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Concentración de nitrato, fosfato y boro en el agua residual para la irrigación de cultivos en Valle del Mezquital, Hidalgo
Nitrate, phosphate and boron content in wastewater for crop irrigation in Mezquital Valley, Hidalgo

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Palabras clave: calidad del agua de riego; irrigación; reúso del agua residual; toxicidad por boro
Keywords: agricultural water quality; boron toxicity; irrigation; wastewater reuse

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Resumen

Introducción: La Ciudad de México genera un volumen de agua de origen residual de 57 $m^3 s^{-1}$, esta agua se conduce por la red de drenaje: gran canal-interceptor poniente-emisor central, hacia el Estado de Hidalgo, y durante su curso, un volumen importante de esta agua se vierte en canales de riego y se utiliza en la irrigación de cultivos en Valle del Mezquital.

Método: en este estudio se determinó la concentración de nitrato (NO_3^-), fosfato (PO_4^{3-}), boro (B^{3+}), cloruro (Cl^-), calcio (Ca^{2+}), magnesio (Mg^{2+}) y potasio (K^+) en 188 muestras de agua. El objetivo fue evaluar el riesgo de toxicidad por iones específicos (B^{3+} y Cl^-) y el contenido de nutrientes (N, P, K, Ca y Mg) del agua residual utilizada en el riego de cultivos agrícolas.

Resultados: la concentración de nitrato (NO_3^-) fue muy heterogénea (CV=59.83 %) y se atribuyó a la lixiviación de fertilizantes nitrogenados. El fosfato (PO_4^{3-}) tuvo un valor máximo de 65.7 mg L^{-1}, y su concentración se atribuyó a la descarga de agua residual de origen doméstico. La concentración de boro (B^{3+}) fue menor de 1.88 mg L^{-1}. El riesgo de toxicidad debido al uso de esta agua en la irrigación puede ocasionar la disminución en el rendimiento de cultivos sensibles como el frijol.

Conclusión: el agua de origen residual sin tratamiento, utilizada en la irrigación en Valle del Mezquital, puede ocasionar problemas de toxicidad en algunos cultivos; la concentración de nitrato y fosfato en el agua residual de la red de drenaje Ciudad de México-Valle del Mezquital fue elevada, lo cual, representa riesgo para los organismos acuáticos por la contaminación y posible eutrofización de los cuerpos de agua. El riesgo de toxicidad por B^{3+} y Cl^- puede ocasionar efectos negativos en la germinación y rendimiento del cultivo de frijol.

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Abstract

Introduction: Mexico City generates an approximate volume of wastewater of 57 $m^3 s^{-1}$, the wastewater is conduct by the drainage network: main channel-west interceptor-central emitter, and conducted to Hidalgo State, during it course, an important volume is poured into irrigation channels and is used for crop irrigation in the Mezquital Valley.

Method: in this study, nitrate (NO_3^-), phosphate (PO_4^{-3}) boron (B^{3+}) and chloride (Cl^-) content in 188 wastewater samples was determined. The objective was to assessment the risk of toxicity by specific ions (B^{3+} and Cl^-) and the nutrients content (N, P, K, Ca y Mg) in wastewater used for crop irrigation.

Results: the nitrate (NO_3^-) concentration was very heterogeneous (CV=59.83 %) and this was attributed to the lixiviation of nitrogen fertilizers. The maximum phosphate (PO_4^{-3}) value was 65.7 mg L^{-1}, and its concentration was attributed to the discharge of household wastewater. The boron concentration (B^{3+}) was less than 1.88 mg L^{-1}. The risk of toxicity due to the use of wastewater in irrigation may cause a decrease the yield of sensitive crops, such as beans.

Conclusion: untreated wastewater used in irrigation in Mezquital Valley, may cause toxicity problems in some crops; the nitrate and phosphate concentrations in wastewater of the Mexico City-Mezquital Valley drainage network were high, and these were attributed to the discharges of domestic and industrial wastewaters and to agricultural drainage, high concentrations of nitrate and phosphate represent a risk for aquatic organisms due to pollution and the possible eutrophication of water bodies. The risk of toxicity by B^{3+} and Cl^- can have a negative effect on the germination and yield of bean crops.

Introduction

Mexico City has an estimated population of 8 985 339 inhabitants (INEGI, 2017), which makes it a challenge to satisfy the population’s growing needs regarding the allocation of drinking water, drainage and sanitation. Most rivers in Mexico City have been enclosed in pipes, and their surface waters have been classified as polluted. The rivers under these conditions are: Churubusco, de las Avenidas, de los Remedios, San Juan, de la Compañía, San Buenaventura and Tlamaco dam; therefore these rivers can be considered a part of the drainage system (Perló-Cohen & Zamora-Saenz, 2017). It is estimated that 70 % of the drinking water source in Mexico City is groundwater, and over 26 % is imported from the Lerma and Cutzamala systems; 77 % of the population consumes less than 150 L of water per day, and 96 % of the population has drainage coverage (Guerrero *et al*., 2009; Ortega-Font, 2011). Considering these reports, it is estimated that population in Mexico City generates an approximate volume of wastewater of 57 m^3 s^{-1}, (CONAGUA, 2012); this wastewater goes through the drainage network: grand channel-west interceptor- central emitter (Aguilar-Garduño *et al*., 2007), and conducted to Hidalgo state. During its course, an important volume is poured into irrigation channels and is used for crop irrigation in the Mezquital Valley (CONAGUA, 2012). In Hidalgo State an agricultural area of approximately 456 855.69 hectares is sown, 80 % of which is rainfed and 20 % undergoes irrigation systems; the greatest surface is used for maize, bean, and oats forage crops (SIAP, 2017).

Many authors agree that wastewater is an important source of organic matter (Fuentes-Rivas *et al*., 2017) and nutrients such as nitrogen (N) and phosphorus (P) [Belaid *et al*., 2012], and applying this water to agricultural irrigation will provide a considerable amount of nutrients for crop nutrition (Romero-Álvarez, 1997; Rascón-Alvarado *et al*., 2008; Zamora *et al*., 2008). However, the nitrate and phosphate concentration found in wastewater may be due to the excessive application of fertilizers in agriculture (Hem, 1985; Chávez-Alcántar et al., 2011; Guangwei Huang, 2013), and its excess concentration can be lixiviated and cause pollution of groundwater, which may cause damages to the health of people who consume water from contaminated wells, as well as the progressive eutrophication of water bodies (Figueruelo-Alejano & Marino-Dávila, 2004); the importance of high nitrate concentrations in drinking water (10 mg L^{-1} N = 44 mg L^{-1} NO_3^-) lies in health problems for children, who are prone to catching hemoglobinemia (Hem, 1985; OMS, 1998).

Other earlier studies have proven that wastewater contains elements that are potentially toxic for aquatic organisms (Robledo-Zacarías *et al*., 2017) and heavy metals, added to the soil by irrigation, accumulate on the arable layer of agricultural soils (Siebe, 1994; Prieto-García *et al*., 2007; Flores-Magdaleno *et al*., 2011) and can be absorbed and accumulated in plants (Vázquez-Alarcón et al., 2001); furthermore, contact with wastewater affects the health of the overall population (Cifuentes *et al*., 1994; Cifuentes *et al*., 2000). On the other hand, wastewater poured into receiving bodies is a high risk for human health and the environment, since medications and narcotics have been found in wastewaters, and can potentially cause toxic effects (even in low concentrations) in aquatic organisms and soil microorganisms (Robledo-Zacarías *et al*., 2017).

