the mouth of 3 lagoons and 8 rivers, with 3 stations in Jauja, 14 in Huancayo, 3 in Concepcion and 1 in Chupaca (Table 2.1).

The parameters that were taken into account include dissolved oxygen (DO), total phosphorus (TP), nitrates (NO₃-), biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), thermotolerant coliforms (TC), manganese (Mn), iron (Fe), cadmium (Cd) and lead (Pb).

The bodies of water considered in the study have been defined by the NWA in 3 categories according to their main use: Cat. 1-A2 Human consumption after conventional treatment, Cat. 3 Vegetable irrigation and animal drinking, and Cat. 4 Lakes and Lagoons (Fig. 2.1). More than 80% is classified as Cat. 3, so this category was taken for comparison with the PEQS and the FAO.

Table 2.1 Description and location of the monitoring stations

N°	Code	Description	Coordinates	
			Lat (N)	Long (W)
1**	RShul1	Shullcas R before DWTP	12° 0.20'	75° 8.75'
2***	RAcha1	Achamayo R before confluence with MR	11° 55.85'	75° 19.32'
3**	RChan1	Chanchas R	12° 6.90'	75° 13.46'
4**	RChia1	Chia R before intake for aquaculture activities	11° 52.51'	75° 14.14'
5**	RChia2	Chia R before confluence with Achamayo R	11° 53.05'	75° 15.72'
6***	RCons1	Consac R after confluence with Huasiviejo R	12° 0.16'	75° 34.77'
7*	RCuna1	Cunas R	11° 59.73'	75° 28.37'
8**	RCuna2	Cunas R before confluence with Mantaro R	12° 3.76'	75° 14.66'
9*	RMant11	MR after confluence with Pachacayo R	11° 46.37'	75° 42.50'
10*	RMant12	MR before intake for irrigation activities	11° 48.46'	75° 29.67'
11***	RMant13	MR before confluence with Achamayo R	11° 55.93'	75° 19.53'
12**	RMant14	MR before dump	12° 2.57'	75° 14.73'
13**	RMant15	MR after and before dumps	12° 2.90'	75° 14.59'
14**	RMant16	MR	12° 3.24'	75° 14.40'
15**	RMant17	MR after and before dumps	12° 4.17'	75° 14.18'
16**	RMant18	MR after confluence with Shullcas R	12° 4.60'	75° 14.04'
17**	RMant19	MR after WWTP discharge	12° 10.10'	75° 14.52'
18**	RShul2	Shullcas R before dump and after WWTP	12° 4.19'	75° 13.87'
19**	LHuah1S	Exit of Huacrachocha L (flows into Shullcas R)	12° 2.58'	75° 6.16'
20**	LLasu1S	Exit of Lasuntay L (flows into Shullcas R)	11° 55.56'	75° 3.70'
21****	LÑahu1S	Exit of Ñahuinpuquio L (flows into Cunas R)	12° 4.10'	75° 20.40'

* Jauja, ** Huancayo, *** Concepcion, **** Chupaca

R designates river, L designates lagoon, MR designates Mantaro River, WWTP Wastewater treatment plant, DWTP Drinking water treatment plant

2.2.3 Statistical Analysis

Pearson's correlation analysis is a method that measures the linear relationship between two variables and is defined as a correct statistical technique to determine the correlation between water quality parameters (Sharma et al. 2020).

This step began with the standardization of the raw data through the Z-scale transformation that generates a mean of 0 and a variance of 1 in order to eliminate the impact of the dimensions and finally calculate the correlation coefficients, where values close to +1 or -1 indicate a good relationship and those close to 0 show a low relationship between the 2 water quality variables evaluated. The previous analysis was performed using the R program version 4.1.1.

2.2.4 Spatial Variation Analysis

Spatial variation analysis was performed in ArcMap 10.8. Data preparation was performed from the digital elevation model (DEM) provided by the Ministry of the Environment (Ministry of the Environment 2022) with a resolution of 30 by 30 m. Using the Arc Hydro Tools package, the drainage lines and 39 subcatchments were calculated (Fig. 2.2). The input data correspond to the average of each monitoring station in the wet and dry seasons.

