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Mathematical modelling by convection–diffusion with reaction of organic pollution in the wadi Mouillah stream, north-western Algeria

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Abstract: This work describes the behaviour of organic pollutants along the wadi Mouillah watercourse and its main tributaries and their impacts on the Hammam Boughrara dam, located in the NW of Algeria, in the Wilaya of Tlemcen. The use of a database relating to physico-chemical, biotic and hydrological variables, covering the period from January 2006 to December 2009, contributed to the understanding of the spatiotemporal evolution of each variable. The application of a mathematical model of the diffusion by convection-dispersion with a reaction on two characteristic parameters of organic pollution, the biochemical oxygen demand (BOD_5) which records values above the norm, with peaks that can reach 614%, and total phosphorus (P_{tot}), which the concentration is always higher with maxima reaching 53 mg·dm^{-3} favouring eutrophication; this made it possible with precision to synthesise the propagation of pollutants in the liquid mass. The results obtained on the waters of Wadi Mouillah are therefore of poor quality; there is a need to set up a rigorous water quality monitoring system, with water treatment and decontamination devices to preserve the water resources. This will allow to contribute to better management of water quality in terms of combating the spread of pollution. Therefore, they can be used to support decisions in the context of sustainable development.

Keywords: biochemical oxygen demand (BOD_5), diffusion, Hammam Boughrara dam, mathematical modelling, pollution, total phosphorus, wadi Mouillah

INTRODUCTION

The direct discharges of wastewater and other substances into rivers are very harmful to the environment: they pollute water, destroy biomass, degrade soil quality, and have many other negative effects on the environment, health, and even economic development.

From this perspective, we considered that discharges deserve special attention, by studying the behaviour of organic pollutants of urban, agricultural, and industrial origin, resulting from water discharges on the Mouillah River (wadi) and its main tributaries.

The wadi Mouillah is a watercourse that is part of the Tafna watershed, considered the largest water basin in NW Algeria; this wadi is located in the upper part of the watershed, it crosses two main cities, Maghnia (extreme NW of Algeria) and Oujda (extreme NE of Morocco). In other words, this watercourse receives various discharges from industrial, agricultural, and urban sources resulting from these two cities [Bouanani *et al.* 2013].

The various discharges channeled into the liquid flow of the watercourse find refuge in the dam called “Hammam Bougherara”, built at the point of confluence between wadi Mouillah and wadi Tafna. This dam was put in the water in November 1998; it has 56 Mm^3, intended especially to ensure the supply of drinking water to the cities of Oran, Ain Timouchent, Maghnia, and the NW corridors of the Wilaya of Tlemcen. This structure will also serve the irrigation schemes of the middle and lower Tafna.

Monitoring the water quality of the wadi Mouillah is a primary necessity for the protection of the resource stored in the basin of the dam, which receives pollutants released upstream. The quality of the water has seriously affected the hypolimnion

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water supply; since the water of the hypolimnion has become unusable, the collection is carried out from the superficial layers rich in algae, and the treatment of the water requires a large intake of chlorine, an overdose of aluminum sulphate, and the use of powdered activated carbon to combat tastes and odours.

To monitor this quality, the National Water Resources Agency (NWRA) has been carrying out a periodic system of exhaustive water analyses at various fixed and strategic locations upstream of the dam since 1999. However, there is no study specifically focusing on the behavioural mechanisms of pollutants and the spatio-temporal variations of the physicochemical and biological characteristics of the liquid flow.

Thus, the results of the research developed in this work can be applied to any similar and current situation. This work focuses on several axes, in this case: protecting the quality of water resources – diffuse contamination from various sources [Jakubiak, Bojarski 2021], surface water protection methods, and river conservation [Belarbi *et al.* 2020], etc.

In the present study, the results cover the monthly periods from January 2006 to December 2009, of which our objectives are:
– establish a diagnosis of the current state and characterise the spatio-temporal variability of water quality changes along the Mouillah stream, to contribute to the knowledge of the evolution of this ecosystem;
– the aim, on the one hand, is to establish better knowledge of the behaviour of organic pollutants, by studying the diffusion of two important organic elements: the BOD_5 and P_{tot}, along the watercourse and in the basin of the Hammam Boughrara Dam and, on the other hand, to determine the class of quality of the course of water and dam.

MATERIAL AND METHODS

PRESENTATION OF THE STUDY SITE

The Wadi Mouillah is one of the main tributaries in the Tafna watershed (7245 km^2), located at the extreme NW of the Wilaya of Tlemcen (NW of Algeria), its watershed occupies an area of 2000 km^2 and a perimeter of 241 km, of which a significant part is located in Morocco (Fig. 1) [Adjim *et al.* 2018]. The geomorphology of the wadi Mouillah watershed is characterised by a moderately elongated shape (compactness coefficient: 1.5) and an overall slope index of 7.5%. It is made up of very heterogeneous areas made up of mountains (the Traras Mountains to the NW and the Tlemcen Mountains to the south), plains, and valleys. The maximum and average altitudes of the basin are respectively 1430 and 746 m. The main trough concentration time (t_c) is estimated at 12 h [Zekriet, Tounkob 2021].

Wadi Mouillah is dominated by calcareous and vertisols, which run along its main thalweg and extend NE of the Traras mountains and to the foothills of the Tlemcen mountains. It also includes shallow Luvisol calcic formations and developed Fluvisol lands in the northern part of the Maghnia Plain. The southern part of the plain includes crusted Arenosols formed from Miocene salt marls [Megnounif, Ghenim 2013].

Furthermore, its climate is semi-arid, with annual temperatures varying between 15.7 and 18.4°C, precipitation is relatively low and unevenly distributed throughout the year with an interannual average of 297 mm, as for real evaporation at the open water level, the level of the confluence of the wadi Mouillah and Tafna, it was estimated at 1167 mm per year [Direction des Ressources en Eau de la Wilaya de Tlemcen 2000].

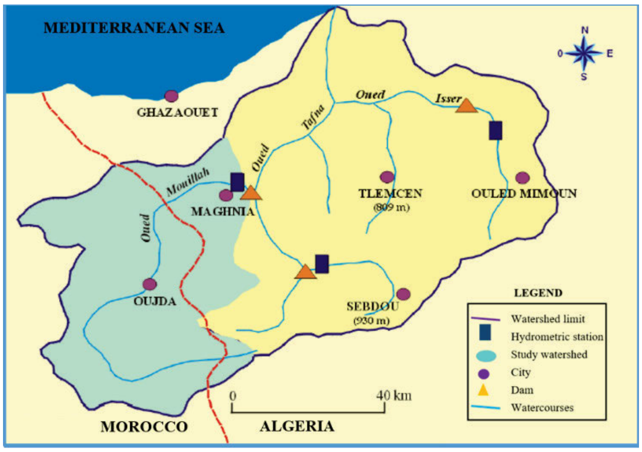

Fig. 1. The location of the Wadi Mouillah watershed; source: Djelita *et al.* [2016], modified

