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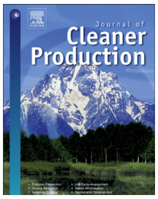

Analysis of water footprint of potato production in the pampean region of Argentina

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ABSTRACT

The water footprint is an indicator of freshwater resources appropriation which brings valuable insight about the environmental impact of consuming a given product. The aim of this study is to quantify the water footprint of potato production in the southeast of Buenos Aires province (Argentina). In this area, potatoes are irrigated using groundwater while, at the same time, both fertilizers and agrochemicals are applied. In order to assess the virtual water content of potato production, the green, blue and grey components of the water footprint were calculated by considering the different volumes of water involved in the crop production arising from evaporation, rainfall, irrigation, and fertilizers pollution. Crop evaporation and irrigation requirements were calculated. Data from application of irrigation were obtained from farmers. Nitrogen fertilization was considered as an indicator to estimate the grey component. The water footprint of potato in this region was 323.99 m^3/t. The evaporative water use (blue and green components) was 56.4%. The relative importance of blue water (24.15%), compared with global estimations, showed the significant role of irrigation on this crop. Groundwater reserves can be affected as a consequence of its intensive exploitation for irrigation. The fraction of grey water (43.6%) was the greatest, indicating the importance of nitrogen fertilizers and the consequent risk of groundwater pollution. This study allowed to evaluate the groundwater appropriation by potato production and emphasized the relevance of agriculture practices, such as irrigation and fertilizers, as well as the groundwater exploitation conditions and legal aspects, on the water footprint of the crop. The lack of sustainability of potato production in the studied region and its possible effects on the hydrological system were demonstrated. Several strategies and recommendations emerged from this study aimed at reducing the water footprint and achieving the sustainability of potato production, such as improvements on the irrigation and fertilization efficiencies, technical advice for farmers, and legal and tax regulation on groundwater use.

1. Introduction

Agriculture is the main consumer of freshwater in the world. The need to feed an increasing population demands an intensive use of natural resources in agriculture, mainly water and soil, together with the application of fertilizers and agrochemicals. Additionally, agriculture activities impact critically on both freshwater quantity and quality. Consequently, the metrics of the environmental impacts of water use by agricultural production systems has experienced an increasing interest (Herath et al., 2014).

Several tools for footprint evaluation which are useful for monitoring impacts on sustainability have been reported (Ĉuĉek et al., 2012). The concept of water footprint, introduced by Hoekstra (2003), provides a valuable framework to analyze the link between human consumption and the appropriation of freshwater. The water footprint (WF) of a product, also known as "virtual water content", is defined as the volume of freshwater used to produce it, which should be measured over the full supply chain (Hoekstra et al., 2011). Total WF includes the water footprints of all the process steps and it is expressed in water volume per unit of product (m^3/t) (Mekonnen and Hoekstra, 2011). Water is named as 'virtual'

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because the amount of water physically contained in the final product is negligible compared to the amount that went into its production (Chapagain and Orr, 2009).

The "water footprint assessment" is defined as a conjunction of quantify the WF of a product or a process, assess the sustainability of this WF and formulate a management strategy (Hoekstra et al., 2011). WF is an indicator of freshwater resources appropriation, whose components are specified geographically and temporally. According to Mekonnen and Hoekstra (2011) the term "freshwater appropriation" includes both consumptive water use (the green and blue water footprint) and water required to assimilate pollution (the grey water footprint).

The virtual water content of a product is useful as an instrument to achieve water security and an efficient water use, thus, tells about the environmental impact of consuming that product (Hoekstra, 2003; El-Sadek, 2011). This concept evidences a complex net of relationships concerning to water and provides significant information for policy and economical actors, users and managers in order to planning and taking decisions on this resource (Chapagain and Orr, 2009; Roth and Warner, 2008). Despite WF concept is a powerful communication tool, it should be considered as a partial tool (Hoekstra et al., 2011); thus, a joint use of WF with other indicators is required for environmental integrated policies (Perry, 2014).