GIS Interpolation. The Inverse Distance Weighted (IDW) method was used through the Geostatistical Analyst tool. This method is one of the most used in the mapping of water quality parameters, and assumes that each value is locally influenced and decreases with distance, therefore, the weights assigned to the interpolation points are based on the inverse of the distance from the point being estimated (Magesh and Elango 2019). The general IDW equation is:

$$\hat{z}(x_0) = \frac{\sum_{i=1}^n z(x_i) \cdot d_{ij}^{-p}}{\sum_{i=1}^n d_{ij}^{-p}}$$

where Z represents the interpolated value, Z_1 represents the nearby or neighboring data points, and d_{ij} are the distances between the data points and the interpolated value.

After interpolation, the values were divided among the subcatchments taking into account the highest value of each parameter in each of them, except for the DO, which included the lowest value. In this last step, 6 subcatchments (23, 24, 25, 26, 27 and 39) were not taken into account; this measure was adopted because there is no monitoring data in these areas and because they are upstream of the other stations, the values obtained were not representative.

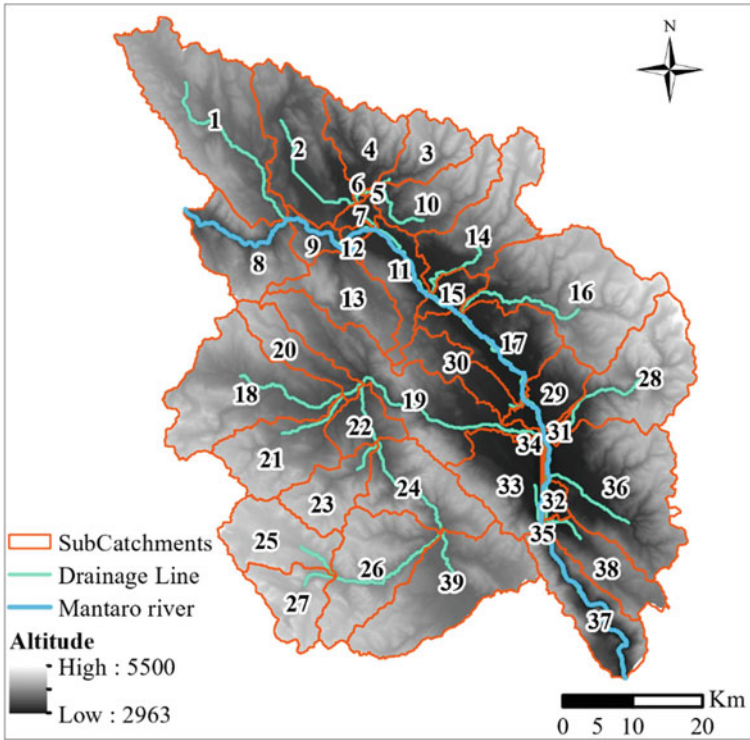


Fig. 2.2 Study area division into subcatchments

2.3 Results and Discussion

2.3.1 Correlation Coefficients

Figure 3a shows a strong positive significant correlation between Pb and Cd ($\rho = 0.58$, $p = 0.001$) and the BOD5 and COD ($\rho = 0.62$, $p = 0.001$), while there is a strong negative significant correlation between NO_3^- and the variables DO ($\rho = -0.61$, $p = 0.001$), BOD5 ($\rho = -0.62$, $p = 0.001$), and Cd ($\rho = -0.57$, $p = 0.001$) for the dry season. Figure 3b shows a moderately strong positive correlation between COD and BOD5 ($\rho = 0.48$, $p = 0.001$), Fe and the variables Pb ($\rho = 0.47$, $p = 0.001$) and COD ($\rho = 0.35$, $p = 0.001$).

and a strong correlation with Mn ($\rho = 0.63$, $p = 0.001$). Finally, TP has a moderately strong positive correlation with the variables Fe ($\rho = 0.41$, $p = 0.001$), Mn ($\rho = 0.41$, $p = 0.001$), COD ($\rho = 0.41$, $p = 0.001$), and negatively with the metal Cd ($\rho = -0.39$, $p = 0.001$) and the variable DO ($\rho = -0.41$, $p = 0.001$) for the wet season.