Regarding land use, bare land constitutes 49% of the area of the watershed, located in its western part, extensive crops cover 21% of its area, normal forest area covers 14% of its area and the rest surface is land. The average annual liquid flow of the wadi Mouillah is estimated between 0.44 and 1.44 m^3·s^{-1}. The annual solid inputs recorded vary between 17.3 and 1038.4 Mg·km^{-2}·y^{-1}, and the interannual average is 252.1 Mg·km^{-2}·y^{-1} [Hamed, Bouanani 2016]. At the confluence of the wadi Tafna and wadi Mouillah is located the Hammam Boughrara dam, filled with water in 1998, its capacity is 177.0 Mm^3, with 56.0 Mm^3 of water that can be regulated and 23.30 Mm^3 constitute the dead volume. The area of its water body varies from 2.5 to 4.8 km^2, its average depth is 15 m, and its maximum depth is 32 m [Haouati *et al.* 2018]. This dam is mainly intended for the drinking water supply of the western part of the Wilaya of Tlemcen, as well as for the irrigation of the agricultural plain of the middle Tafna [Bensaoula, Adjim 2008].

POTENTIAL SOURCES OF POLLUTION

The pollution of the waters of wadi Mouillah is mainly due to domestic, industrial, and agricultural discharges, on both sides of the Algerian-Moroccan border. Urban pollution in the city of Maghnia has been reduced thanks to the connection of 95% of the activated sludge domestic wastewater treatment plant for 150,000 inhabitants' equivalents, with a treatment efficiency of 95%. The quantities of chemical fertilisers, pesticides, and phytosanitary products used in agriculture and leached in times of rain or irrigation to the wadi Mouillah and its tributaries are applied arbitrarily and are not quantified, hence the possibility of involving pollution.

The main source of industrial pollution comes from four main industrial units: that which product the bentonite and bleaching earth; which releases 500 m^3·s^{-1} of water, rich in suspended clay particles and concentrated in heavy metals. That which products the oil, soap, and glycerine; which releases 530 m^3·s^{-1} of water loaded with crude oil and glycerine. That which products the derived from corn; which releases 600 m^3·s^{-1} of water laden with gluten in the wadi Abbes, a tributary of the

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wadi Mouillah, and that which product ceramic; which releases 130 $m^3 \cdot s^{-1}$ of water heavily loaded with minerals in the wadi Abbes.

On the Moroccan side, urban and industrial wastewater from the city of Oujda is practically purified to the tune of 85% by the wastewater treatment plant of 250,000 inhabitants' equivalents. However, the risk of agricultural pollution is the same as that on the Algerian side [Adaouri *et al.* 2019].

SAMPLING, ANALYSIS, AND PARAMETERS STUDIED

Given the different activities identified in the study area (domestic, industrial, and agricultural wastewater), three stations (Mouillah, Legfaf, and dam) were chosen for sampling, distributed downward along the wadi Mouillah, from the Algerian-Moroccan border upstream to the Hammam Boughrara dam downstream (Fig. 2).

For an appreciation of the spatio-temporal diffusion phenomenon of the two parameters characterising pollution, the BOD_5 and P_{tot}, three other stations (Chigueur, wadi Abbes, and Tafna) were included at the level of the wadi Mouillah and its tributaries, in a way allowing to cover the entire upstream part of the Hammam Boughrara dam. These six stations are located downwards from upstream to downstream as follows:
– Mouillah, upstream of the wadi Mouillah, just on the Algerian-Moroccan border; it is 20 km away from the Moroccan city of Oujda;
– Chigueur, located downstream from the seaside resort of Chigueur, on the same watercourse of Mouillah, is 16 km from the first station, just upstream of the city of Maghnia;
– wadi Abbes, one of the main tributaries of wadi Mouillah which crosses the town of Maghnia;
– Legfaf, located at the point of confluence between wadi Abbes and wadi Mouillah, after the town of Maghnia, is 8 km downstream from the station of wadi Abbes and 7 km downstream from Chigueur station;
– Tafna is located at the point of confluence between wadi Mouillah and wadi Tafna, just at the entrance to the basin of the Hammam Boughrara dam. It is 5 km away downstream from the Legfaf station;
– at the level of the water body of the Hammam Boughrara dam above the water intake, where samples are taken at different water depths. It is 2 km away downstream of the Tafna station.

All stations are chosen in an accessible manner and reflect the real characteristics of the surface water of the wadi Mouillah basin in the study area.

At stations, monthly water samples were taken from January 2006 to December 2009. In each sample, electrical conductivity (EC), pH, and dissolved oxygen are measured *in situ*. Water samples analysed in the laboratory of NWRA are taken in polyethylene bottles, rinsed with water from the stream, and then stored at 4°C during transportation. The analysis was performed within 24 h. The chemical compound and elements: nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), nitrogen (N), and total phosphorus (P_{tot}) were analysed in the laboratory using colorimetric assay methods by a spectrophotometer. BOD_5 was measured using a BOD_5 counter. The suspended solids (SS) were filtered through GF/C glass fiber filters, then dried at 105°C and weighed. The organic fraction is determined after heating to 550°C [Rodier *et al.* 1996].

THEORY OF DIFFUSION BY CONVECTION-DISPERSION WITH REACTION

The transport of pollutants in a liquid stream depends on several factors, namely the hydrodynamics of the river, its shape, geology and the physical characteristics of the pollutants, and the biological and chemical characteristics of the water. During the transport of substances, several other phenomena can arise, such as transfer, chemical reactions, decantation, resuspension, eutrophication, etc., making the study of the transport phenomenon much more complex [Merhabi *et al.* 2019].

The diffusion of polluting elements through the wadi Mouillah watercourse and its main tributaries depends on the hydrodynamic flow parameters (periods of floods, normal or low water), the shape of the wadi, the time of stay, and characteristics of rejected items. To better study the phenomenon of the behaviour of polluting parameters, we applied the mathematical model of diffusion by convection and dispersion with reaction, allowing the spatio-temporal analysis of the behaviour of the important pollutants, in this case, P_{tot} and BOD_5.