In this context, the main objective of this work was to quantify the green, blue and grey water footprint of potato production in the pampean region of Argentina, considering that the main environmental issues associated with this production are water consumption by irrigation and water pollution mainly due to the application of nitrate fertilizers.

The general method applied in this study consisted in the estimation of each compound of virtual water content of potato by considering the different volumes of water involved in the crop production arising from evaporation, rainfall, irrigation, and fertilizers pollution.

This study will contribute to address the impact of potato production on water sustainability at local level in one of the areas with the greatest global agricultural productivity. The particular spatial features of the region, such as soil and climate, and conditions of the potato production system (irrigation system, volume of water used, boreholes features) together with the temporal conditions of crop cultivation (potato growth period, dates of irrigation, crop evaporation) were taken into account. Finally, several improvements are recommended to reduce the water footprint of potato production.

1.1. Background

Recently, water footprint (WF) methods have been reviewed by Jeswani and Azapagic (2011) and Chenoweth et al. (2013). These authors stated that WF methods are still evolving and they agreed on the variability of the results that can be obtained from them. Different approaches to study the WF were reported, whose differences are based on how to deal with different forms of water use, including: (i) the attempts to estimate impacts of water use, such as the Life Cycle Assessment (LCA); (ii) the subdivision into blue, green and grey components of WF for a nation or a product; (iii) several studies focused on a spatio-temporal scale of analysis.

From a practical point of view, Vanham and Bidoglio (2013) argued that WF assessment has some limitations and challenges, such as data availability and reliability, which become difficult in its applicability. Furthermore, Herath et al. (2014) denoted that agricultural impacts on freshwater are highly variable depending on local climate and soil features. Thereby, WF assessments require taking account of this variability to be accurate. Chenoweth et al. (2013) mentioned that, despite the methodological differences, the concept of WF has contributed to raising awareness about water use in agricultural and industrial supply chains.

One of the most commonly used method for WF assessment was proposed by Hoekstra et al. (2011). They stated a manual which proposes the global standard for water footprint assessment, and includes definitions and methods to quantify the water footprint components for individual processes and products as well as for consumers and nations. The green water footprint was defined as the volume of rainwater consumed during the production process. In the case of agricultural products, it refers to the total rainwater evapotranspiration plus the water incorporated into the harvested crop. The blue water footprint refers to the consumptive use of fresh surface or groundwater. The main component of blue water is evaporation. It can also include, depending on the product or the process, the water incorporated into the product as well as the water that either does not return to the same catchment area or does not return in the same period. In turn, Hoekstra et al. (2011) defined the grey water footprint as the volume of freshwater that is required to assimilate or dilute the load of pollutants such that they become harmless according to water quality standards.

Some studies about the WF of different crops have been published. Mekonnen and Hoekstra (2011) quantified the green, blue and grey water footprint of global crop production. They reported a water footprint of potatoes of 287 m^3/t.

Estimations of WF were developed for Dutch coffee and tea (Chapagain and Hoekstra, 2007), Korea's grain crops (Yoo et al., 2012a), wheat (Mekonnen and Hoekstra, 2010; Ababaei and Etedali, 2014); maize, soybean and wheat (Aldaya et al., 2010a). Jefferies et al. (2012) analyzed WF and LCA approaches to assess the impacts of two different products on water consumption. It was concluded that both approaches addressed the same issues but from different perspectives and with different purposes. Other studies estimated the WF of irrigated crops in Sudan (Ahmed and Ribbe, 2011), Spain (Aldaya et al., 2010b); Italia (Nana et al., 2014; Lamastra et al., 2014), South Africa (Dabrowski et al., 2009), and Thailand (Gheewala et al., 2014). Additionally, the WF of rice was assessed (Chapagain and Hoekstra, 2011; Yoo et al., 2012b; Zhang et al., 2014) as well as the WF of grape-wine production (Herath et al., 2013). In turn, Chapagain and Orr (2009) proposed a water footprint method which linked global consumption to local water resources. It was applied to Spanish tomatoes grown partly in open systems and partly in plastic-covered greenhouses.