On the other hand, wastewater used in the agricultural area known as the Mezquital Valley had a predominant composition of bicarbonate and sodium (Cuellar-Carrasco *et al*., 2015; López-García *et al*., 2016), therefore the use of wastewater in agriculture can have negative effects on the soil and crops regarding salinity and sodicity (Fuentes-Rivas *et al*., 2017). Toxicity problems in crops arise when some ions are absorbed and accumulated in their tissues in concentrations high enough to cause damage and reduce yields (Ayers & Westcot, 1985). This toxicity depends on the tolerance of a particular crop at extreme levels of ionic concentration (Sánchez-Bernal *et al*., 2013; Can-Chulim *et al*., 2017). The most important ions related to toxicity are: B^{3+}, Cl^- and Na^+; once these ions are absorbed, they are transported to different parts of the plant and during transpiration they accumulate on the leaves.

Nitrogen is a nutrient for plants, however, nitrate concentration between 5 and 30 mg L^{-1} in irrigation water may affect sensitive crops (Ayers & Westcot, 1985), and regarding boron, toxicity presents itself in some crops when there is a concentration between 1 and 2 mg L^{-1} (Maas, 1990). The most frequent toxicity is caused by the content of Cl^- in irrigation water, since this ion is easily absorbed by the root and carried to different parts of the plant (Ayers & Westcot, 1985).

Considering the above, the objective of this investigation was to determine the concentration of nitrate, phosphate and boron in wastewaters and to estimate its content of nutrients, as well as the estimation of the risk of toxicity by specific ions (B^{3+} and Cl^-) that can affect normal crop development in a negative way. The focus of this investigation is quantitative and has a descriptive scope; given that in the area under study the largest area planted is dedicated to maize, bean and oat, these ions may affect each crop in a different way.

Methods

Sampling, water analysis and statistical analysis

To carry out this investigation, during September 2015 and April 2016, 188 wastewater, rivers and dam water samples were collected and analyzed from 135 sampling stations distributed in the Mexico City-Mezquital Valley drainage system (Fig. 1). Samples were collected according to NMX-AA-003-SCFI-1980, and considering the accessibility of the sites (SCFI, 1980).

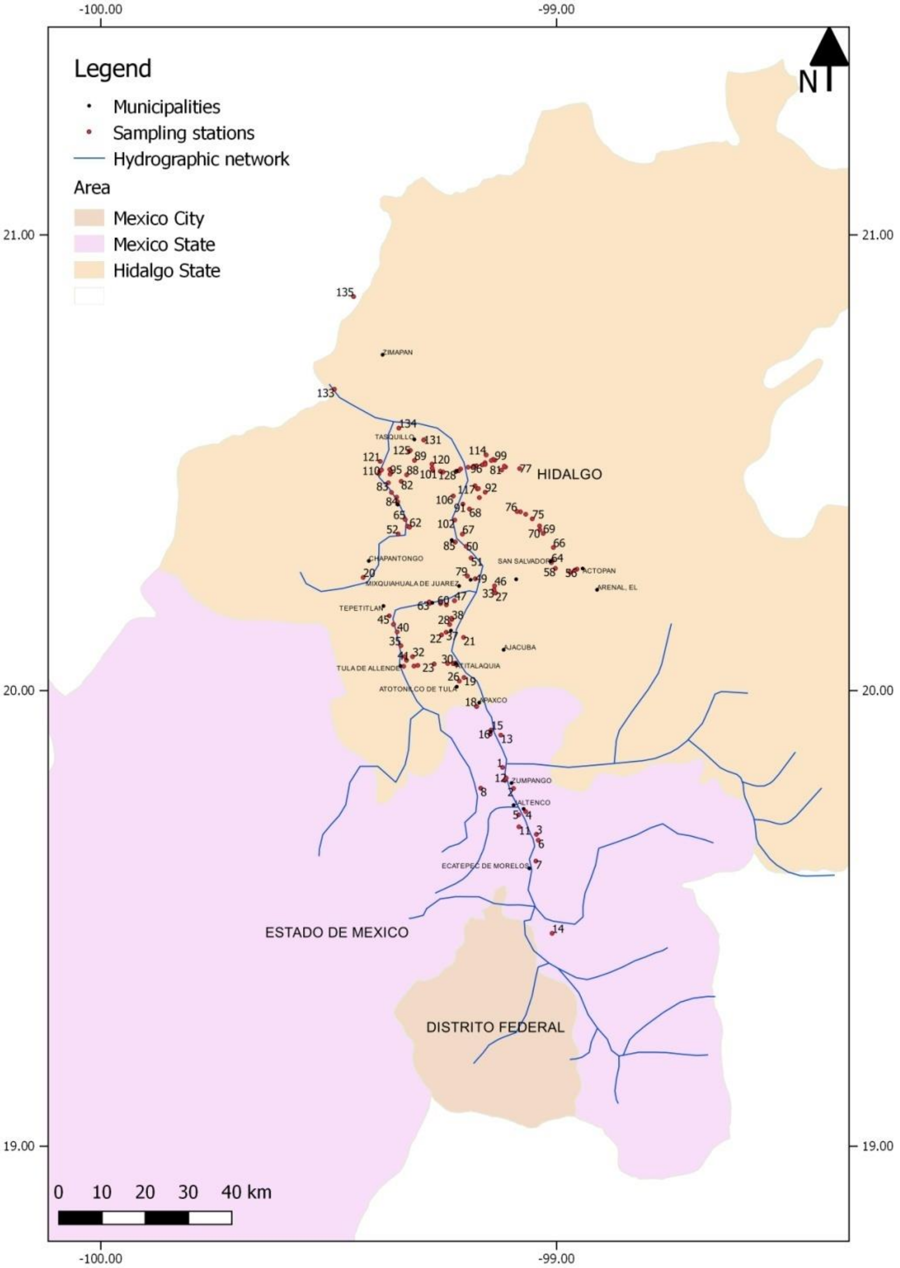

Figure 1. Location of the study area. **Source:** Author's own elaboration.

All the sampling stations (Table 1) were registered with a Geographic Positioning System (GPS Garmin® Etrex Venture HC). In each sampling station, 2 liters of water were collected and distributed into 1 L polypropylene containers previously washed with an HCl solution at 10 % concentration, then rinsed with distilled water. In all the sampling stations the channels flow in the open, the water was taken from the central part of the drainage channels at an approximate depth of 30 cm using a plastic 10 L bucket. Later, the containers were washed three times with the same collected water (Sánchez-Bernal *et al*., 2014).

Table 1. Sampling stations in México City-Mezquital Valley hydrographic network.