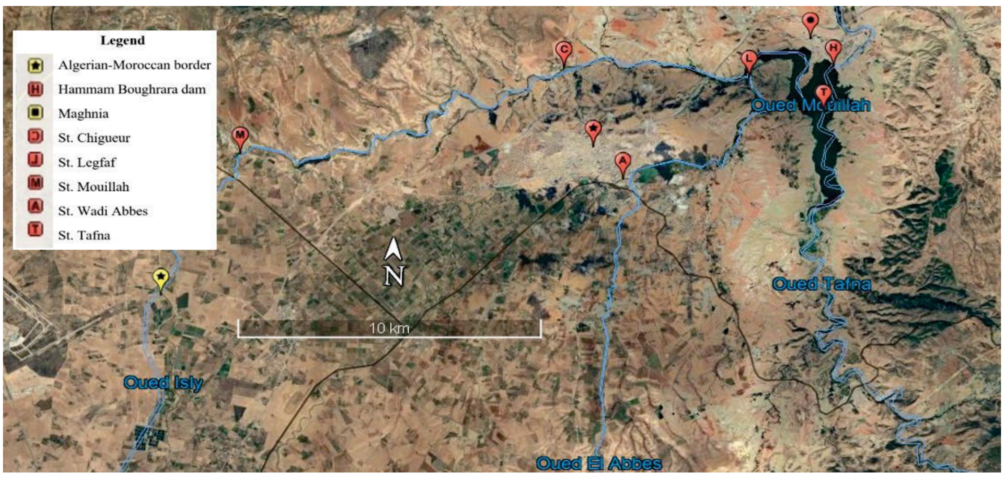

Fig. 2. Aerial photograph of the location of the sampling stations; source: own elaboration based on Google-Earth Jun 2020

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The law of diffusion gives a relation between the distributions of an extensive quantity (which must be a physical entity) in the flux space. Considering an extensive quantity of local volume density $c_f\,(x, y, z, t)$, the density vector of the flow q_f, proportional to the volume density gradient, is oriented in the direction of decreasing densities [PADET 1991], thus:

$$q_{fi} = -k \text{ grad } c_f \tag{1}$$

$$q_{fi} = -k \, \frac{\partial c_f}{\partial x_i} \tag{2}$$

where: k = diffusivity; the intrinsic magnitude of the fluid dependent on temperature and pressure, x = distance.

The application of the balance sheet equation makes it possible to arrive at a relationship between the flow and the sources.

Consider a domain of fluid materials D, delimited by a fixed surface S, through which a physical entity $c_f(x, y, z, t)$ is transported by diffusion (Fig. 3), as well as by the fluid in motion at velocity $\vec{V}$, this transport is called convection. The transport by diffusion and convection is given by the Equation (3):

$$c_f \vec{v} + k \, \overrightarrow{\text{grad}} \, c_f \tag{3}$$

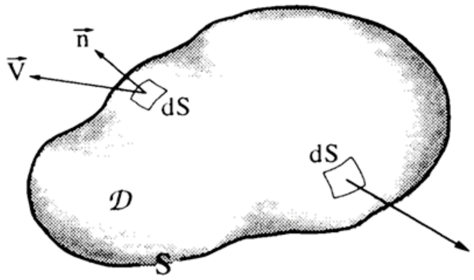

Fig. 3. Material domain D_S subjected to a balance for a physical quantity c_f, source: GRAF and ALTINAKAR [2000], modified

The general balance sheet equation in local form is expressed [DAILY, HARLEMAN 1966] as:

$$\frac{\partial c_f}{\partial t} + \text{div}\left(c_f \vec{v}\right) = -\text{ div } \vec{q}_f + \vec{q}_e \tag{4}$$

where: $\vec{v}$ (u, v, w) = local velocity vector; $\vec{q}_f$ = source flow per unit area; $\vec{q}_e$ = flow of sources in the D area per unit volume; div $(c_f\,\vec{v})$ = convection of physical magnitude.

Convection–diffusion exists in Equation (3), the velocity of the translation vector is nonzero: $\vec{v}$ $(u, v, w) \neq 0$ (u, v, w = the decomposition of the velocity in the axes: x, y and z).

The balance of matter, in Cartesian coordinates, is written as follows.

$$\frac{\partial c}{\partial t} + \text{u}\,\frac{\partial c}{\partial x} + \text{u}\,\frac{\partial c}{\partial y} + u\frac{\partial c}{\partial z} = \varepsilon_m\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2}\right) \tag{5}$$

where: C = the local concentration; diffusivity e_m is constant.

We consider, that the convection-diffusion is unidimensional in a medium at non-zero velocity. In a station, $x = 0$, an average concentration is introduced permanently and constantly C_0 = constant, the solution to the unidimensional convection-diffusion Equation (Eq. 5) is given [DAILY, HARLEMAN 1966] through:

$$C(x,t) = \frac{C_0}{2}\left(\exp\frac{Ux}{\varepsilon_m}\cdot\ \text{erfc}\ \frac{x+Ut}{\sqrt{4\varepsilon_m t}} + \text{erfc}\ \frac{x-Ut}{\sqrt{4\varepsilon_m t}}\right) \tag{6}$$

where: U = the velocity decomposition in the x axis, erfc(A) = the complementary error function [ABRAMOWITZ, STEGUN (eds.) 1964].

The evolution of the concentration $C(x, t)$ is shown in Figure 4, the concentration of value $C_0/2$ will move approximately at the velocity of the flow U.

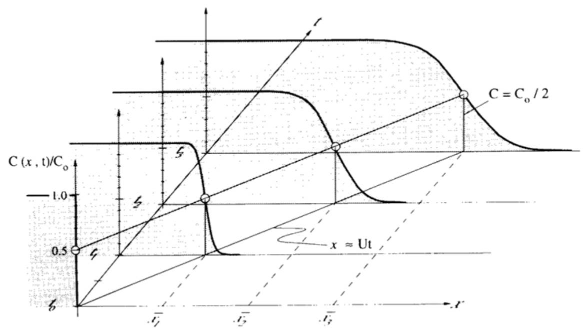

Fig. 4. Evolution of the concentration, $C(x, t)$; source: GRAF and ALTINAKAR [2000], modified

The diffusivity coefficient ε_m (generally equal to K_x) is given for natural rivers by an approximate value:

$$K_x = 0.011\frac{B^2 \cdot U^2}{h \cdot u_*} \tag{7}$$

where: B = the mean base of the minor river bed; U = the flow velocity; h = the height of the flowing water; u_* = friction velocity, this is often admitted equal to:

$$u_* = 0.1U \tag{8}$$

The approximate and high values of K_x are associated with flows with areas of large geometric irregularities (the case of wadi Mouillah), and water only slowly participate in the mixing process [RUTHERFORD 1994].

The dispersion with reaction is studied to know the self-purifying power of the rivers (such as wadi Mouillah). The equation of convection-dispersion (Eq. 5) is then written:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = K_x\frac{\partial^2 C}{\partial x^2} \pm (K_r\ C) \tag{9}$$

where: $(K_r\ C)$ = first-order chemical reaction term; it expresses the rate with which an active substance increases or decreases by the reaction; K_r = the degradation coefficient, reaction coefficient of the substance in the mixture, in dimension $(1/t)$; U, C = the velocity and the average concentration respectively in the section.

We consider the transport of a continuous source as permanent, and the longitudinal dispersion is negligible:

$$\frac{\partial C}{\partial t} = 0 \quad \text{and} \quad \text{K}_\text{x}\frac{\partial^2 \text{C}}{\partial \text{x}^2} = 0 \tag{10}$$

Accordingly, the equation of convection-dispersion with reaction (Eq. 10) is written:

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$$U\frac{\partial C}{\partial x} = (K_r C) \tag{11}$$

This equation is used as a basis for modelling studies of the water quality in rivers, including its integration by variable separation:

$$\frac{C_x}{C_0} = \exp^{\pm K_r \frac{x}{U}} \tag{12}$$

where: C_x = variation of the concentration in the x axis.