Considering that irrigation is the dominant human activity leading to water stress, Pfister and Bayer (2014) argued that is necessary to consider the temporal aspects of a given crop in order to evaluate the WF and proposed to measure the monthly water stress.

Furthermore, other useful approaches, based on hydroinformatics and artificial intelligence, have been reported for the analysis of study cases on water sustainability (Chau, 2006, 2007; Lee et al., 2014; Zhao et al., 2006).

The above mentioned studies highlight the usefulness of the WF as an indicator of water appropriation to evaluate the dependence of a country on virtual water imports related to a given crop.

Regarding potato production, a recent study estimated the WF of rain-fed potato in the Manawatu region of New Zealand using the hydrological water-balance method (Herath et al., 2014). It is worth to mention that this method differs from the approach of Hoekstra et al. (2011) because the green WF is considered as the net change in the soil moisture storage and the blue WF as the net change in the groundwater storage (Herath et al., 2013). Then, both parameters are quantified by measuring the daily change of soil moisture and drainage under field conditions. Furthermore, Herath et al. (2014) defined the grey component as the use-fraction of the assimilation capacity of water resource in the local hydrological system and estimated it by measuring the leaching of nitrogen below the root zone under field conditions. In this way, Herath et al. (2014) obtained that blue WF of potato was negative since irrigation was not used, and argued that potato production does not impact on water quantity, rather, it contributes to groundwater recharge. Their estimation of green WF was 15.8 m^3/t and the grey component reached 133.1 m^3/t.

To the authors' knowledge, studies about WF of potato in Argentina, and even in South America, have not been reported in the literature. This study constitutes the first attempt to know about the groundwater appropriation by a relevant crop in the pampean region of Argentina.

1.2. Potato production in the pampean region

The potato crop (*Solanum tuberosum*) of the Spunta variety is specially developed in pampean region of Argentina. In this paper, we specifically analyze the production in Tandil district, located in the southeast of Buenos Aires province (Fig. 1) because it is one of the main producers of potato in that region, together with the neighboring district of Balcarce. The features of these two districts are very similar thus the results are expected to be comparable.

Potatoes are planted in mid-October and harvested in the second week of next February. Farmers grown potatoes in plots of around 50 ha, which are usually rented for one growth season. The yield reaches 50 tons per hectare (t/ha) and the acreage was 4300 ha in the season 2011–2012. The main destinations of production are 80% for national fresh consumption and 20% for national industry.

Potatoes are grown in an open environment and irrigated by sprinkler systems since November 10th to the end of next January. According to the farmers interviewed in this study, total irrigation reaches 275 mm for each growth season, distributed as follows: no irrigation during October, 50 mm in November, 110 mm both December and January, and no irrigation in February. Water for irrigation is obtained from boreholes exploiting the phreatic aquifer. Water extraction reaches around 80–120 m^3/hour and the sprinklers work between 18 and 24 h per day. The use of fertilizers and other agrochemicals is a common practice in potato production in the pampean region of Argentina. The main one is urea, whose application reaches 150 kg/ha. It should be noted that pressure on aquifers due to irrigation, in addition with the use of fertilizers, can affect water quantity and quality, including the increasing of water salinity and declining of water tables.

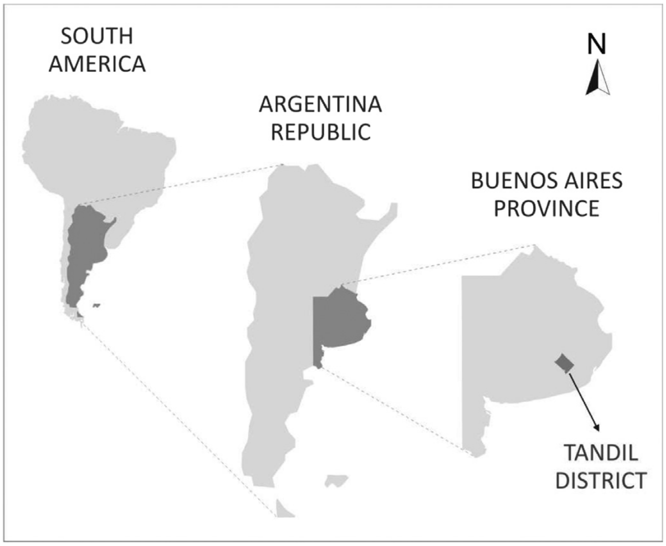

Fig. 1. Location of the study area.