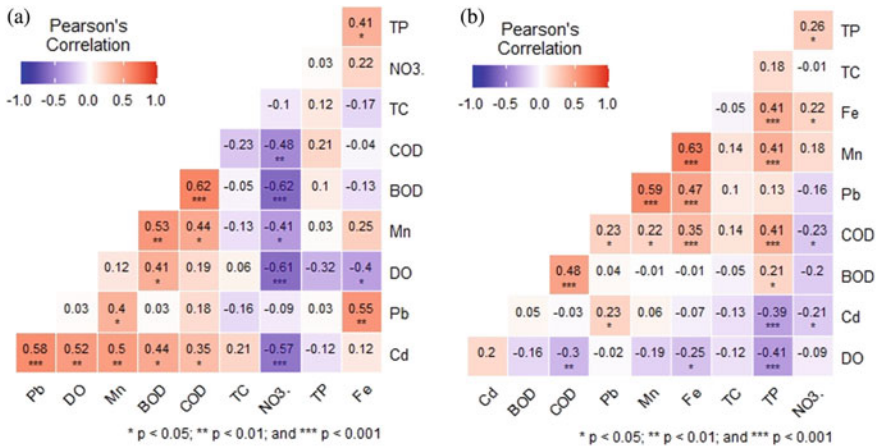


Fig. 2.3 Correlation matrix of water quality parameters in dry season (a) and wet season (b)

2.3.2 Spatio-Seasonal Variation

Physico-chemical parameters. The DO presents higher average values in the wet season, the maximum value in both seasons is focused on the most populated areas of the Middle sub-basin, considering that the wastewater in the area does not have a WWTP, they are still above the PEQS (4 mg/L) (see Fig. 4a, b).

The concentrations of TP and NO₃⁻ increase as the altitude decreases, which is where the agricultural activity begins, even so, the concentrations of nitrates are below the limit values (VL) recommended by the FAO (TP = 2 mg/L, nitrates = 5 mg/L) (FAO 2022), on the contrary, the TP exceeds them in both seasons.

Subcatchment 28, which is where the city of Huancayo, the main urban area, is located, shows TP concentrations twice as the LV (see Fig. 4c, d). NO₃⁻ have higher values in the dry season in the area of the Cunas River just before it joins the Mantaro River (Subcatchment 19), understanding this for the potential runoff and the use of fertilizers in agriculture and a lower flow that generates a lower dilution capacity (see Fig. 4e, f); in all cases a lower concentration and below the LV is seen after the only WWTP in the area (Subcatchment 33). (Custodio et al. 2021b) conducted a study at the end of the wet season from 2017 to 2019 in the Cunas river, they found average values of 6.02 mg/L and 0.065 mg/L of DO and TP, respectively, and a maximum value of 1.79 mg/L of the nitrate parameter in 2019, showing lower results than the present study for the last two parameters and a similar result for DO.

The BOD₅ and COD values exceed the PEQS (BOD₅ = 15 mg/L, COD = 40 mg/L) in the subcatchments located around the urban area and agricultural area, having BOD₅ concentrations 8 and 6 times higher in the wet and dry season respectively, and in the case of COD, 7 and 5 times higher in the wet and dry seasons (see Fig. 5a, b). (Custodio et al. 2021b) found average values of 10.22 mg/L for the BOD₅