ID	Coordinates		Altitude	Sampling station	Reference	State
	N	W	m			
1	19.8313333	-99.1186944	2293	Irrigation channel	Zumpango-Tequisquiac	Mexico State
2	19.7851667	-99.09475	2278	Channel la laminadora	Nextlalpan-Zumpango	Mexico State
3	19.6843611	-99.0446389	2246	Channel Tonanitla I	Sta. María Tonanitla	Mexico State
4	19.7343056	-99.0678611	2245	Channel Nextlalpan	Nextlalpan	Mexico State
5	19.7271944	-99.0835556	2244	Channel Sn. Francisco	Nextlalpan	Mexico State
6	19.6715333	-99.0404833	2240	Channel Tonanitla II	Sta. María Tonanitla	Mexico State
7	19.6256167	-99.04575	2239	Pemex bridge channel	Los Héroes de Tecámac	Mexico State
8	19.7855556	-99.1666389	2239	Grand channel	Zumpango	Mexico State
9	19.7855556	-99.1666389	2239	Irrigation channel	Zumpango	Mexico State
10	19.8029167	-99.1136111	2238	Zumpango lagoon	Zumpango	Mexico State
11	19.7009444	-99.0829167	2235	East emitter tunnel vent 11	Tultepec	Mexico State
12	19.808	-99.1106944	2233	Ávila Camacho drain	Zumpango	Mexico State
13	19.9021111	-99.1226389	2228	Tunnel Tequixquiac	Tequixquiac	Mexico State
14	19.4670883	-99.0100833	2225	Peñon-Texcoco road channel	Texcoco	Mexico State
15	19.9135	-99.1437778	2213	Tequixquiac stream	Tequixquiac	Mexico State
16	19.9039722	-99.1460556	2204	Tunnel Tequixquiac	Tequixquiac	Mexico State
17	19.9649167	-99.1756944	2180	Tula River	Apaxco de Ocampo	Mexico State
18	19.9649167	-99.1756944	2180	Apaxco drainage	Apaxco de Ocampo	Mexico State
19	20.0285556	-99.2033056	2145	Irrigation channel Texas	Atotonilco de Tula	Hidalgo State
20	20.2482222	-99.4245	2118	Chapatongo River	José María Pino Suarez	Hidalgo State
21	20.1166667	-99.2042778	2111	Irrigation channel Teltipan	Teltipan de Juárez	Hidalgo State
22	20.1220833	-99.2525278	2105	Channel Tlahuelilpan	Tlahuelilpan	Hidalgo State
23	20.0582778	-99.26875	2103	Channel Pemex II	Atitalaquia-Cardonal-Tula	Hidalgo State
24	20.0565833	-99.2196944	2098	Irrigation channel Atitalaquia	Atitalaquia	Hidalgo State
25	20.0536944	-99.3130278	2094	Channel Pemex IV	El llano-Tula de Allende	Hidalgo State
26	20.02075	-99.2135556	2093	Tula River	Atotonilco de Tula	Hidalgo State
27	20.2139444	-99.1340833	2091	Irrigation channel Morelos III	Mixquiahuala	Hidalgo State
28	20.1449167	-99.2347222	2091	Irrigation channel Tlahuelilpan	Tlahuelilpan	Hidalgo State
29	20.0591389	-99.2270833	2089	Irrigation channel la Quina	Atitalaquia	Hidalgo State
30	20.0591389	-99.2270833	2089	Waterfall la Quina	Atitalaquia	Hidalgo State
31	20.0593889	-99.2392222	2087	Channel Pemex I	Atitalaquia-Cardonal	Hidalgo State
32	20.0742778	-99.3162778	2085	Channel Endho	El llano-Tula de Allende	Hidalgo State
33	20.2214167	-99.1373333	2079	Irrigation channel Morelos II	Mixquiahuala	Hidalgo State
34	20.05525	-99.3046389	2077	Channel Pemex III	Atitalaquia-El llano	Hidalgo State
35	20.0984167	-99.3417778	2076	Channel Villagran I	Tula-Sta. Ana Ahuehuepan	Hidalgo State
36	20.0745833	-99.3337222	2064	Channel Canadiense	Tula -Sta. Ana Ahuehuepan	Hidalgo State
37	20.1279722	-99.2423611	2050	Channel Tlahuelilpan	Tlahuelilpan	Hidalgo State
38	20.1557222	-99.2303333	2049	Channel Requena	Tlahuelilpan	Hidalgo State
39	20.1588056	-99.2304444	2047	Irrigation channel el Tinaco	Tlahuelilpan	Hidalgo State
40	20.1286667	-99.3500556	2047	Channel Villagrán II	Sta. Ana Ahuehuepan	Hidalgo State
41	20.0662222	-99.3295556	2040	Green bridge channel	Tula de Allende	Hidalgo State
42	20.1971389	-99.2241944	2024	Irrigation channel Tezontepec II	Tezontepec-Mixquiahuala	Hidalgo State
43	20.1451667	-99.3579722	2022	Endhó dam	Endhó	Hidalgo State
44	20.1451667	-99.3579722	2022	Endhó dam (drain)	Endhó	Hidalgo State
45	20.1638611	-99.3673611	2017	Irrigation channel	Endhó	Hidalgo State
46	20.2298056	-99.1363056	2016	Irrigation channel Morelos I	Mixquiahuala	Hidalgo State
47	20.1971389	-99.2241944	2014	Irrigation channel Tezontepec I	Tezontepec-Mixquiahuala	Hidalgo State
48	20.0531111	-99.3357222	2002	Tula River	Tula de Allende	Hidalgo State
49	20.2453333	-99.17875	2000	Irrigation channel el Progreso	Progreso	Hidalgo State
50	20.3163611	-99.1985278	1994	Irrigation channel la Mora	Xochitlán	Hidalgo State
51	20.2908333	-99.1878611	1994	Irrigation channel Xoxitlan	Xochitlán	Hidalgo State
52	20.3436389	-99.3477222	1989	Dolores dam	Cerro Azul-Oxtotipan	Hidalgo State
53	20.1908611	-99.2547778	1984	Irrigation channel Tezontepec IV	Tezontepec	Hidalgo State
54	20.3606667	-99.3273056	1984	Channel Rojo Gómez	Cerro Azul-Xamajé	Hidalgo State

Table 1. Continuation.