Moreover, two law requirements are generally not fulfilled by farmers: (i) boreholes are not reported to water authority, (ii) drilling permission is not transacted. Furthermore, those boreholes are commonly built without following proper design parameters and they are usually close-located or even near pollution sources. In addition, the situation of rented lands in many cases worsens the problem because farmers do not care about water resource and they often leave boreholes without superficial protection.

2. Methods

In this study, we focus on the virtual water content of potato production considering that virtual water refers to the amount of water that is required in this process. To this aim, we adopted the approach of Hoekstra et al. (2011) and followed the guidelines of Chapagain and Orr (2009).

The approach of Hoekstra et al. (2011) was adopted because it has been widely used at global level, which allows the comparison of our results with those obtained from other studies. Moreover, Hoekstra et al. (2011) and Chapagain and Orr (2009) methods are advantageous because of the feasibility of the procedures and quantifications included to be applied in the pampean region area, where there is a lack of the detailed data required to carry out other procedures, such as hydrological water balance under field conditions.

The virtual water content of a primary crop (VWC_c; m^3/t) is calculated as:

$$VWC_c = \frac{WU_c}{Y_c} \tag{1}$$

where WU_c is the volume of water used for crop production (m^3/ha) and Y_c is the volume of crop produced (t/ha). The yield crop (Y_c) is given by the expression:

$$Y_c = \frac{\text{production (tons)}}{\text{area (hectares)}} \tag{2}$$

According to the above authors, the volume of water used for crop production (WU_c) adds two components, namely:

a) $WU_{evaporative}$: the volume of water evaporated resulting from the addition of the evaporation of rainfall from crop land, named “green water use” (WU_g), and the evaporation of irrigation water from crop land, known as “blue water use” (WU_b);
b) $WU_{non\text{-}evaporative}$: the volume of polluted water resources due to leached fertilizers, chemicals or pesticides from agricultural land. It is known as “grey water use” (WU_p), whose acronym takes the letter *p* of pollution.

The WU_g and WU_b components depend on both the specific crop evaporation requirement and the soil moisture availability in the field in the region. In the case of potato crop in the pampean region, the soil moisture is maintained by effective rainfall and by irrigation water supply, being WU_g is equal to the crop evaporation requirement during the growth season.

The crop evaporation requirement for potatoes (ET_c [t] mm/day) was calculated according to Penman-Monteith method with subsequent modifications introduced by Doorenbos and Pruitt (1990), because it permits to obtain the daily ETc for each month during the growth period.

ET_c includes the crop coefficient (K_c) for the respective growth period and the reference crop evaporation (ET_0; mm/day) at that particular location and time. The ET_0 is only affected by climatic parameters of the pampean region. It expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider crop characteristics nor soil factors. The effects of the features that distinguish field crops from grass are integrated into the crop coefficient (K_c). K_c is useful to know the water demands of potato and it was established considering crop stages.

Total green water use (WU_g) in crop production is calculated by summing-up green water use for each time-step over the entire length of crop period (L)

$$WU_g = \sum_{t=0}^{L} ET_c \tag{3}$$

where ET_c is expressed in terms of volume per hectare (m^3/ha) by multiplying with a factor of 10.