With the concentration of the reference given by:

$$C_0 = \frac{G_0}{Q} \quad \text{and} \quad \mathrm{G}_0 = \frac{M_0}{t} \tag{13}$$

where: G_0 = total mass flow rate of the substance; Q = total flow rate of the mixture; M_0 = the initial mass of the substance.

For a decreasingly active substance, Equation (11) is written:

$$\frac{C_x}{C_0} = \exp^{-K_r \frac{x}{U}} \tag{14}$$

Given the complexity of the problem, it was essential to make some simplifications on the morphological characteristics of the wadi, the conditions of flow, and the distribution of the concentration.

However, the assumptions set have no influence on the spread of pollution in the watershed, these assumptions are:
– the cross-section at the sampling stations has a rectangular shape, width B, where the height of the water body is h;
– the flow in rivers is considered unidimensional;
– the average velocity corresponds to the recorded flow rate;
– the concentrations of the parameters analysed at the outlet level are considered to be a continuous and constant source;
– the concentrations are assumed to be distributed over the entire cross-section.

The concentration of BOD_5 satisfied in the mixture, which initially exists at the level of the various sampling stations, is calculated using the relation given by Equation (12), knowing that this equation can be used to study the evolution of the concentration of biochemical oxygen demand.

Some indicative values of the degradation coefficient K_r [Fair *et al.* 1968] are shown in Table 1.

RESULTS AND DISCUSSIONS

POTENTIAL HYDROGEN (pH)

The observed values indicate that the pH often varies from neutral to alkaline for all wadi Mouillah stations. Indeed, for the Mouillah and Lagfaf stations, the pH is considered neutral. Except for a few months from 2007 to 2008, when the waters of wadi Mouillah and Lagfaf became acidic, this is mainly due to the discharges accumulated at the point of confluence of industrial wastewater. As at the Hammam Boughrara dam, the waters are often alkaline throughout the years 2006–2009. The alkalinity of the water is mainly due to the presence of carbonates, allowing to buffer the water which flows by runoff and seepage in the water [Tremblay *et al.* 2014], marly cover, and dolomitic limestone. The change in pH between the two campaigns does not exceed two pH units and the curves (Fig. 5a) are very variable and do not follow a regular law. The pH tends to increase from upstream to the Hammam Boughrara dam. This is explained by the dilution of the water in the dam.

Table 1. Reaction coefficient of organic matter contained in wastewater

Kind of wastewater	K_r (d^{-1})	C_{BOD5} (mg·dm^{-3})
Wastewater, charged	0.39	>250
Wastewater, lightly loaded	0.35	150–250
Wastewater, purified	0.12–0.23	15–75

Explanations: K_r = diffusivity coefficient, C_{BOD5} = concentration of biochemical oxygen demand.
Source: Graf and Altinakar [2000], modified.

ELECTRICAL CONDUCTIVITY

The recorded conductivity's average values show great variations. They oscillate between 914 μS·cm^{-1} at the Dam station in July 2009 and 3500 μS·cm^{-1} at the Legfaf station in the dry period. The temporal distribution of the *EC* for the waters studied showed a decrease during the rainy period (Fig. 5b). The explanation for this decrease is the dilution of water by the contribution of rainwater. However, the surface water of wadi Mouillah, which exceeds the Algerian standard for surface water (2700 μS·cm^{-1}) [JORADP 2012], indicates excessive mineralisation attributed to the wastewater of Oujda and Maghnia. The highest values are recorded at Legfaf station. This indicates the presence of polluting mineral matter, on the one hand from the city of Maghnia, and on the other hand by the accumulation of mineral matter dissolved in the waters of the wadi Mouillah from upstream, with the recording of a significant dilution by the flow, especially in winter, only the standard is often a little exceeded. At the dam, the *EC* remains appreciably lower than the Algerian standard due to the dilution of the stored water.

TOTAL SUSPENDED MATTER (*TSS*)

Figure 5c indicates that the suspended solids for all stations ranged from 6 to 941 mg·dm^{-3}. It can be seen that the suspended solids are more important in winter that is to say during October–January period, sometimes high values are recorded at the end of the winter season, between March and April. This winter period, known for strong floods and a high content of suspended solids, is the result of a brutal hydrological event; a load of this content can be attributed to intense erosion of the watershed due to thunderstorms, which cause an increase in water levels suspended matter. During this period, *TSS* are higher than those measured in summer, an observation consistent with several studies carried out in the river [Terfous *et al.* 2001]. The highest suspended solids are recorded at the Mouillah station indicating the transport of suspended solids from the city of Oujda accentuated by the rejection of its important industrial zone, followed by the Lagfaf station, transporting suspended solids from different confluence troughs, reinforced by discharges from the Maghnia city industry, mainly factories that manufacture bentonite and ceramics. These values decrease immediately downstream of the