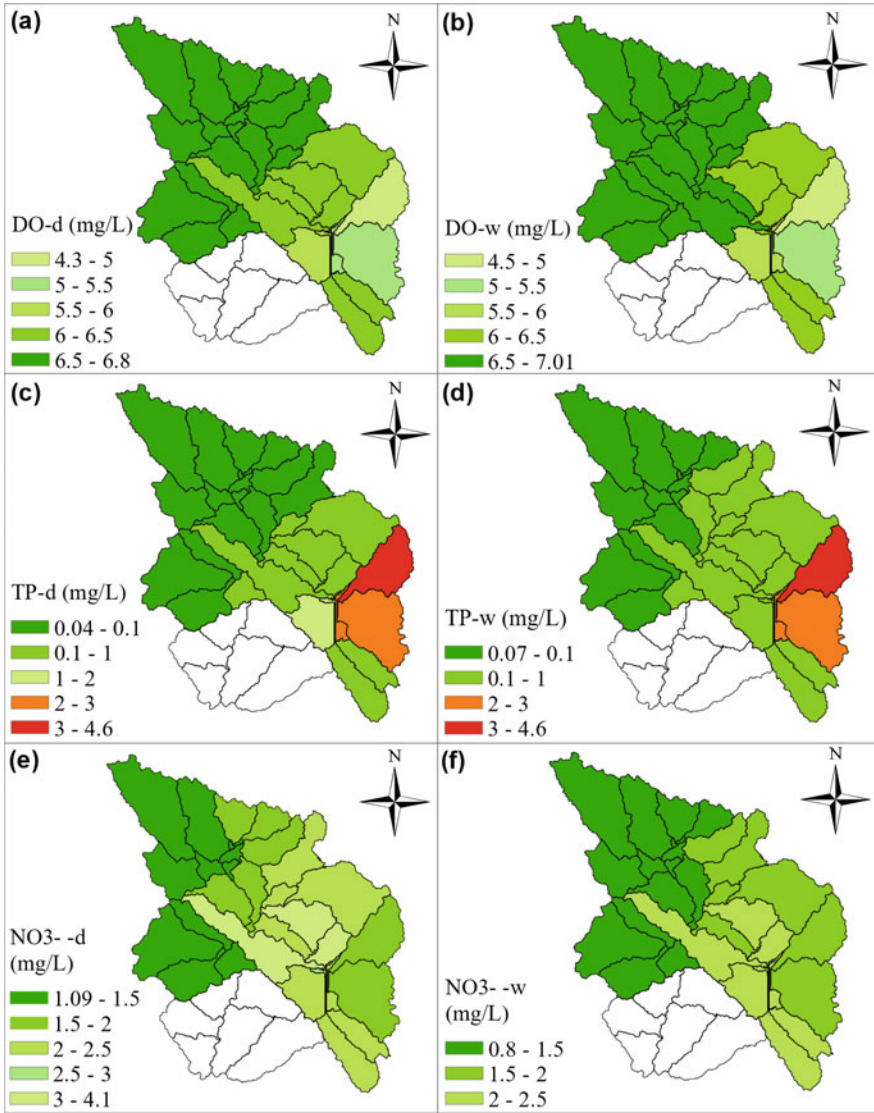


Fig. 2.4 Spatial distribution of Dissolved Oxygen, Total Phosphorous and nitrates in dry and wet season (left and right side, respectively)

parameter in the wet season, a concentration that is within the range of our study for the Shullcas River.

These values are related to the lack of municipal wastewater treatment plants in one of the main cities of central Peru. The high values of organic matter are also linked to the direct discharge of wastewater from slaughterhouses in the Shullcas, Mantaro, Achamayo and Chanchas rivers and the presence of dumps (National Water