Total blue water use (WU_b) is the sum of minimum irrigation requirement (I_r) and the effective irrigation water supply (I_{eff}) in the region for each time-step over the entire length of potato crop period (L).

$$WU_b = \sum_{t=0}^{L} \left(I_r + I_{eff}\right) \tag{4}$$

I_r was calculated by Rodríguez (2005) for the main types of soil in Tandil district. Data from field irrigation were obtained from interviewed farmers. Meanwhile, I_{eff} refers to water stored as soil moisture and available for crop evaporation. Therefore, the irrigation efficiency, which reaches 67% for sprinkler system as used in the pampean region and affect the total irrigation, was considered to obtain the effective irrigation supply (I_{eff}).

Regarding the use of agrochemicals, this study considers the relationship between the chemical fertilizer use and the consequent pollution of the local environment to the consumption of these products. Nitrogen was selected as the indicator of the impact of fertilizer used in the potato production system due to the fact that farmers usually fertilize with urea in this region.

The dilution volume of water is the theoretical amount of water that would be required to dilute pollutants emitted during the production process to such an extent that the quality of the water would remain below water quality standards (Chapagain and Orr, 2009). The standard recommendation by the Environmental Protection Agency (EPA, 2005) is 10 mg/L (measured as nitrogen), equivalent to 45 mg nitrate per liter (mg NO_3/L). This value coincides with the permissible limit of nitrates in water for human consumption set by the Argentinean Alimentary Code as 45 mg NO_3/L. Thus, we used this value to estimate the volume of water necessary to dilute polluted return flows to permissible limits (WU_p).

Table 1
Abbreviation list.

Concept	Abbreviation
Virtual water content of a crop	VWC_c
Water used for crop production	WU_c
Yield crop	Y_c
Green water use	WU_g
Blue water use	WU_b
Grey water use	WU_p
Crop evaporation requirement	ET_c
Crop coefficient	K_c
Reference crop evaporation	ET_0
Irrigation requirement	I_r
Effective irrigation water supply	I_{eff}
Length of crop period	L
Green virtual water content	VWC_g
Blue virtual water content	VWC_b
Grey virtual water content	VWC_p
Total Water Footprint	WF

The green (VWC_g), blue (VWC_b) and grey (VWC_p) virtual water contents are calculated following Eq. (1). Finally, the total water footprint (m^3/t) of the process of growing potato is the sum of the green, blue and grey components:

$$WF = VWC_g + VWC_b + VWC_p \tag{5}$$

Table 1 shows the abbreviation list of all the concepts involved in the Methods and Results Sections.

3. Results and discussion

Yield of potato crop was calculated through Eq. (2) with data of the season October 2011–February 2012, where 210,000 tons of potatoes were harvested in an area of 4300 ha, giving $Y_c = 48.83$ t/ha.

Green water use (WU_g) is equivalent to potato crop evapotranspiration in this region. Table 2 shows ET_c of potato for each month of growing. Total ET_c for all the growth period determined by Eq. (3) reached 510 mm, which expressed in volume per hectare resulted in $WU_g = 5100$ m^3/ha. Thus, the green virtual water content (VWC_g) calculated through Eq. (1) was 104.44 m^3/t.

In a previous work (Rodríguez, 2005) irrigation requirements (I_r) for three mapping unit of soil which belong to the main kind of soil present in the pampean region of Argentina (typic argiudolls) were determined (Table 3). Irrigation requirements for the total crop season gave a mean value of 198.1 mm. Effective irrigation (I_{eff}) is equivalent to the mean volume of water that farmers use to irrigate potatoes in this region (275 mm) affected by the sprinkler system efficiency (67%). It resulted $I_{eff} = 184$ mm. Thus, blue water use (WU_b) calculated through Eq. (4) gave a value of 382.1 mm. This value means a volume of 3821 m^3/ha. The blue virtual water content (WVC_b) calculated through Eq. (1) was 78.25 m^3/t.