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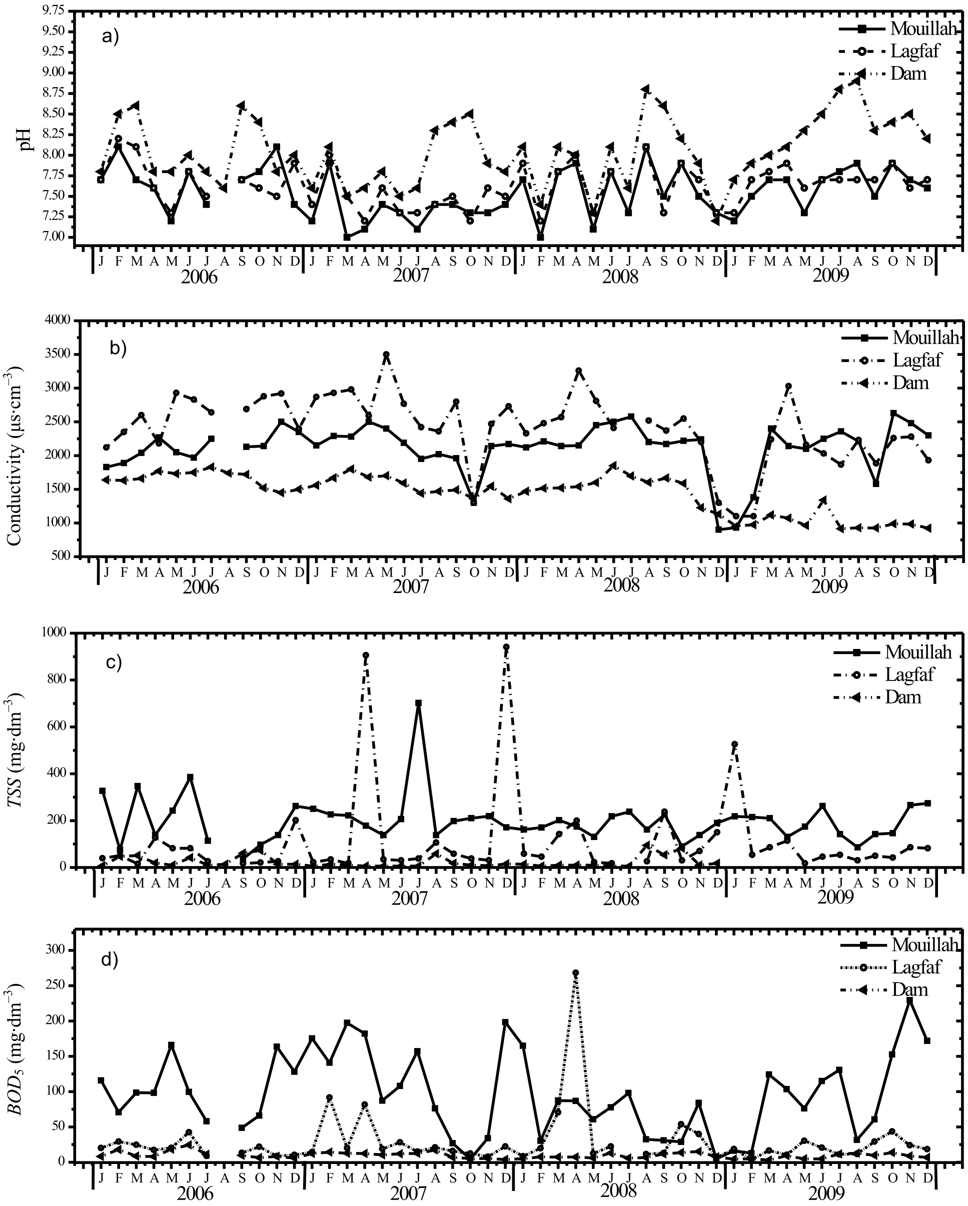

Fig. 5. Spatio-temporal variation of: a) pH, b) electrical conductivity (*EC*), c) total suspended solids (*TSS*), d) biochemical oxygen demand (BOD_5); source: own study

Hammam Boughrara dam, following a settlement of the suspended matter in its basin. However, they reach acceptable values after the drop carried out for irrigation of the agricultural areas located after and around the dam. In addition, the comparison of the concentrations of suspended matter in the wadi Mouillah with the Algerian standard places these waters in a grid of average quality.

BIOCHEMICAL OXYGEN DEMAND (BOD_5)

Figure 5d shows that the concentrations are higher than the current Algerian standard of 35 mg·dm^{-3} [JORADP 2012] at the Mouillah station at the expression for December 2008, and January and February 2009. An almost homogeneous oscillation during dry and wet periods shows the homogenisation of discharges from the Moroccan territory. In Lagfaf, BOD_5 is often around the standard. It should be noted that the commissioning of the municipal activated sludge treatment plant in Maghnia in 2005 and the start of the main Maghnia industries to treat their waste had a great influence on the quality of the water. At the Hammam Boughrara dam, due to the dilution and the biological activity that degrades BOD_5, it is almost always below the admissible standard.

TOTAL PHOSPHORUS (P_{TOT})

Figure 6a shows that the concentration of total phosphorus in the surface water of wadi Mouillah varies between 0.16 and 53 mg·dm^{-3} (Mouillah) in the wet season, and between 0.22 mg·dm^{-3} (Dam) and 42.87 mg·dm^{-3} (Mouillah) in the dry season.

The highest values are recorded upstream of the Mouillah station (source of contamination of Moroccan origin). On the other hand, in Legfaf, at the point of confluence of discharges from the industrial zone of Maghnia, the P_{tot} values are eligible, especially during the dry season, where the flow is caused only by

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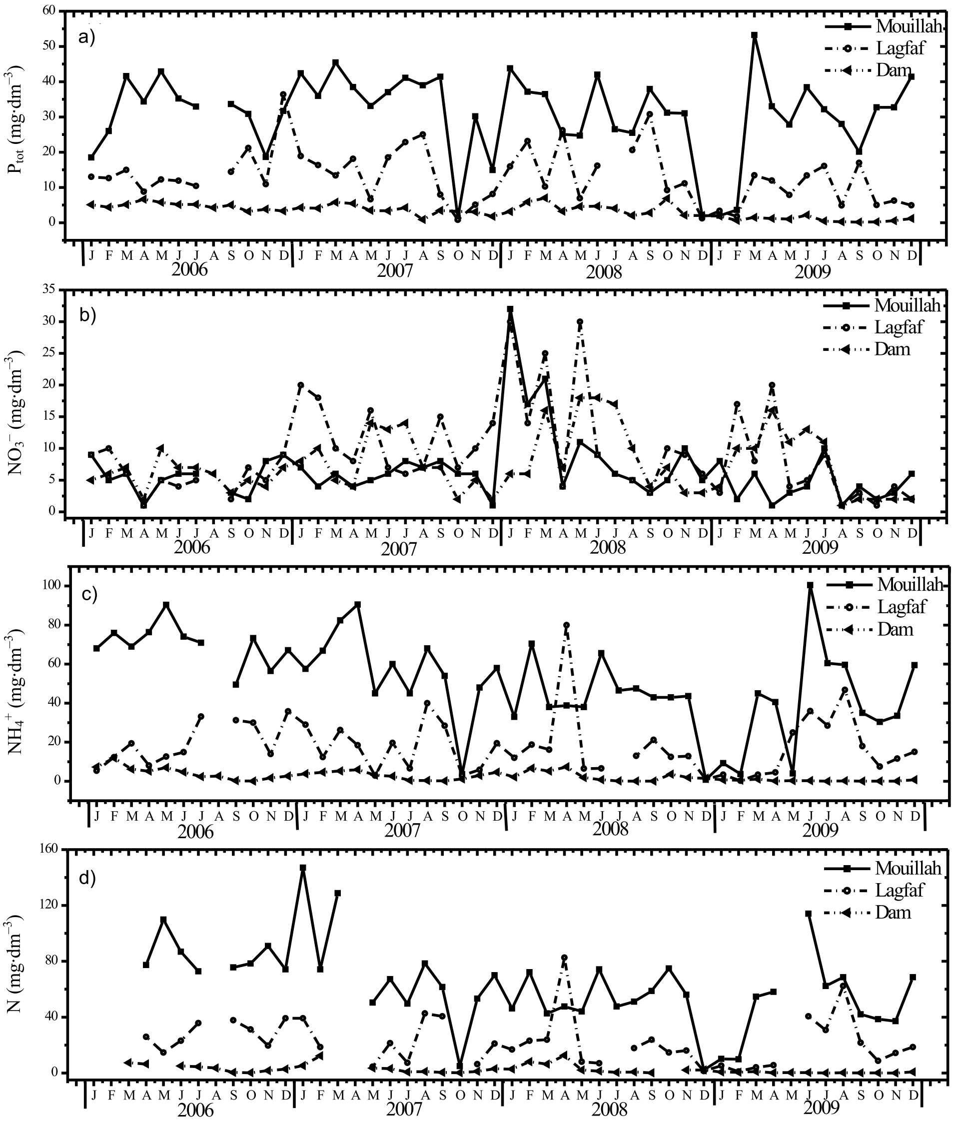

Fig. 6. Spatio-temporal variation of: a) total phosphorus (P_{tot}), b) nitrates (NO_3^-), c) ammonium nitrogen (NH_4^+), d) total nitrogen (N); source: own study

the discharges of wastewater. However, at the Hammam Boughrara dam, the phosphates follow a spatial variation, relatively marked by an increasing tendency during the dry season. These values could be explained by the urban discharges surrounding the agglomerations and the discharge of phosphorus trapped in large amounts in the sediments. This placed these waters in the low class (often higher than the current Algerian standard of 0.5 mg·dm^{-3}).

