



Estimating Nitrogen Runoff From Agriculture to Coastal Zones by a Rapid GIS and Remote Sensing-Based Method for a Case Study From the Irrigation District Río Mayo, Gulf of California, México

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Alejandro Jose Souza,
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of Biodiversity (CONABIO), Mexico

*Correspondence:

Alfredo Ortega-Rubio
aortega@cibnor.mx
Daniel A. Revollo-Fernández
darevollof@conacyt.mx;
drevollofer@gmail.com

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David A. González-Rivas¹, Felipe O. Tapia-Silva^{2,3}, José Jesús Bustillos-Guzmán¹, Daniel A. Revollo-Fernández^{2,4*}, Luis F. Beltrán-Morales¹, Daniel B. Lluch-Cota¹ and Alfredo Ortega-Rubio^{1*}

¹ Center for Biological Research of the Northeast (CIBNOR), La Paz, Mexico, ² Autonomous Metropolitan University, Iztapalapa, Mexico, ³ Centro de Investigación en Ciencias de Información Geoespacial, Mexico City, Mexico, ⁴ CONACYT-UAM, Departamento de Economía, Universidad Autónoma Metropolitana, Mexico City, Mexico

Coastal eutrophication due to agricultural runoff is one of the main ecological problems for coastal zones around the world. The increase in nutrients has created multiple consequences on marine ecosystems, such as harmful algal blooms, zones of hypoxia or anoxia, and loss of biodiversity. The coastal areas of México are no exception. In the scientific community, there has been a great effort to estimate the amount of nutrients that enter marine ecosystems. However, a rapid method to make this estimation without field data is still required. In this study, the cultivated area and the entrance of nutrients to the coastal marine environment were determined for one of the main irrigation districts located in the state of Sonora, which drains into the Gulf of California, Mexico. We used an elevation model combined with the digitization of drain canal maps to delimitate sub-basins and allocate the coastal runoff entry points. Landsat 8 satellite data were classified and validated for the period of two agrarian cycles (2015–2016) to obtain the agriculture parcels by sub-basins. The quantity of the nutrient runoff was estimated using the cultivation area and nitrogen runoff percentage, according to values found in published reports. As a result, we identified eight sub-basins, two of which stand out for the amount of nitrogen that drains both into a coastal lagoon and directly to the sea. We confirmed this information by correlation analysis using Moderate Resolution Imaging Spectroradiometer (MODIS) of the diffuse attenuation coefficient at 490 nm $K_d(490)$ detected around the coastal runoff entry points. We concluded that there is a high input in the coastal zones and lagoons of nutrients and other pollutants from the agricultural zones of the Río Mayo irrigation district. We also concluded that the performance of the method applied to estimate the volume of the nitrogen runoff is useful, rapid, and can be improved with *in situ* data.

Keywords: agricultural runoff, nitrogen runoff, nutrient estimation, eutrophication, Landsat 8, Gulf of California

INTRODUCTION

Increased nutrient concentrations due to fertilizer runoff from agricultural areas is one of the main ecological problems for coastal zones (Páez-Osuna et al., 2017). The increase in nutrients has had multiple consequences on marine ecosystems, such as harmful algal blooms, zones of hypoxia or anoxia, and loss of biodiversity (Breitburg et al., 2018). This is a global problem that has been documented for various seas, including the Baltic Sea, the China Sea coast, as well as the Mississippi delta and its influence on the Gulf of Mexico (Raymond et al., 2012; Breitburg et al., 2018).

Estimating fertilizer runoff from agricultural areas is usually a complex exercise, since it involves a large number of sampling sites distributed over a large area with different terrain characteristics, which can range from inaccessible mountainous areas to coastal plains (He and DeMarchi, 2014; Hofmeister et al., 2016; López-Vicente et al., 2016). As a result, certain areas are left unsampled. In addition, the temporality of planting, that is, the agricultural cycles and, in some cases, the modification of the hydrological basin by new channels and drains (Rhoads et al., 2016), should also be taken into account. Nevertheless, estimating the runoff of agricultural compounds toward both continental and marine bodies of water is essential to understand their potential effects (Davidson et al., 2014; Breitburg et al., 2018).