ID	Coordinates		Altitude	Sampling station	Reference	State
	N	W	m			
55	20.4243889	-99.3511944	1978	Irrigation channel Vicente Aguirre	Alfajayucan	Hidalgo State
56	20.2664167	-98.9554444	1977	Wastewater channel	Actopan	Hidalgo State
57	20.2641944	-98.9601667	1975	Irrigation channel Actopan	Actopan	Hidalgo State
58	20.2681111	-99.0028333	1973	Irrigation channel Sn. Salvador	Poxindejé	Hidalgo State
59	20.1910278	-99.2791667	1973	Water spring Tezontepec	Tezontepec	Hidalgo State
60	20.1881389	-99.2420278	1972	Irrigation channel Tezontepec III	Tezontepec	Hidalgo State
61	20.2595	-98.9707778	1970	Drain Boxthá	Actopan	Hidalgo State
62	20.3584722	-99.3228056	1970	Rojo Gómez dam	Cerro Azul	Hidalgo State
63	20.1943889	-99.2796111	1964	Tula River	Tezontepec	Hidalgo State
64	20.2808056	-99.0116111	1949	Water well Sn. Salvador	Sn. Salvador	Hidalgo State
65	20.3753056	-99.33225	1946	Irrigation channel Xamajé	Xamajé	Hidalgo State
66	20.3139722	-99.0073333	1936	Irrigation channel caxuxi	Bominthza	Hidalgo State
67	20.3431667	-99.2069167	1928	Irrigation channel Tlacotlapilco	Tlacotlapilco	Hidalgo State
68	20.3984167	-99.1915278	1927	Irrigation channel Ecoalberto	Tlacotlapilco	Hidalgo State
69	20.3448056	-99.0295833	1926	Irrigation channel boxani	Lagunilla	Hidalgo State
70	20.3526667	-99.03675	1924	Irrigation channel Lagunillas II	Lagunilla	Hidalgo State
71	20.2860278	-99.0091944	1921	Agricultural drainage	Sn. Salvador-El Bondhó	Hidalgo State
72	20.3869167	-99.0679444	1920	Irrigation channel Yolotepec II	Yolotepec	Hidalgo State
73	20.36125	-99.0375	1920	Irrigation channel Lagunillas II	Lagunilla-Patria Nueva	Hidalgo State
74	20.3921944	-99.0794167	1917	Irrigation channel Yolotepec I	Yolotepec	Hidalgo State
75	20.3767778	-99.0536667	1917	Irrigation channel Yolotepec III	Yolotepec-Patria Nueva	Hidalgo State
76	20.3928056	-99.0868333	1913	Irrigation channel	Yolotepec-Julián Villagrán	Hidalgo State
77	20.4871111	-99.0813611	1887	Irrigation channel debodhé-florida	Pozuelos	Hidalgo State
78	20.2513017	-99.19595	1887	Tula River	Progreso	Hidalgo State
79	20.2513017	-99.19595	1887	Infiltration water	Progreso	Hidalgo State
80	20.4347222	-99.3625556	1872	Vicente Aguirre dam	Antonio Corrales	Hidalgo State
81	20.4838889	-99.1206389	1862	Debodhé dam	Debodhé	Hidalgo State
82	20.4590556	-99.3411667	1850	Irrigation channel Xigüi	Vía Huichapan-Ixmiquilpan	Hidalgo State
83	20.4559167	-99.3693056	1846	Irrigation channel Sn. Francisco	Alfajayucan-Yonthé Grande	Hidalgo State
84	20.4142778	-99.3487778	1845	Alfajayucan River	Alfajayucan	Hidalgo State
85	20.326	-99.2226389	1837	Tula River	Chilcuautla	Hidalgo State
86	20.326	-99.2226389	1837	Infiltration water for nopal irrigation	Chilcuautla	Hidalgo State
87	20.326	-99.2226389	1837	Infiltration water for nopal irrigation	Chilcuautla	Hidalgo State
88	20.4733611	-99.3290833	1837	Irrigation channel el Portezuelo	Portezuelo	Hidalgo State
89	20.5050278	-99.3119167	1803	Irrigation channel Portezuelo 2	Portezuelo	Hidalgo State
90	20.4785	-99.3635278	1803	Irrigation channel el Bermejo	Yonthé Grande	Hidalgo State
91	20.4092222	-99.2058333	1800	Irrigation channel El Alberto	Tlacotlapilco-Ixmiquilpan	Hidalgo State
92	20.43525	-99.1568333	1793	Main channel alto Ixmiquilpan	Taxadhó	Hidalgo State
93	20.4851667	-99.3663056	1791	Reservoir el Bermejo	Yonthé Grande	Hidalgo State
94	20.5001389	-99.1571389	1790	Irrigation channel Arenalito	El Nith-Debodhé	Hidalgo State
95	20.4748333	-99.3655	1790	Irrigation channel Yonthe Grande	Yonthé Grande	Hidalgo State
96	20.4950278	-99.1635556	1789	Irrigation channel la estación	El Nith-Debodhé	Hidalgo State
97	20.4961667	-99.1568889	1789	Irrigation channel bangandhó	El Nith-Debodhé	Hidalgo State
98	20.4234167	-99.1696389	1789	Irrigation channel Maguey Blanco	Parque acuático Maguey Blanco	Hidalgo State
99	20.5055556	-99.1357222	1788	Irrigation channel EST-57	Debodhé	Hidalgo State
100	20.4905833	-99.1123333	1787	Debodhé dam (drain)	Debodhé	Hidalgo State
101	20.4829444	-99.2718611	1784	Irrigation channel dexthó	Ixmiquilpan-Portezuelo	Hidalgo State
102	20.3741944	-99.2236389	1784	Tula River	Tlacotlapilco	Hidalgo State
103	20.4924722	-99.1148056	1775	Irrigation channel Debodhé	Debodhé	Hidalgo State
104	20.5072778	-99.1392222	1772	Irrigation channel capula	Debodhé	Hidalgo State
105	20.4268889	-99.2270556	1769	Tula River in Ecoalberto	Tlacotlapilco-Ixmiquilpan	Hidalgo State
106	20.4268889	-99.2270556	1769	Irrigation channel	Tlacotlapilco-Ixmiquilpan	Hidalgo State
107	20.5047222	-99.1435278	1766	Agricultural drainage bangandhó	El Nith-Debodhé	Hidalgo State
108	20.4902222	-99.1944167	1761	Irrigation channel	El Nith-Debodhé	Hidalgo State
109	20.4426389	-99.1741111	1759	Wastewater channel	El Tephé	Hidalgo State
110	20.4819167	-99.38775	1758	Infiltration water	Sn. Fco. Sacachichilco	Hidalgo State
111	20.4756944	-99.3901389	1758	Sn. Francisco River	Sn. Fco. Sacachichilco	Hidalgo State
112	20.4432222	-99.1718333	1755	Wastewater channel el Tephé	El Tephé	Hidalgo State
113	20.4933056	-99.1760833	1754	Agricultural drainage	El Nith-Debodhé	Hidalgo State
114	20.5170278	-99.15475	1752	Chicabasco River	Capula-El Rosario	Hidalgo State
115	20.5170278	-99.15475	1752	Irrigation channel Chicabasco	Capula-El Rosario	Hidalgo State
116	20.48825	-99.2731667	1752	Drenaje agrícola Dexthó	Ixmiquilpan-Portezuelo	Hidalgo State
117	20.4493611	-99.1791111	1750	Irrigation channel Siqueiros	El Tepe	Hidalgo State
118	20.4841667	-99.3843333	1747	Channel Xigatza	Sn. Fco. Sacachichilco	Hidalgo State
119	20.4923333	-99.1822778	1746	Irrigation channel La joya	El Nith-Debodhé	Hidalgo State
120	20.4969722	-99.2736667	1746	Irrigation channel Dexthó 2	Ixmiquilpan-Portezuelo	Hidalgo State
121	20.5029167	-99.38725	1746	Madho Corrales dam	Sn. Fco. Sacachichilco	Hidalgo State
122	20.4795278	-99.2492222	1745	Irrigation channel el mexicano	Ixmiquilpan-Portezuelo	Hidalgo State
123	20.4810278	-99.2553333	1742	Irrigation channel el mexicano 2	Ixmiquilpan-Portezuelo	Hidalgo State

Table 1. Continuation.

ID	Coordinates		Altitude	Sampling station	Reference	State
	N	W	m			
124	20.5248889	-99.3238056	1720	Irrigation channel Tasquillo	Tasquillo	Hidalgo State
125	20.5270833	-99.321	1709	Irrigation channel Tasquillo	Tasquillo	Hidalgo State
126	20.4863056	-99.2108056	1706	Irrigation channel	Ixmiquilpan	Hidalgo State
127	20.0605	-99.2221111	1694	Salt River Atitalaquia	Atitalaquia	Hidalgo State
128	20.4806667	-99.2210833	1693	Tula River	Ixmiquilpan	Hidalgo State
129	20.4821389	-99.2151944	1693	Wastewater channel	Ixmiquilpan	Hidalgo State
130	20.5499722	-99.2916389	1645	Tula River	Juchitlán	Hidalgo State
131	20.5499722	-99.2916389	1645	Water spring	Juchitlán	Hidalgo State
132	20.5499722	-99.2916389	1645	Baths Tzindejéh	Juchitlán	Hidalgo State
133	20.66125	-99.48775	1596	Zimapán Dam	Saucillo	Hidalgo State
134	20.576	-99.3463611	1590	Tula River	Tasquillo	Hidalgo State
135	20.8645	-99.4455	935	Moctezuma River	La Mora	Queretaro State