NITRATES (NO_3^-)

Figure 6b shows a slight variation in nitrate concentrations for Mouillah (1 and 32 mg·dm^{-3}), Lagfaf (1 and 30 mg·dm^{-3}), and Hammam Boughrara dam (1 and 18 mg·dm^{-3}). It can be concluded that the amount of nitrates recorded in the surface waters of the wadi Mouillah basin is less than the amount suggested by Algerian and international standards (50 mg·dm^{-3}). This indicates that the waters of the tributaries and those stored at the dam are not subject to the risk of pollution by nitrates. However, nitrate concentrations in the dry period are higher, indicating nitrate pollution in the dry period. This could be attributed to the discharge of wastewater that has not undergone any prior treatment from certain villages and hamlets located between the Moroccan border and the Hammam Boughrara dam along the river, and to low oxygen levels dissolved.

AMMONIUM NITROGEN (NH_4^+)

Figure 6c shows that the concentrations vary between 0.01 and 7.14 mg·dm^{-3} in the dam station. The relatively high quantities recorded at the stations of Mouillah (3.6 and 100.5 mg·dm^{-3}) and Legfaf (0.9 and 80 mg·dm^{-3}) reflect the process of incomplete degradation of organic matter. The measured values of ammonium ions in the waters of wadi Mouillah make it possible to classify these waters in the mediocre class (Mouillah and Legfaf) according to the Algerian surface water quality grid.

TOTAL NITROGEN (N)

Figure 6d shows that the concentrations are relatively high recorded at the Mouillah stations (a maximum of 147.0 mg·dm^{-3}) and then at Legfaf (with peaks of 82.6 mg·dm^{-3}) exceeding the

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recommended normal value of 15 mg·dm^{-3} [JORADP 2012]. This is explained by the uncontrolled wastewater discharged into the wadi, in addition to the leaching of agricultural lands often subjected to the application of nitrogen fertilisers, as well as the very responsive livestock in this space. Otherwise, the results indicate that the Mouillah stream in terms of Algerian discharge standards is in the mediocre class. At the dam level, the variation in total nitrogen is between 0.01 and 12.6 mg·dm^{-3}, less than the standard, after dilution and operation of the dam as an optional lagoon [NADIA, WISSAL 2020].

DIFFUSION OF BIOCHEMICAL OXYGEN DEMAND (BOD_5) AND TOTAL PHOSPHORUS (P_{TOT})

The propagation of BOD_5 and P_{tot} is a convection-diffusion problem. For such a situation, we use Equation (11) to simulate the concentration distribution, $C(x, t)$, for time ranging from 0.5 to 24 h, assuming different values for the distance, x, that goes from the sampling point to the entrance to the dam reservoir. The shape characteristics of the sections of the wadi, as well as the element flow and that of the analysed element in question (concentrations and mass of pollutants borrowed from the series of samples taken during the period from 2006 to 2009) that allow the study of the propagation of BOD_5 and P_{tot} in the middle of the wadi Mouillah watershed are summarised for each station in Table 2.

Spatio-temporal variations in the degradation of BOD_5 and P_{tot} at the stations of Mouillah, Chigueur, Wadi Abbes, Legfaf, Tafna and Hammam Boughrara dam are represented, respectively, by curves in Figures 7 and 8. Figure 7a–e shows that for the same distance, the BOD_5 is lower when the time associated with it is low. This could be explained by BOD_5 fact that the propagation is done slowly; in addition, at short durations, the bacteriological latency phase is exceeded and the microorganisms have already reached the rapid growth phase, where the degradation of organic matter is extensive. This degradation is asymptotically toward the zero value as long as the distance is important.

However, it takes a lot more distance to reach a very low BOD_5 when the weather is important [HOCINAT, ALI-KHODJA 2018].

Notwithstanding, over different distances, when the assigned duration is long, the BOD_5 tends to come closer to align with the maximum concentration. However, the spread of BOD_5 (the most important in the whole watershed) is slow at short durations. This is the direct cause of rapid degradation of bacteria, in particular those of anaerobic types (heterotrophs), the latency phase of which is exceeded, where the microorganisms have already reached the phase of rapid growth.

During short periods of time, the degradation very quickly approaches zero asymptotically. The cumulative concentrations of BOD_5 that arrive at the Hammam Bougherara dam, after having travelled different distances from their sampling stations, corresponding to the temporal variation of the propagation of BOD_5 in the basin of the Hammam Boughrara dam (Fig. 7f).

The degradation is very low with long periods of times, yet even with short periods of times, the value of BOD_5 is very high and far exceeds the standard of 30 mg·dm^{-3}, set by the World Health Organization (WHO).

Thus, given the importance of the discharges, the purifying power of the wadi Mouillah watershed is weak, and without consequence on the degradation of BOD_5, more of the self-purification is of the anaerobic type, the yield of which is lower aerobic self-purification [PETIOT 2017].

We note for the concentration of P_{tot} at the level of the Mouillah station that for 1800, 3600, and 7200 s the values are cancelled respectively, at 4000, 8000 and 16,000 m, and after the duration of 14,400 s the value of the P_{tot} recorded at the mouth of the reservoir is inferior to the norm, but it would allow the proliferation of blue algae. Beyond this period, phosphorus exceeds the norm greatly (Fig. 8a). And for the Lagfaf station, the durations of 1800, 3600, 7200, 14,400 and 21,600 s, the value of the concentration is cancelled respectively, at 1000, 1500, 4000, 6000 and 8000 m and after half a day, the value of the total recorded at the mouth of the reservoir is lower than the norm, however, it would allow the proliferation of blue algae [PAQUIN 2018].