Some research has shown the advantages of remote sensing (RS) and Geographic Information Systems (GIS) to estimate nitrogen input in the coastal zones. Sun et al. (2016) used GIS to upscale and visualize total nitrogen runoff losses from field to regional scales. They also characterized significant spatiotemporal variation characteristics during rice seasons, which were positively related to fertilizing rates and precipitation. Mouri et al. (2010) used Landsat images and multivariate analysis to survey the load of total nitrogen in stream water in the Nagara River Basin. Chang (2008) showed the capacities of GIS analysis to study processes that occurred in the past. He examined spatial patterns of eight parameters of water quality – including total nitrogen – in the period 1993–2002 and concluded that spatial analysis of watershed data at different scales is useful in identifying the fundamental spatiotemporal distribution of water quality. In a more recent work, Mainali and Chang (2018) analyzed the seasonal trends of water quality parameters, including total nitrogen, in the Han River Basin (HRB) of South Korea using the Mann–Kendall test. They explored the effects of anthropogenic (land cover and population) and natural (topography and soil) factors using Moran's Eigenvector-based spatial filtering regressions at four different spatial scales. All these examples show advantages of using GIS and RS to estimate nitrogen input coming from agricultural and urban areas in particular water bodies.

In the northwestern area of the Gulf of California, there is extensive use of chemicals in fertilizer, particularly nitrogen based. Studies show that the observed average of 250 kg/ha, although recommended by both agricultural organizations and the *Instituto Nacional de Investigaciones Forestales* (SAGARPA, 2015), are actually excessive (Beman et al., 2005; Harrison et al., 2005; Christensen et al., 2006; Armenta-Bojórquez et al., 2012). Therefore, it can be safely assumed that large amounts

of fertilizers are swept toward the coastal zones, increasing the input of nutrients.

Sonora is one of the main agricultural and fishing states in Mexico, distinguished for both its coastline on the Gulf of California as well as its mountainous areas. Sonora is one of the main states within Mexico facing the problem of agricultural runoff. It is among the top producers of grains and vegetables, grown mostly in the coastal valleys. The valleys have an extensive network of drainage canals for irrigation and wells for groundwater extraction in districts like Río Mayo, El Yaqui, or Guaymas (Pedroza-González and Hinojosa-Cuéllar, 2014). The runoff flows directly into the Gulf of California and its beaches.

While it has been estimated that the agricultural areas of Sonora and Sinaloa only contribute with (~0.6% of the nitrogen input to the Gulf of California (Páez-Osuna et al., 2017), it also has been reported that this effect can occur at local and medium scale and that these agricultural areas are one of the main vectors of pollution (pesticides, fertilizers, etc.) of the marine systems surrounding the Gulf of California (Beman et al., 2005; Montes et al., 2012).

The objective of our research was to study the amount of agricultural nitrogen fertilizer entering the coastal ecosystem of the Gulf of California. For this purpose, we used the agricultural parcels as a study case in the irrigation district of Río Mayo (Sonora estate, Mexico) to generate a rapid GIS and remote sensing-based methodology.

MATERIALS AND METHODS

Study Zone

The irrigation district of Río Mayo is located in the southern part of Sonora (**Figure 1**). It has an average annual precipitation of 388 mm and an average annual temperature of 21.4°C (Pulido Madrigal, 2016). Its operation started in 1863 when the first canal was built, which extracted water from the Río Mayo (Lorenzana-Durán, 2004). This district covers part of the municipalities of Navajoa, Etchojoa, and Huatabampo and is currently made up of 16 modules, with a capacity of $\sim 1,386 \times 10^6$ m³ of water, which feed a channel network of $\sim 1,250$ km in length (Mayo, 2016). The main agricultural production is made during two cultivation periods, spring–summer and autumn–winter.

According to Conagua (2017), wheat was the main crop, with more than 73% of the total area for the autumn–winter 2015–2016 cycle in the irrigation district, while for the spring–summer cultivation cycle, the main crops were corn and safflower. For the studied area, the use of nitrogen ranges between 150 and 400 kg/ha for the cultivation of wheat, with an average of 250 kg/ha (Matson et al., 1998; Harrison and Matson, 2003; Beman et al., 2005; Harrison et al., 2005; Armenta-Bojórquez et al., 2012).