Otherwise, farmers usually fertilize with urea applying 150 kg of $CO(NH_2)_2$/ha, which contains 46% of nitrogen. It means an input of 69 kg N/ha, that expressed as nitrate reaches 310.5 kg NO_3/ha. To dilute this concentration to a permissible value in groundwater of 45 mg/L is required a volume of 6,900,000 L/ha. It means that grey water use (WU_p) reached 6900 m^3/ha. The grey virtual water content (VWC_p) calculated through Eq. (1) showed a value of 141.3 m^3/t.

In this way, the water footprint of the potato production in the pampean region of Argentina, which is equivalent to the total virtual water content of the crop, obtained through Eq. (5) was $WF = 323.99$ m^3/t.

The grey water footprint was the main fraction (43.6%) of the total WF (Fig. 2). This implies that the volume required to assimilate leached nitrogen fertilizers, even without considering other agrochemicals, plays a significant role in the potato production in the pampean region. These results indicate the great importance of agriculture practices and their impacts on water quality and the need to consider them in virtual water trading scenarios (Dabrowski et al., 2009). According to Herath et al. (2014), nitrate

Table 2
Evapotranspiration of potato crop.

	October 17th–31st	November 1st–30th	December 1st–31st	January 1st–31st	February 1st–22nd
ET_c (mm)	24.49	62.79	167.82	178.42	76.48

Table 3
Irrigation requirements (mm) of potatoes in three units of soils (Rodríguez, 2005).

Mapping unit of soil	October 17th–31st	November 1st–30th	December 1st–31st	January 1st–31st	February 1st–22nd	Total (mm)
Az 12	0	0	84.7	79.9	31.8	196.4
Ta 19	0	0	86.8	80	31.8	198.6
Ta 20	0	0	86.8	81.5	31	199.3

application can be minimized by adopting alternative practices for fertilizer management. This assumes that farmers need to know the soil characteristics, especially the content of nutrients and the nutrient requirements of potato in each growth stages, in order to evaluate the moment to fertilize and the amount to be used.

The fraction of green (32.25%) and blue (24.15%) water were small (Fig. 2). However, $WU_{evaporative}$ was higher than $WU_{non\text{-}evaporative}$. Blue WF might be minimized through a more efficient irrigation, which considers soil moisture and crop water requirement during the different stages of the crop season.

Fig. 2 shows the relevance of the water footprint of potato production regarding agricultural practices. The predominance of grey water footprint, due to the intensive application of agrochemicals, and the relative importance of blue water footprint, as a result of the irrigation system used in the area, are clearly observed. From these results, it is deduced that the field irrigation does not respond to the crop requirements in the region because farmers apply a given volume of water without considering neither the soil moisture nor the need of water in each growth stage. In the case of the fertilizers, their application is also done regardless of both the soil characteristics and the nutrient requirements during the growth period.

The characteristics of boreholes as well as the legal aspects of groundwater management are other practices causing a further reduction of the water sustainability of the crop. As we mentioned in Section 1.2, most of the boreholes built for potato irrigation lacks of the adequate design criteria for groundwater protection. Furthermore, numerous boreholes are neither authorized nor controlled by the water authority despite the existing laws regulating groundwater exploitation.

From the comparison of our results with other studies, it is observed that the total WF of potatoes in the studied region was 11.4% greater than the value calculated by Mekonnen and Hoekstra (2011) at a global level, which reached 287 m^3/t. In turn, the green water was the highest component (66.55%). The share of grey water (21.95%) and the fraction of blue water (11.5%) were smaller than our results. These differences may be due to the fact that WF was calculated globally and the method did not consider climatic and soil variations.