Table 2. Biochemical oxygen demand (BOD_5) and total phosphorus (P_{tot}) propagation parameters at the station level

Parameter	Mouillah		Chigueur		Wadi Abbes		Lagfaf		Tafna	
	BOD_5	P_{tot}	BOD_5	P_{tot}	BOD_5	P_{tot}	BOD_5	P_{tot}	BOD_5	P_{tot}
C (mg·dm^{-3})	90	31.5	93	18	776	102	3700	77.5	776	102
U (m·s^{-1})	0.09	0.09	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Q (m^3·s^{-1})	0.11	0.11	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
H (m)	0.15	0.15	0.10	0.1	0.28	0.28	0.28	0.28	0.17	0.17
B (m)	8.00	8.00	3.00	3.00	3.00	3.00	3.00	3.00	5.00	5.00
S (m^2)	1.2	0.2	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
K_r (d^{-1})	0.35	0.43	0.35	0.08	0.39	0.004	0.39	0.004	0.39	0.02
M_0 (kg)	9.90	3.46	0.93	0.18	7.76	1.02	37.00	0.77	7.76	1.02
M_1 (kg·m^{-2})	8.28	2.90	1.12	0.22	9.31	1.22	44.40	0.93	9.31	1.22

Explanations: BOD_5 = biochemical oxygen demand, P_{tot} = total phosphorus, C = concentration, U = velocity, Q = flow, H = depth, B = length, S = section, K_r = diffusivity, M_0 = initial mass, M_1 = final mass.
Source: own study.

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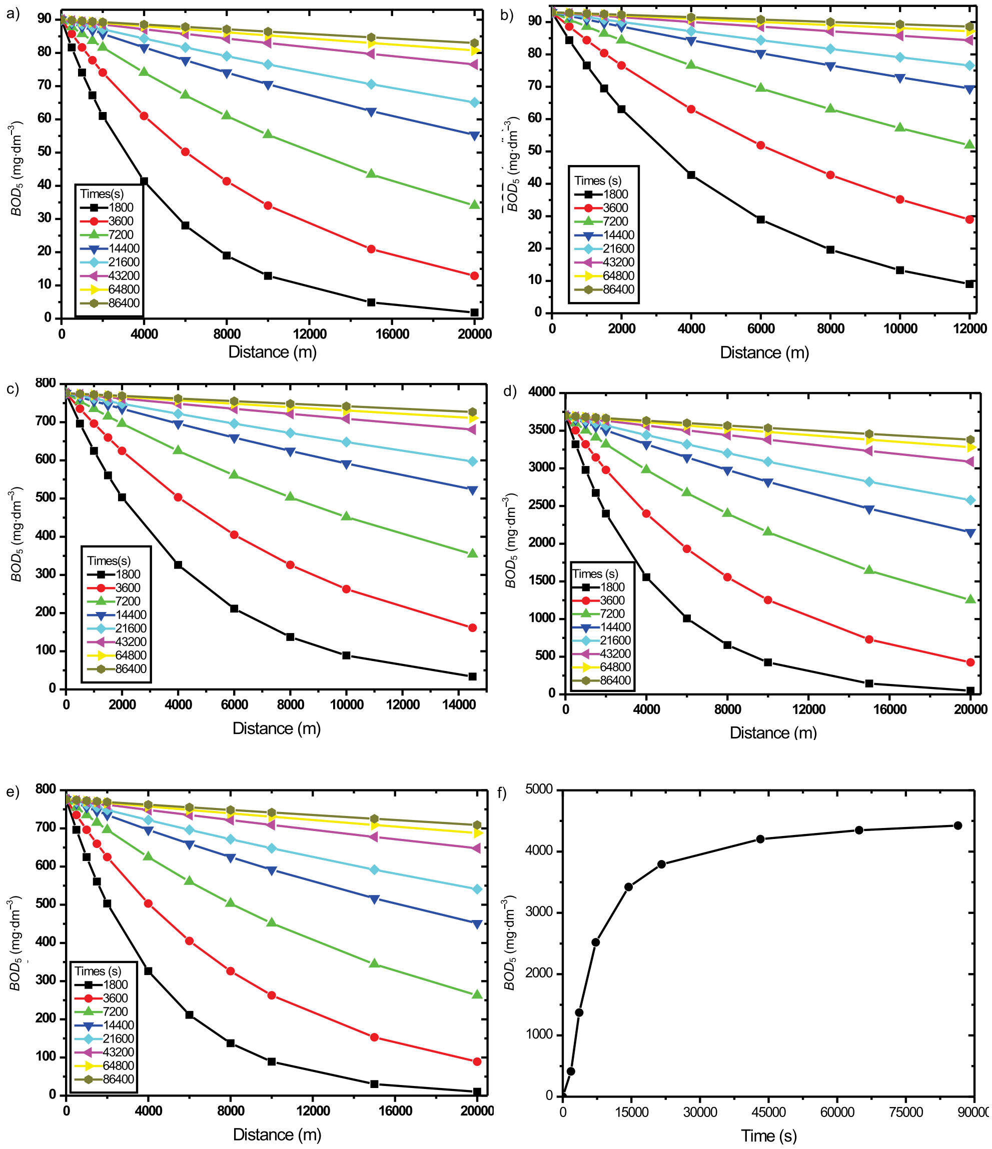

Fig. 7. Spatio-temporal degradation of biochemical oxygen demand (BOD_5) from the stations: a) wadi Mouillah, b) Chigeur, c) wadi Abbes, d) Lagfaf, e) Tafna, f) reservoir; source: own study

Beyond this time, the phosphorus gradually exceeds the norm (Fig. 8b). Figure 8a, b shows that the diffusion of the P_{tot} is proportional to the times granted. In other words, at low times, the concentration is quickly reduced. While the diffusion manifests itself gradually in the medium with longer durations until they become asymptotic at the initial concentration.

However, as for the three stations: wadi Abbes, Lagfaf, and Tafna, the concentration of P_{tot} are very quickly reduced as a function of time and space (Fig. 8c–e).

In other words, the diffusion of phosphorus is weak and the concentration tends toward zero after 24 h and before traveling a distance of 4000 m for the three wadi (Abbes, Lgfaf, and Tafna).

This could be due to the flow conditions in the rivers, the influence of which is important to the phenomenon of propagation. The change in concentrations of P_{tot} transited through the water body of the dam is proportional to the duration of diffusion (Fig. 8f).

It also depends on flow conditions such as flow and geometric shape and morphology of wadis. It is noted that the concentrations of P_{tot} exceed the standard after 4.5 h. Beyond that, the curve becomes asymptote at the maximum concentration recorded with the increase in the diffusion time.

CONCLUSIONS

In this study, based on a database covering a period from January 2006 to December 2009, we focused specifically on the mechanisms of spatio-temporal variations in the physicochemical and biological characteristics of the wadi Mouillah and the diffusion of two polluting biological parameters: biochemical oxygen demand (BOD_5) and total phosphorus (P_{tot}) and their impact on the Hammam Boughrara dam.

On the five analysis stations distributed in a descending manner upstream of the Hammam Boughrara dam, the spatio-temporal diagnoses prove a deterioration in the quality of the water of the watercourse, in particular downstream of the towns of Oujda (Mouillah Amont station) and Maghnia (Legfaf station).