Overall Research Design

The methodology implemented in this manuscript is shown in **Figure 2**. We separated the methodology into the following parts: hydrological characterization (blue), land cover classification

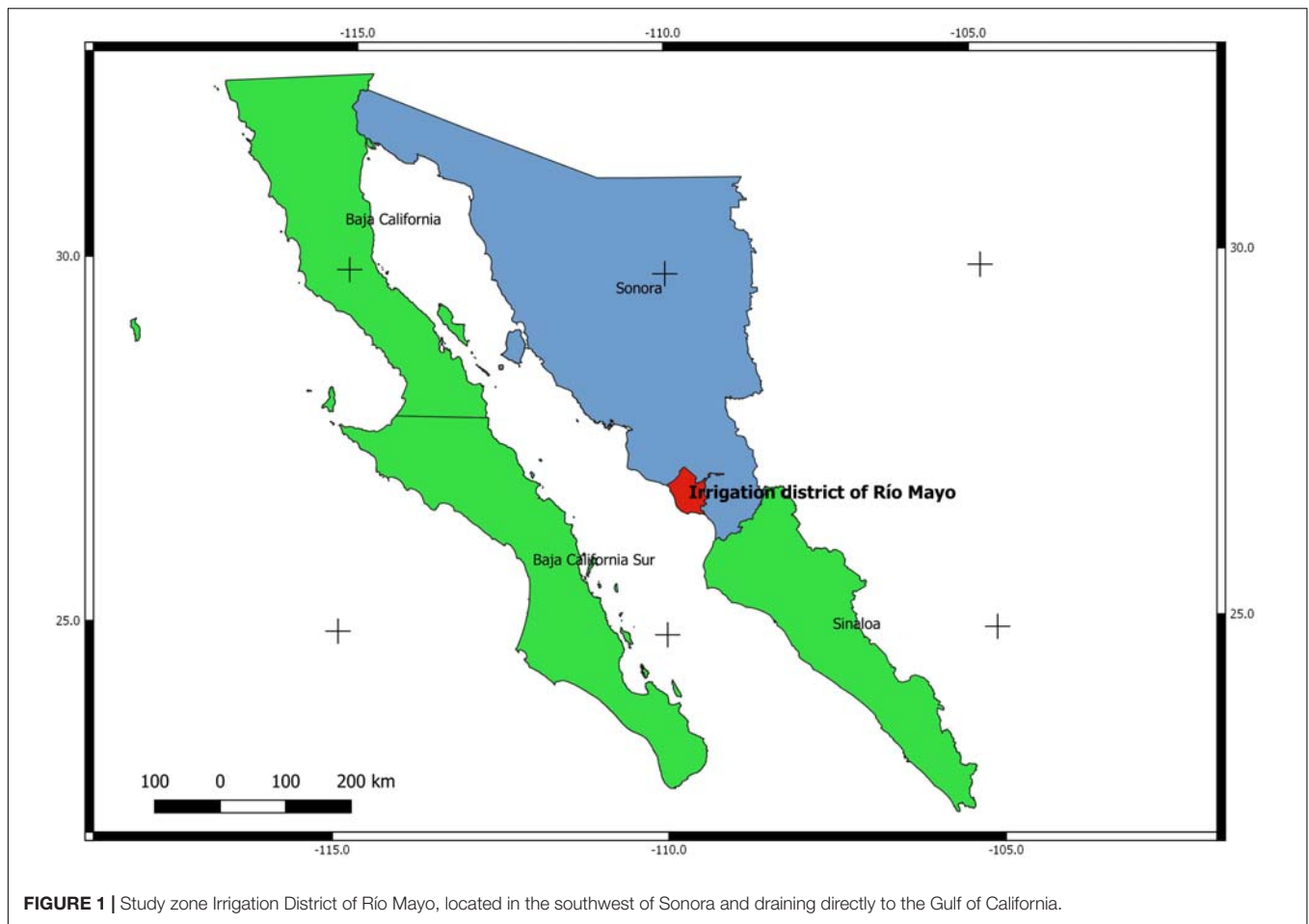


FIGURE 1 | Study zone Irrigation District of Río Mayo, located in the southwest of Sonora and draining directly to the Gulf of California.

(green), selection and validation of the image (orange), estimation of the total of nitrogen runoff to the coastal zone (red and purple), and confirmation of determination using MODIS $K_d(490)$ estimated values for zones around the entry point. These parts are explained in the following sections.

Hydrological Analysis

Allocation of Runoff Marine Entry Points

In order to determine the marine runoff entry points, the hydrological connectivity, and the sub-basins, we used the elevation model *Continuo de Elevaciones Mexicano* 3.0 at 15 m, obtained from INEGI (2017). This model was adjusted (“burned,” i.e., reducing the elevation value in the pixels) in the parts corresponding to the canal maps digitized from the irrigation district page (Mayo, 2016) to make sure that the drainage network obtained by the model matched the actual channel network. This process was done using the software QGIS 2.18.16 (QGIS Development Team, 2018). To model the course followed by the runoff in each of the agricultural areas, we used the *r.watershed* module of the GRASS GIS 7.4 software with a limit parameter (flow accumulation threshold value) of 500 cells. For the watersheds, a threshold of 1,000 cells was used. These thresholds were selected to obtain the drainage network,

as well as the watersheds formed for each of these networks within the study area.