The concentration of NO_3^-, PO_4^{3-} and B^{3+} was determined by spectrophotometry (JENWAY® 7305 Spectrophotometer), with different dependent wavelengths based on the Beer-Lambert law, which indicates that by knowing the absorbance at a given wavelength it can be used to estimate the concentration (Rodger, 2013):

$$\mathrm{A} = \varepsilon \mathrm{Cl} \tag{1}$$

Where: A is light absorption, ε is the coefficient of extinction or dependent wavelength (nm), C is the concentration (mol L^{-1}) and l is the length of the sample through which light passes (cm). NO_3^- was determined using the salicylic acid nitration method (Robarge *et al*., 1983); PO_4^{3-}, with the ascorbic acid method (Eaton *et al*., 1998), and to find the concentration of B^{3+}, the H-Azomethine method was used (Rodier, 1978). In all three cases, solutions of known concentrations were used to establish the calibration lines. The regression equations used were the following:

$$\mathrm{NO_3^-} = (119.81 \times \mathrm{A}) + 1.3416;\ \mathrm{R}^2 = 0.986 \tag{2}$$

$$\mathrm{PO_4^{3-}} = (8.9707 \times \mathrm{A});\ \mathrm{R}^2 = 0.994 \tag{3}$$

$$\mathrm{B^{3+}} = (6.6675 \times \mathrm{A}) + 0.0609;\ \mathrm{R}^2 = 0.995 \tag{4}$$

The ions Ca^{2+}, Mg^{2+} were determined by volumetric titration with disodic EDTA (0.01 N), and the volumetric titration of Cl^- was carried out with silver nitrate (0.05 N). The concentration of K^+ was determined with a flame spectrometer (Instrumentation Laboratory® AutoCal Flame Photometer 643), the detection limit was 5 meq L^{-1} of K^+ [Eaton *et al*., 1998; Richards *et al*., 1982]. The procedure to verify the correct analysis of water samples was the anion-cation balance criterion established in standard methods for the examination of water and wastewater (Eaton *et al*., 1998).

Once all the results were obtained from the chemical analysis of water, a statistical analysis was carried out on each one of the variable, which consisted in determining: normality test using the Kolmogorov-Smirnov method, skewness, kurtosis, minimum, maximum, mean, median, standard deviation, range, coefficient of variation (CV), quartiles, and extreme values (Montgomery & Runger, 2015). The software used was SAS® version 9.0 and the graphs were created in SigmaPlot® version 10.0.

To establish the risk of toxicity by specific ions, the concentrations of B^{3+}, and Cl^- were considered according to the criteria established in different investigations (Ayers & Westcot, 1985; Maas, 1990; Richards *et al*., 1982). The estimation of the nutrient content was carried out based on the results obtained from the concentrations of NO_3^-, PO_4^3, B^{3+}, Ca^{2+}, Mg^{2+} and K^+ using the dimensional analysis technique and considering 1 m irrigation sheet, which is normally applied on crops in the Mezquital Valley.

$$1\text{ mm} = \frac{1\text{ L}}{\text{m}^2}\text{ y }1000\text{ mm} = \frac{10{,}000{,}000\text{ L}}{10{,}000\text{ m}^2} \therefore 1\text{ m}_{\text{irrigation sheet}} = \frac{10{,}000{,}000\text{ L}}{\text{ha}} \tag{5}$$

$$\left(\frac{\text{mg}}{\text{L}}\right) \div 1{,}000{,}000 = \frac{\text{kg}}{\text{L}}; \left(\frac{\text{kg}}{\text{L}}\right)\left(\frac{10{,}000{,}000\text{ L}}{\text{ha}}\right) = \frac{\text{kg}}{\text{ha}} \tag{6}$$

Results and discussion

Nitrate, phosphate and boron content in wastewater

The concentrations of nitrate, phosphate, and boron in wastewater in the Mexico City-Mezquital Valley drainage network (Table 2) were determined. For the three ions, the coefficient of variation was found to be high, indicating the heterogeneity in the concentration of these ions in the wastewater.

Wastewater contains nitrogen, phosphorous, potassium, copper, iron and zinc and its use can reduce the need for fertilizers (Duncan & Cairncross, 1990). However, in this study, the concentration of nitrate was attributed precisely to the use of fertilizers; the wastewater, in its course across the agricultural area known as the Mezquital Valley, becomes enriched with these ions that are lixiviate from agricultural soils and transported in drainage water. The continuous use of wastewater may cause problems in the natural fertility soil, and in the protection of water resources due to the high concentration of sodium, nitrate and phosphate salts (Belaid *et al*., 2012).

Table 2. Nitrate, phosphate and boron content.

	NO_3^-	PO_4^{3-}	B^{3+}
	------------------------------------- mg L^{-1}	-------------------------------------	
Skewness	0.726	0.986	0.268
Kurtosis	0.350	2.842	0.283
K-S	0.01	0.01	0.01
Minimum	1.440	0.00	0.00
Maximum	177.342	65.776	1.881
Mean	60.656	14.319	0.822
Median	57.185	15.490	0.777
Std. Dev.	36.294	10.804	0.318
Range	175.902	65.776	1.881
CV	59.836	75.451	38.782
Q_1	34.866	3.754	0.621
Q_3	73.467	22.293	1.028
95 %	134.570	29.145	1.381

K-S: Kolmogorov-Smirnov normality test (p-Value), α=0.05; n=188

Source: Author's own elaboration.

The main drainage channel for Mexico City, through the 14-Peñón-Texcoco highway, had a nitrate concentration of 3.908 mg L^{-1}, and the 16-Tequisquiac tunnel, 2.180 mg L^{-1} of nitrate. The highest concentration of this ion was found in the Tula River water in 17-Apaxco and 26-Atotonilco (153.380 mg L^{-1} and 154.578 mg L^{-1} respectively), in 112-agricultural drainage water (177.342 mg L^{-1} of NO_3^-) and filtration water in 30-Atitalaquia (146.431 mg L^{-1} of NO_3^-), indicating that wastewater coming from Mexico City, in its course through the State of Hidalgo is used in agriculture, and the excess of nitrogenated fertilizers is leached and evacuated by agricultural drainage, as well as the wastewater that is poured into the Tula River, so this River receives urban and industrial wastewater and agricultural drainage, which explains it nitrate concentration.

The data are asymmetrical (*p-value* $< \alpha$); the third quartile (Q_3) had a value of 73.467 mg L^{-1} of NO_3^-, and the median was of 57.185 mg L^{-1} of NO_3^-. These data indicated that wastewater contain excess of nitrate (> 30 mg L^{-1}), 19 % of the water samples had between 5 mg L^{-1} and 30 mg L^{-1} of NO_3^-, and only six water samples contained lees than 5 mg L^{-1} of NO_3^-.

The excess nitrate is due to the discharging of agricultural drainage into this hydrographic network, this occurs by the altitudinal gradient (from 2293 masl to 935 masl); finally, the flow of water is evacuated by the Moctezuma River. Use of the wastewater for agricultural irrigation may decrease the yield and quality of sensitive crops; their sensitivity to high ion concentration varies during the crop's phenological stages, so as the crop's needs decrease, high ionic concentration may be harmful (Ayers & Westcot, 1987). Figure 2 illustrates the data distribution on the nitrate concentration found in the Mexico City-Mezquital Valley drainage network.