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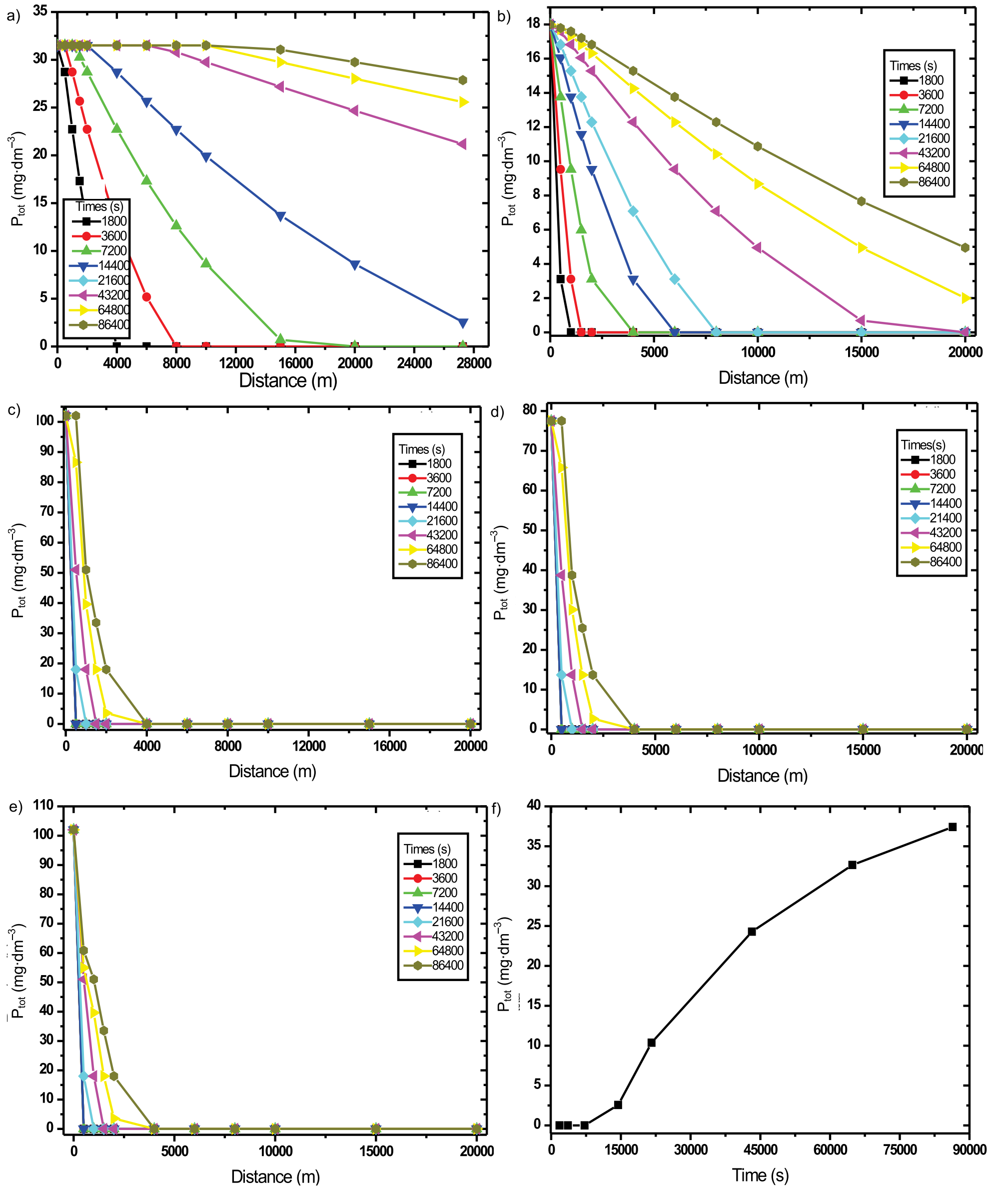

Fig. 8. Spatiotemporal degradation of total phosphorus (P_{tot}) from the stations: a) wadi Mouillah, b) Chigeur, c) wadi Abbes, d) Lagfaf, e) Tafna, f) reservoir; source: own study

Indeed, the current state of the watercourse reveals high concentrations of certain parameters such as BOD_5, which records values above the Algerian standard, especially at the Mouillah station (source of contamination of Moroccan origin), then at the station of Legfaf after the town of Maghnia and just before the dam, with peaks that can reach 614% (in Mouillah) and 471% (in Legfaf), indicating very significant organic pollution along the watercourse.

For P_{tot}, the concentration always remains above the standard, the highest values of which are recorded upstream of the Mouillah station with maxima reaching 53 mg·dm^{-3} (Mouillah) and 35 mg·dm^{-3} (Legfaf). Therefore, these waters rich in phosphorus, with a slightly alkaline pH (between 7.1 and 9.1) promote the proliferation of algae, leading to a decrease in transparency and dissolved oxygen, which are signs of eutrophication.

For nitrogenous matter, relatively high quantities are reported from the Mouillah stations (maxima of 100.5 mg·dm^{-3} for ammonium and 147 mg·dm^{-3} for total nitrogen) and Legfaf (more than 80 mg·dm^{-3} for ammonium and total nitrogen), implying incomplete degradation of organic matter; allow the water of the Mouillah stream to be classified as poor quality.

At the Hammam Boughrara dam, the spatial variation analysed of the analysed materials is relatively marked by an increasing trend during the dry season, of which the main flows of the Mouillah watercourse (the main resource of the dam) are the discharges directly discharged. During this period, the water from the structure is in the low quality class. In addition, this contamination tends to decrease at the dam level, in wet periods after dilution, and the phenomenon of self-purification. Therefore, during this wet season, the dam operates as an optional type of lagoon, allowing aerobic surface and anaerobic purification in-depth, without neglecting the risk of resuspension of the pollution accumulated at the bottom of the dam, which remains very probable, especially during rapid variations in the water body, thus rendering the quality of the stored water mediocre and bad

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for any direct use. However, from a biotic point of view, the excessive concentrations of nutrients such as total phosphorus and nitrogen as limiting factors of the trophic state classify the waters of our dam in a hypertrophic state.

The degradation of the material is explained by the diffusion model applied to the P_{tot} and the BOD_5, their concentration of which decreases with the increase of the distance and the duration of the journey. During low-water periods, at low flows and therefore a long journey time, the overall results show that surface water represents signs of degradation. On the other hand, when the watercourse is well fed, the diffusion study indicates a degradation of the material, which becomes very significant along the way; this can be linked to the self-purification power of the watercourse.

In conclusion, the results obtained on the waters of wadi Mouillah are of poor quality; there is, therefore, a need to set up a rigorous water quality monitoring system, with water treatment and decontamination devices to preserve the water resources which become obligatory in the face of the degradation of these aquatic ecosystems. In addition, this work could help to set specific objectives that allow better management of water quality in terms of trophic response within the framework of sustainable development and decision support.

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