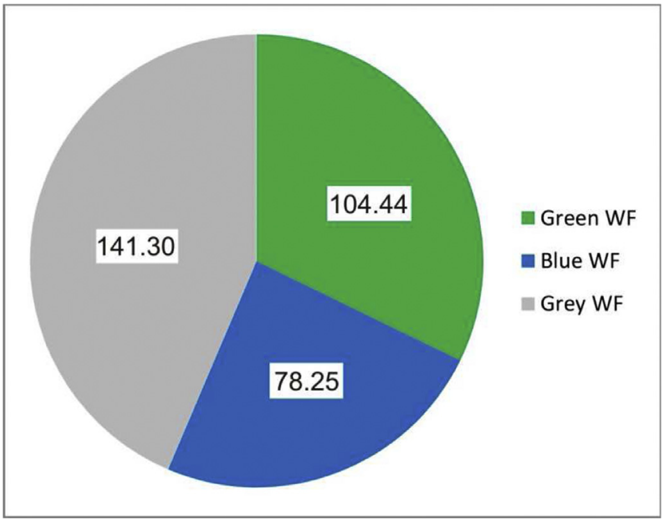

Fig. 2. Components of water footprint of potato (m^3/t).

Moreover, our results of blue and green WF differ from Herath et al. (2014). Irrigation was not considered in their study, therefore blue WF was negligible. The green component (15.8 m^3/t) was lower than our results. This discrepancy might be explained by the differences between climatic conditions and soil features. Nevertheless, the grey WF (133.1 m^3/t) was similar despite they considered a high input of nitrate fertilizer (120 kg N/ha), which may be attributed to the different method applied.

Although the information provided by WF is necessary to evaluate the water management, it may result insufficient to establish the sustainable water limits of any given system (Chapagain and Orr, 2009). Therefore, further hydrological information is required in order to get a deeper understanding of the local impact of the crop production on the environment. Thus, we compared the water extraction for potato irrigation with the groundwater recharge in Langueyú creek basin, located in Tandil district. According to Barranquero et al. (2012), groundwater recharge in this basin, specifically in plains and piedmont areas, reaches 12.5% of total precipitation. Mean precipitation is 838 mm (period 1900–2003), so groundwater recharge in that region is 104.75 mm/year. Potatoes were grown in 4300 has in season 2011–2012 where the infiltration was 4.5 hm^3. At the same time, farmers extract in this area a volume of 11.82 hm^3 of water for irrigation, which exceeded the volume of groundwater recharge for the crop land specifically. Even though this estimation is a simplification, since it does not consider process of aquifer transmissivity, the result alerts on problems related to the decreasing of water table levels caused by the intensive exploitation for irrigation.

4. Conclusions

In this work we analyzed the appropriation of freshwater due to potato production in the pampean region of Argentina. The results showed that Tandil district produces 210,000 tons of fresh potatoes annually, which evaporates 38.36 Mm^3/yr of water and would require 29.67 Mm^3/yr of water to dilute leached nitrates.

The water footprint of potato production reached 323.99 m^3/t. Assuming that one potato is equal to 200 g, the water consumed per potato resulted in an averaged value of 64.8 L.

This study indicates the presence of risks to groundwater quality and quantity. The large fraction of grey water footprint alerts on the importance of fertilizers in potato production in this region. Moreover, the relative importance of blue water compared with global estimations demonstrated the significant role of irrigation in this region. As a consequence of the intensive exploitation of phreatic aquifer carried out by potato production, groundwater reserves can be affected.

Our assessment of the WF of potato production in this region, together with the conditions of boreholes exploitation, demonstrated the relevance of agricultural practices on the water footprint and showed the lack of sustainability of the production unveiling its potential effects on the hydrological system.

From this study, some guidelines emerge with the aim of achieve a sustainable potato production. These include: (i) performing a more efficient irrigation through the measurement by potato producers of both soil moisture and irrigation water requirement under field conditions will allow a reduction of blue WF. Technical advice about irrigation system, including the evaluation of the dates of application according to the growth stages and the use of more efficient irrigation devices, is also suggested in this point; (ii) adapting the use of fertilizer to reduce the grey WF according to the particular characteristics of the soils and to the nutrient requirements of the crop in each stage of growth; (iii) bringing farmers technical advice by agronomists, hydrologists and hydrogeologists in order to improve the irrigation and fertilization efficiencies, to adopt proper design/protection criteria for building of boreholes, and to preserve the groundwater quality against pollution; (iv) suitable legal and tax controls on groundwater use to regulate both the construction of drillings and the water volumes extracted.

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