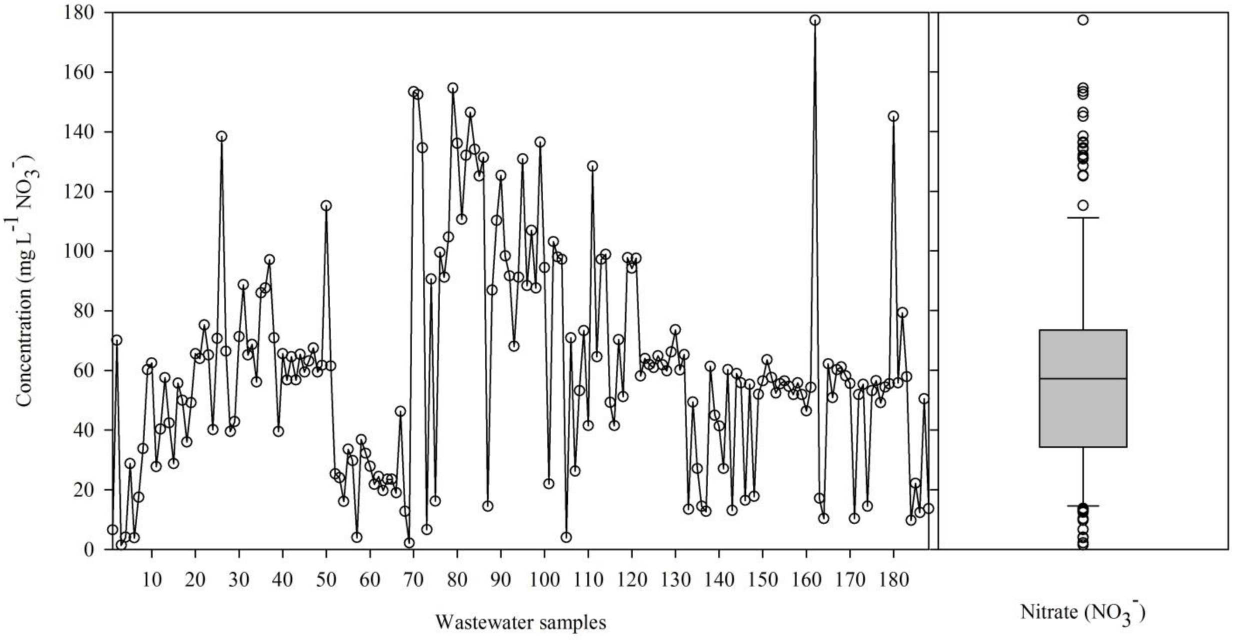

Figure 2. Distribution of the concentration of nitrate in the Mexico City-Mezquital Valley drainage network. **Source:** Author's own elaboration.

On the other hand, water runoff and infiltration with high nitrate content due to fertilization practices, creates an important problem of widespread pollution in water resources, and if the nitrate reaches groundwater bodies, it can cause serious health problems for people, who consume this water (Aruzo *et al*., 2006).

In Mexico, the highest nitrate concentration permitted in sources of drinking water is (10 mg L^{-1} N = 44.26 mg L^{-1} NO_3^-) (Secretaría de Salud, 2000). This investigation did not analyze the quality of groundwater, but it is possible that the Mezquital Valley aquifer has infiltrations of wastewater, since more than 80% of the main channels are not revetted (Lesser-Carrillo *et al.*, 2011). In this sense, there is a possibility that a part of this excess concentration of NO_3^- can lixiviate into the aquifer (Belaid *et al.*, 2012), since irrigation sheet of over 1 m are applied in the crops irrigation, indicating that there is a leaching fraction greater than 0.45, it helps to keep low salinity levels (Hoffman, 1990), but it increases the risk of ions lixiviation such as NO_3^- outside the root zone of the crops.

The concentration of nitrogen is obtained using the following equations:

$$\frac{\mathrm{NO_3^-\ (mg\,L^{-1})}}{4.42688} = \mathrm{N(mg\,L^{-1})} \tag{7}$$

$$\frac{\mathrm{N(mg\,L^{-1})}}{1{,}000{,}000} = \mathrm{N(kg\,L^{-1}); N(kg\,L^{-1}) \times (10{,}000{,}000\ L\,ha^{-1}) = kg\,ha^{-1}\ of\ N} \tag{8}$$

Estimated nitrogen content was 137.01 kg ha^{-1}, for a 1 m irrigation sheet. The excessive concentration of salts and nutrients such as N are a risk for long-term agricultural production, although this conclusion must be verified for diverse types of crops and soils irrigated with wastewater (Belaid *et al.*, 2012).

Regarding phosphate (Fig. 3), a high coefficient of variation was found. Maximum PO_4^{3-} values were found in different irrigation channels: 65.776 mg L^{-1} (46-irrigation channel 1, Morelos colony, Actopan-Ixmiquilpan road), 60.849 mg L^{-1} (24-irrigation channel Atitalaquia), 36.899 mg L^{-1} (23-irrigation channel Pemex, Atitalaquia-Tula road), 36.212 mg L^{-1} (21-Teltipan-Tlaxcoapan road) and 36.091 mg L^{-1} (11-Eastern emission channel, Ecatepec). The latter corresponds to the discharge of wastewaters from Mexico City. Infiltration water (in Progreso and Chilcuautla) and the Juchitlán spring, in this agricultural area, presented the lowest concentration values for PO_4^{-3} (<0.083 mg L^{-1}), indicating a sanitation of wastewater through the soil. The mean value for PO_4^{3-} was 14.319 mg L^{-1}, and the median had a value of 15.490 mg L^{-1} of PO_4^{3-}. Q_1 had a value of 3.754 mg L^{-1} of PO_4^{3-}, and Q_3 had a value of 22.293 mg L^{-1} of PO_4^{3-}; 95 % of the water samples had a concentration of PO_4^{3-} lower than 29.145 mg L^{-1}.

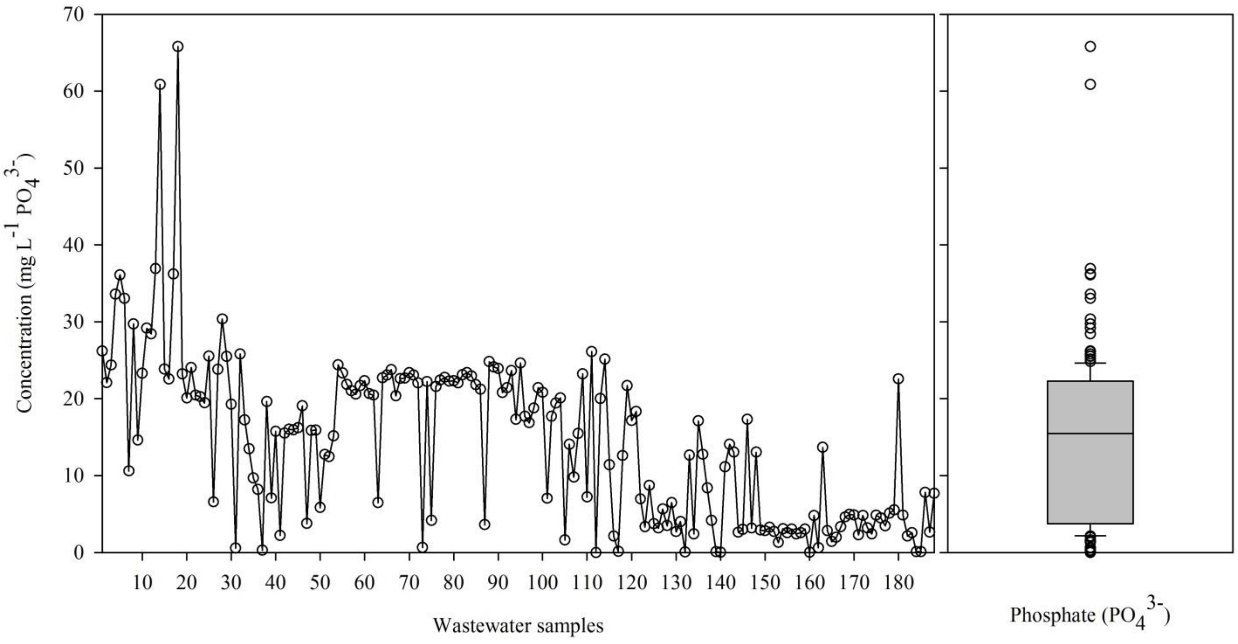

Figure 3. Distribution of the concentration of phosphate in the Mexico City-Mezquital Valley drainage network. **Source:** Author's own elaboration.