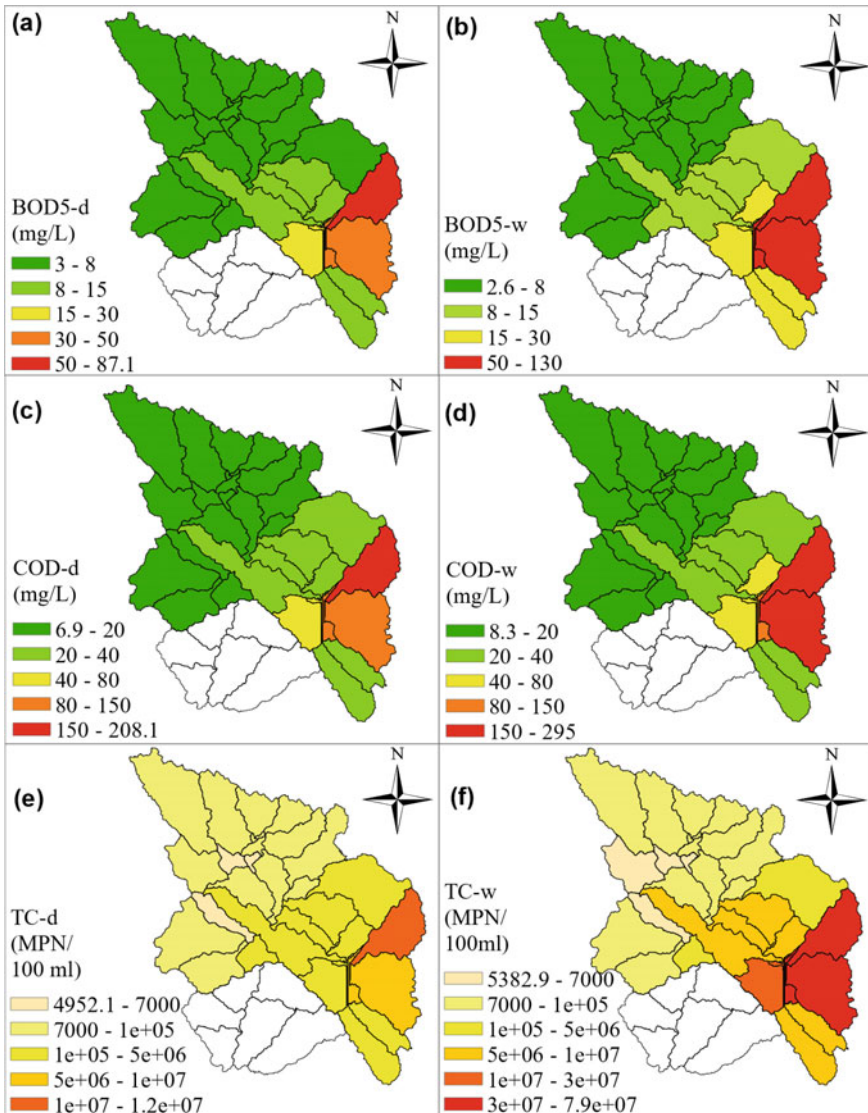


Fig. 2.5 Spatial distribution of BOD5, COD and TC in dry and wet season (left and right side, respectively)

Authority 2015) that in the wet season generate a greater amount of leachate that enters the Mantaro river.

Microbiological Parameter. The concentrations of thermotolerant coliforms do not meet the PEQS values (1000 MPN/100 ml) in any of the subcatchments, reaching excessive values of 79,000,000 MPN/100 ml in the wet season, almost 7 times more

than in the dry season (see Fig. 5e, f). The WNA has identified polluting sources of domestic and municipal wastewater in almost all the districts of the study area (National Water Authority 2022), a fact that generates conflict with all the economic activities in the zone, especially those of direct use and without water treatment such as agriculture.

Heavy Metals. The mean concentrations of Mn exceed the PEQS (0.2 mg/L) in the northern and highest part of the study area, as well as in the urban area in the dry season, with maximum values of 0.47 mg/L. The dry season has higher values, but the wet season covers more subcatchments that do not comply with the standard (see Fig. 6a, b). Fe values do not violate the Peruvian law (5 mg/L) in any of the cases; however, unlike Mn, there is an increase in the wet season in both, the north and the south of the study area. Like Fe, the average concentrations of Cd do not violate Peruvian regulations (0.01 mg/L), higher values can be seen in the upper and lower parts of the Mantaro River in the wet season and in the lower part in the dry season (see Fig. 2.6c–f).

The average concentrations of Pb fail to comply with the PEQS (0.05 mg/L) in the wet season with a maximum value of 0.055 mg/L, in both seasons there are higher values in the lower part of the Mantaro River (see Fig. 7a, b). Custodio et al. (2020) reported maximum values of 0.5 mg/L and 0.0045 mg/L of Fe and Pb in the Mantaro River located in the Jauja sector in the wet season, Custodio et al. (2021b) found average values of 1.57 mg/L of Fe and in the year 2020, Custodio et al. (2021a) reported an average value of Fe and Pb of 0.42 mg/L and 0.0065 mg/L, respectively, in the agricultural sector, and of 0.34 and 0.0063 mg/L in the urban sector, being in all cases concentrations below what was found in the study.