Precipitation Patterns Analysis

The periods and volume of precipitation measured at the stations located in the area of study were obtained from the database of the National Climatological Observatory of Mexico’s National Meteorological Service (SMN, 2018) and from data of climatological activity between 2015 and 2016 from the INIFAP (2018).

Land Cover Classification to Detect Planted Areas

To determine the total planted agricultural area, the classification must represent the maximum agricultural area per cycle; in this case, the maximums corresponded to the months of February, 2016 and September, 2016. Therefore, previously made classifications cannot be used, since the agricultural area can change in each season. For this reason, we used Landsat 8 images path and row (34–41). Landsat images are open access and offer enough resolution for the land cover determination without needing to compose an image for study zones. The selected images corresponded to the two agricultural cycles: autumn–winter 2015–2016 and spring–summer 2016 (one per month).

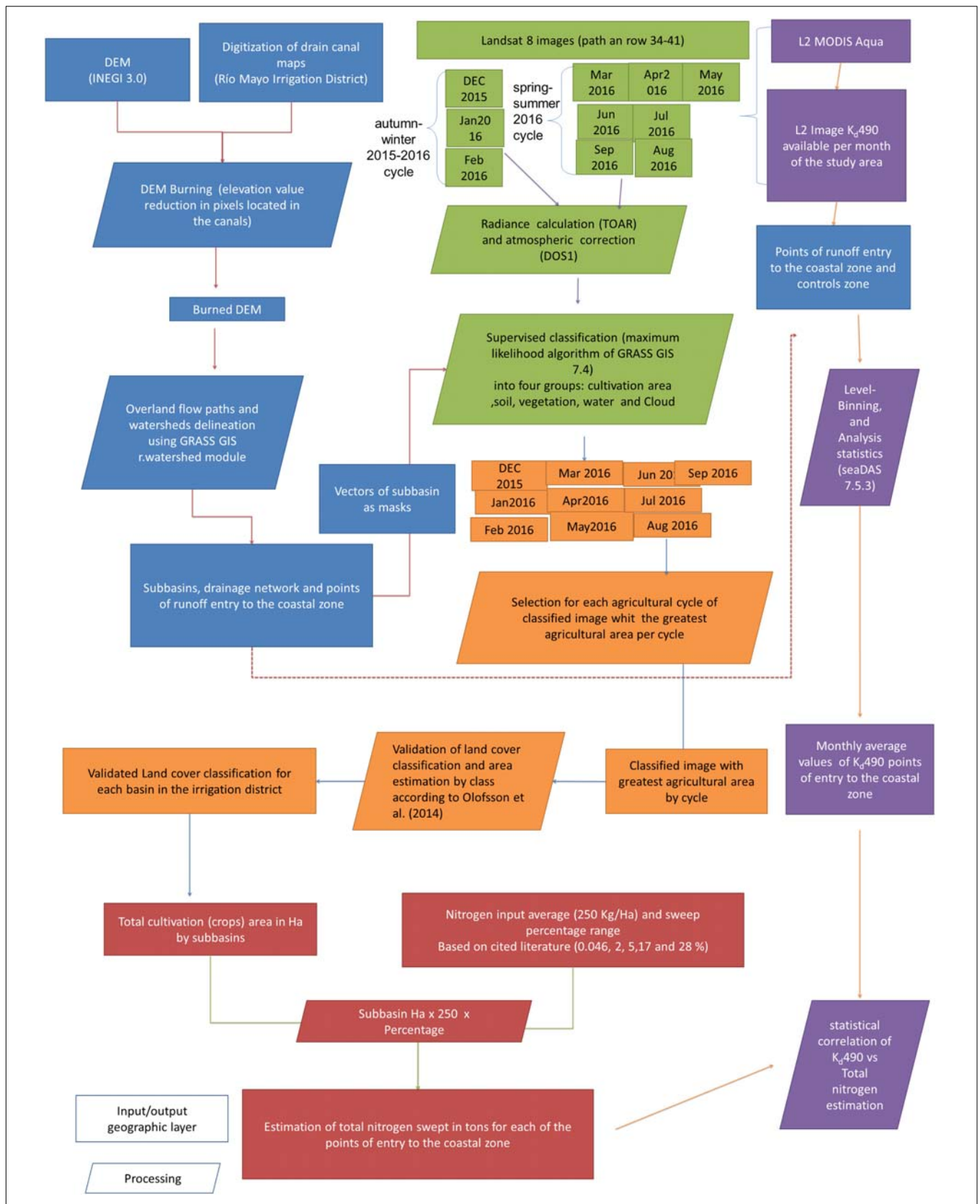


FIGURE 2 | Methodology flowchart for estimating nitrogen runoff from crops to the coastal zones.