The concentration of phosphorous and phosphate is obtained using the following equations:

$$\frac{\mathrm{PO_4^{3-}}\ (\mathrm{mg\ L^{-1}})}{3.06618} = \mathrm{P}(\mathrm{mg\ L^{-1}}) \qquad (9)$$

$$\frac{\mathrm{P}(\mathrm{mg\ L^{-1}})}{1{,}000{,}000} = \mathrm{P}(\mathrm{kg\ L^{-1}});\ \mathrm{P}(\mathrm{kg\ L^{-1}}) \times (10{,}000{,}000\ \mathrm{L\ ha^{-1}}) = \mathrm{kg\ ha^{-1}\ of\ P} \qquad (10)$$

In this case, the concentration of phosphorus in the water is, on average, of 4.66 mg L^{-1}. This value indicates the hypertrophic condition in which the water is found (Moreno-Franco *et al*., 2010); domestic and industrial wastewater are the main source of phosphorus, as well as agricultural drainage, and its main characteristic is that it is composed of detergents that derive from anthropogenic activity (Lizárraga-Mendiola *et al*., 2013; Ongom *et al*., 2017) and the leaching of phosphated fertilizers. The phosphorus content was estimated in 46.6998 kg ha^{-1} on average for a 1 m irrigation sheet, which was attributed to the discharge of wastewater and the leaching of phosphated fertilizers. Normal phosphate values in irrigation water are generally below 2 mg L^{-1}

(Ayers & Westcot, 1985); in this case, the excess concentration of phosphate may be due to agricultural, domestic and industrial discharge (Velázquez-Machuca *et al.*, 2010).

Risk of toxicity due to the concentration of boron and chloride

The concentration of boron (B^{3+}) was attributed to borax waste ($Na_2B_4O_7 \cdot 10H_2O$), which is widely used as a cleaning agent, and therefore present in domestic and industrial wastewaters (Hem, 1985). This ion is important in agriculture, although amounts lower than 1 mg L^{-1} are toxic to some crops such as citrus fruits and beans, hence boron is the most likely element to cause toxicity in crops (Page *et al.*, 1990).

Figure 4 shows the distribution of B^{3+} in wastewater. The highest values were the following: 1.881 mg L^{-1} (14-grand drainage channel near the Peñón-Texcoco road), 1.568 mg L^{-1} (113-agricultural drain, Nith-Debodhé road), 1.565 mg L^{-1} (11-eastern emission tunnel, Tonanitla-Xaltocan road, in Ecatepec), 1.494 mg L^{-1} (61-Boxtha drain in Actopan) and 1.461 mg L^{-1} (4-Nextlalpan). The mean and median were 0.822 mg L^{-1} and 0.777 mg L^{-1}, respectively. Irrigation with this water may cause decrease in the yield of sensitive crops to a concentration of B^{3+} of over 0.3 mg L^{-1}, whereas tolerant crops do not show symptoms at a concentration of B^{3+} in the soil solution of 4 mg L^{-1} (Page *et al.*, 1990). It is recommended that the effects of irrigation water be measured directly on the soil and crops, yet it has been found that crop yields decrease as the concentration of B^{3+} increases to toxic levels (Pratt & Suarez, 1990):

$$y = 100 - m(x - A) \qquad (11)$$

Where y is the relative yield of a crop (%); m is the decrease in yield per unit increase B^{3+} concentration; A is the maximum concentration of B that does not reduce yield (threshold); x is the B^{3+} concentration in irrigation water.

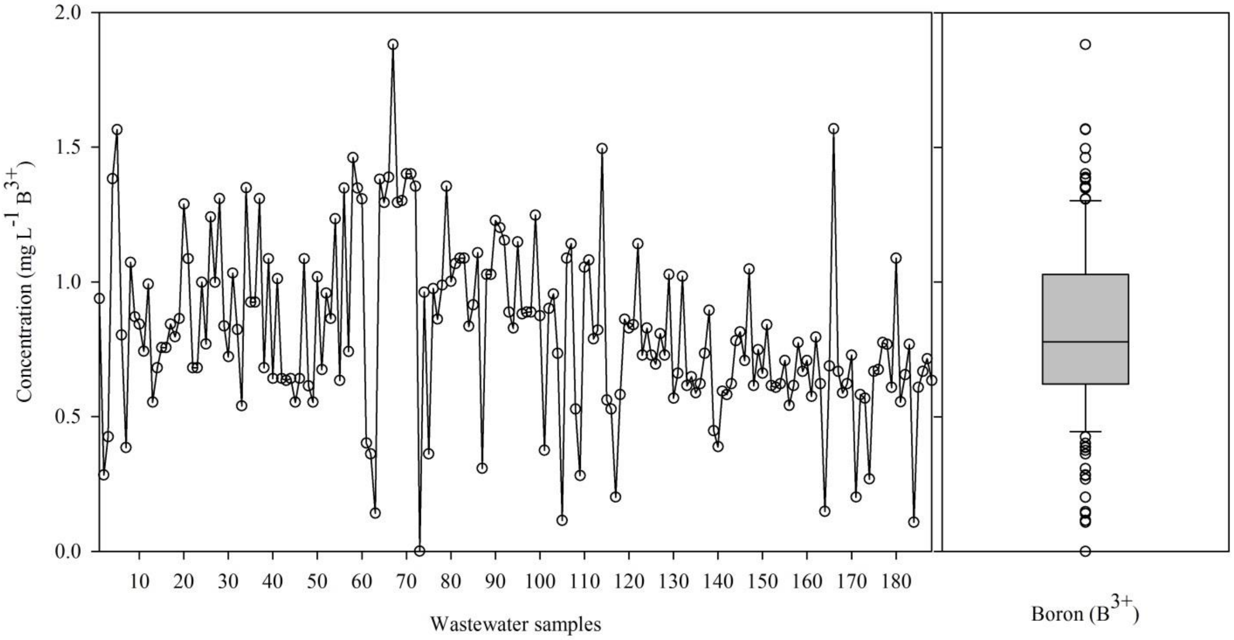

Figure 4. Distribution of the concentration of boron in the Mexico City-Mezquital Valley drainage network. **Source:** Author's own elaboration.

For one concentration of B^{3+} in irrigation water, there is a different concentration of B^{3+} in the root zone, depending on the leaching fraction. In this case, the leaching fraction is estimated in 0.45 and this value helps keep low salinity levels, and as the leaching fraction decreases, the salinity in soil water increases, due to the effect of concentration (Pratt & Suarez, 1990) and this represents a risk of toxicity for crops, mainly for bean, which is considered sensitive to electric conductivity (EC < 1 dS m^{-1}) and B^{3+} (< 1 mg L^{-1}) (Maas, 1990).