The NWA has not identified natural or anthropogenic polluting metal mining sources in the study area (National Water Authority 2022); and despite this, the values of heavy metals exceed the recommended standards. Chira (2021) states that the main cause of the presence of heavy metals is the metallurgical activity of La Oroya, which is located upstream (upper Mantaro sub-basin). Although this activity has directly generated poor water quality for many years, in the 2015–2021 period it can be seen that the highest concentrations of these metals are not found in the initial part of the middle sub-basin, so other activities could be causing this problem.

These concentrations can be explained by the presence of mining deposits, not yet in operation, in the sub-basins where high concentrations of heavy metals have been found, these deposits contain the following metals: Pb, Zn, Cu, Fe, Mn (Junin Regional Technical Commission 2015) that could be naturally contributing these values. Similarly, accumulations of Pb and Fe have been reported in the soils of Jauja and Concepcion, areas that collide with the Mantaro River, with Pb values that exceed the PEQS for soil. This has been generated as a consequence of mining and metallurgical activities of the Upper Sub-basin, and to a lesser degree by industrial waste, use of agrochemicals and urban effluents (Custodio et al. 2021c), which may be a possible source of water contamination. Chira (2021) indicates that there is sufficient statistical evidence to correlate the Cd content in the water and in the soil of the Mantaro Basin. Likewise, 4 non-metallic mining discharges have been identified into the Mantaro River in subcatchment 8 (northern zone), mainly of travertine

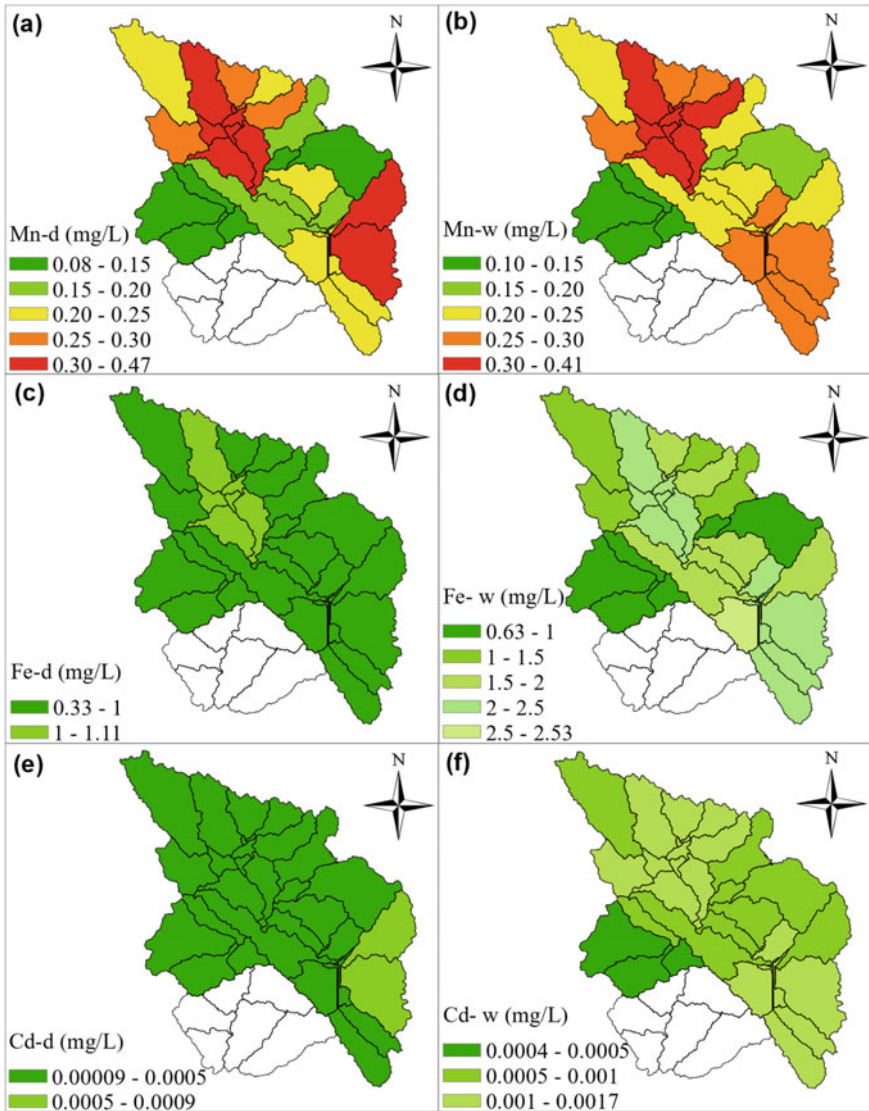


Fig. 2.6 Spatial distribution of Mn, Fe and Cd in dry and wet season (left and right side, respectively)

(Carpio and Chong 2018) and because its composition includes considerable percentages of Mn and Fe, the non-metallurgical activity could be contributing concentrations of heavy metals, added to this, mining liabilities have been reported in the highest parts of subcatchments 1, 2, 10, 14, 28, and in the lowest parts of subcatchments 17, 32 and 36 (National Water Authority 2015).

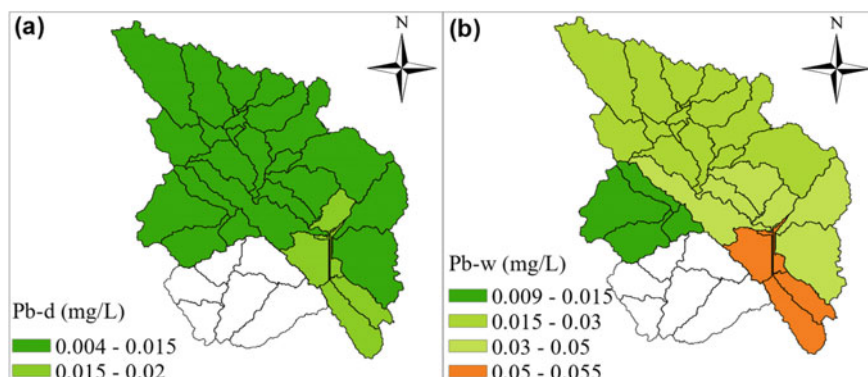


Fig. 2.7 Spatial distribution of Pd in dry and wet season (left and right side, respectively)

Considering that there are 19,742 agricultural water use rights for surface water from the Shullcas, Mantaro, Cunas, Consac, Chanchas and Achamayo rivers, 2,696 from the Mantaro river, concentrated in subcatchments 11 and 17, and having a farm activity that plans to increase areas with access to irrigation from surface water sources (National Water Authority 2021), it is important to reanalyze the current state of water quality in the Middle Mantaro Sub-basin and generate better control and care of our resource.

2.4 Conclusions and Recommendations

The Middle Mantaro Sub-basin presents poor water quality between 2015 and 2021. The main parameters that exceed Peruvian and FAO environmental regulations in the dry season are: total phosphorus, BOD5, COD, thermotolerant coliforms and Mn, and in the wet season: total phosphorus, BOD5, COD, thermotolerant coliforms, Mn and Pb. Concentrations were higher in the wet season for all parameters except for Mn, nitrates and TP. The most affected subcatchments by physical–chemical parameters are 10, 28, 36, 32, 31, 35, 29, 33, 34, 37, 38, which is where the urban area is concentrated; the most affected by the microbiological parameter are all, and by heavy metals are 27, the: 1, 2, 8, 9, 4, 5, 6, 3, 12, 7, 11, 13, 10, 14, 19, 30, 17, 29, 28, 31, 32, 33, 34, 35, 36, 37, 38, the latter being the ones that generate the greatest concern. The sources of contamination for the physical–chemical and microbiological parameters focus on municipal, domestic, slaughterhouse wastewater, dumps and agricultural activities, while for heavy metals they are found in mining liabilities, mining deposits, non-metallic mining, and agrochemicals.

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