The risk of toxicity by chloride (Cl^-) was estimated with the ionic concentration of Cl^- in irrigation water, and according to the following values (Ayers & Westcot, 1985): without restriction of use when the concentration of Cl^- is < 4 meq L^{-1}, use restriction is moderate between 4 meq L^{-1} and 10 meq L^{-1} of Cl^- and the use is not recommended when concentrations are over 10 meq L^{-1} of Cl^-. The mean was 5.077 meq L^{-1} of Cl^- and the median was 4.935 meq L^{-1} of Cl^-. The coefficient of variation was 36 % and indicates very heterogeneous Cl^- values, Q_1 had a value of 3.610 meq L^{-1} of Cl^-, the value in Q_3 was 6.215 meq L^{-1} of Cl^-, and 95 % of the water samples had less than 7.960 meq L^{-1} of Cl^-. According to the distribution of these data (Fig. 5), there is a risk of toxicity due to the concentration of Cl^- for sensitive crops such as bean (Maas, 1990).

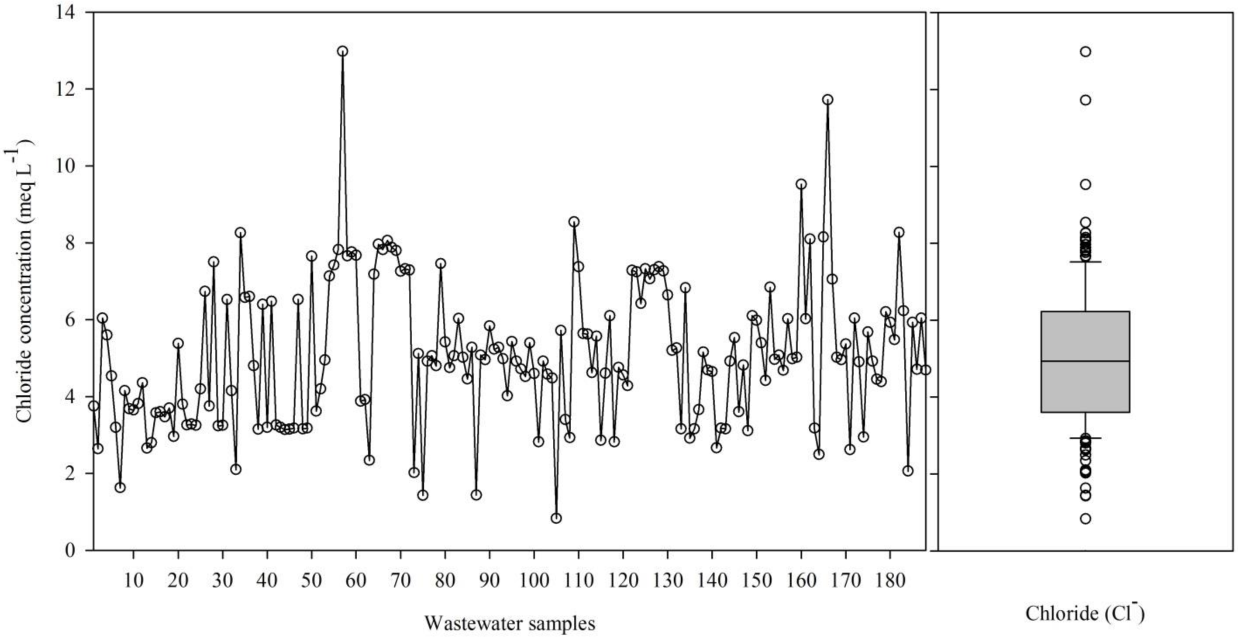

Figure 5. Distribution of the chloride concentration in the Mexico City-Mezquital Valley drainage network. **Source:** Author's own elaboration.

The extreme values for the concentration of Cl^-, higher than the upper limit, were found in drainage water: 12.98 meq L^{-1} (4-Nextlalpan), 11.72 meq L^{-1} (113-Nith-Debodhé road), 9.52 meq L^{-1} (97-Bangandhó), 8.54 meq L^{-1} (56-Actopan) and 8.27 meq L^{-1} in the 129-Mercado-Ixmiquilpan sampling station.

Content of nutrients and organic matter in wastewater

Regarding the content o N, P, K, Ca, Mg, total solids (TS) and total volatile solids (TVS or total organic matter OM), Table 3 shows the corresponding data. The following sequence was found, from higher to lower concentration: Ca > Mg > K > N > P. This water contains organic matter (276 mg L^{-1}), as well as a considerable amount of total salts (>770 mg L^{-1}), mostly sodium and bicarbonate (Cuellar-Carrasco *et al*., 2015; López-García *et al*., 2016), which creates the risk of salinization for soils and crops irrigated with this water.

Table 3. Content of nitrogen, phosphorous, potassium, calcium, magnesium, total solids and total volatile solids.

	Min.	Max.	Mean	Median	Std. Dev.	Range	CV	Q_1	Q_3	95 %
N	0.325	40.060	13.701	12.918	8.198	39.735	59.83	7.876	16.596	30.398
P	0.00	21.452	4.670	5.052	3.523	21.452	75.45	1.224	7.270	9.505
K	6.256	66.473	29.257	26.980	10.509	60.217	35.92	24.047	31.673	51.224
Ca	9.616	76.152	42.290	42.886	12.645	66.533	29.90	34.869	50.100	64.128
Mg	8.266	88.860	40.761	39.497	13.783	80.594	33.81	29.045	50.083	63.211
TS	232	2472	1015.383	1046	340.784	2240	33.56	724	1224	1512
TVS	84	660	271.936	276	96.286	576	35.40	190	342	424

All the variables are expressed in mg L^{-1} units; TS: total solids; TVS: total volatile solids or total organic matter; n = 188

Source: Author's own elaboration.

According to the data obtained by Can-Chulim et al. (2017) the increase in the ionic concentration reduces the percentage of germination of *Phaseolus Vulgaris* and $NaHCO_3$ was the salt that caused the lowest percentage of germination, in this sense, a negative effect on the bean crops irrigated with wastewater in the Mezquital Valley is expected.

Regarding the content of organic matter, the remaining residue after calcination does not provide a precise distinction between organic and inorganic residues, given that the loss by calcination is not limited only to organic matter, but also includes losses produced by the decomposition of some mineral salts. It is recommendable to determine the chemical oxygen demand and biochemical oxygen demand in wastewaters (Eaton *et al*., 1998). This investigation only provides an approximation to the organic matter content by determining the total volatile solids.

Conclusions

According to the results obtained under the conditions in which this investigation was carried out, we concluded that the concentration of nitrate and phosphate in the wastewater of the Mexico City-Mezquital Valley drainage network was high, and this was attributed to the discharges of domestic and industrial wastewaters and to agricultural drainage.

The high concentration of these ions represents a risk, due to the possible gradual eutrophication of the water bodies. There is also a risk of contamination of the aquifers, since over 80 % of the irrigation channels are not revetted, and this may cause the leaching of NO_3^-.

Regarding the content of nutrients, the following sequence was found, from higher to lower concentration: Ca > Mg > K > N >P. The value of the median, regarding the organic matter content, was 276 mg L^{-1}, and the median for total solids was 1 046 mg L^{-1}, therefore the total salt concentration was 770 mg L^{-1}.

The risk of toxicity by B^{3+} and Cl^- can have a negative effect on the germination and yield of bean crops (to a lesser extent, maize, oat and alfalfa), since it is sensitive to the concentration of these ions found in wastewaters. The use of this water is still restricted, since this study does not consider the microbiological aspects or the heavy metals that can accumulate in the soil and crops. Likewise, it has been proven that the contact of the general population with this water causes public health problems in the agricultural area known as the Mezquital Valley. It is recommendable to perform the wastewater treatment before it is discharged into receptor bodies. Finally, the concepts presented here must be verified experimentally in the soil and crops irrigated with wastewater in this agricultural area.

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