The **Supplementary Appendix** shows the images that were used. The digital level values of all the images were converted to Top of Atmosphere Radiance (TOAR). We used the Dark Object Subtraction (DOS1) method in QGIS 2.18 to correct for atmospheric effects.

In order to obtain the total planted area per season, as well as its geographical location, we used supervised classification (maximum likelihood algorithm of GRASS GIS 7.4), and each image was categorized into four groups: cultivation area (all the parcels that are photosynthetic active), soil (land or parcel that has no use or vegetation), vegetation (mangle, bushes, or surrounding trees), and water (shrimp farms, estuaries, coastal lagoons), while for the image that corresponds to the autumn–winter cycle, due to a small area with clouds close to 5% of the studied zone, we added a fifth class (cloud). As a result of the classification, we obtained the plots belonging to a basin and its drainage outlet.

Validation of Land Cover Classification

We used the method proposed by Olofsson et al. (2014) to validate the classification for the entire irrigation district of the Río Mayo, as well as for each of the determined sub-basins. This method includes calculating the sample size and assigning it in the categories of coverage types, based on the best result of five hypothetical assignments. Olofsson et al. (2014) suggest using Cochran's (Cochran, 1997) formula to calculate sample size (η):

$$\eta \approx \left(\frac{W_i S_i}{S(\hat{O})} \right)^2 \quad (1)$$

where $S(\hat{O})$ is the standard error of the estimated overall accuracy that we would like to achieve, W_i is the mapped proportion of area of class i , and S_i is the standard deviation of stratum i , calculated according to Cochran's formula (1977) as:

$$S_i = \sqrt{U_i(1 - U_i)} \quad (2)$$

where U_i is the user's accuracy of class i (the proportion of the area mapped as class I that has reference class I : cultivation area $S(\hat{U}_{ca})$, soil $S(\hat{U}_s)$, vegetation $S(\hat{U}_v)$, water $S(\hat{U}_w)$, and cloud $S(\hat{U}_c)$). We used an $SS(\hat{O})$ of 0.015 for the sample size calculation.

To determine sample allocation to strata, Olofsson et al. (2014) suggest allocating a sample size of 50–100 for each change strata, using the variance estimator for user's accuracy $\hat{V}[\hat{V}(\hat{U}_i)]$, Equation 3] to decide the sample size needed to achieve certain standard errors for the assumed estimated user's accuracy for that class.

$$\hat{V}(\hat{U}_i) = \hat{U}_i(1 - \hat{U}_i)/n_i - 1 \quad (3)$$

where n_i is the sample size allocated to class i . Olofsson et al. (2014) indicate that $n-r$ sample units remain after a sample size of r units has been allocated to the rare class strata. They suggest allocating the sample size of $n-r$ proportionally to the area of each remaining stratum. As a next step, they point out that the anticipated estimated variances can be computed (based on the sample size allocation) for user's and overall accuracy and area

using following Equations (3)–(5).

$$\hat{V}(\hat{O}) = \sum_{i=1}^q W_i^2 \hat{U}_i(1 - \hat{U}_i)/n_i - 1 \quad (4)$$

where $\hat{V}(\hat{O})$ is the estimated variance for overall accuracy.

$$S(\hat{P}_{.k}) = \sqrt{\sum \frac{W \hat{P}_{ik} - \hat{P}_{ik}^2}{n_i - 1}} \quad (5)$$

where $S(\hat{P}_{.k})$ is the standard error of the proportion of area mapped as class k .

In particular, five possible “allocations” were constructed for each watershed, with an average of 613 samples, distributed in four classes for the month of February. For the month of September, averages of 790 samples were allocated in the five classes.

Determination of Reference Data

After having selected the best sample allocation to strata, the reference data to validate the classification was obtained by the following procedure. A visual inspection of each of the sample units was performed to assign the reference land cover type using the true color composite of the used Landsat images, together with corresponding Google Earth™ imagery. For February, the reference data had a month of difference and 2 months difference for September. This was based on the availability of Google imagery. A random allocation of the points defined as n_i was performed using QGIS 2.18.

Estimating Accuracy, Area, and Confidence Intervals of Plated Areas

We used the method proposed by Olofsson et al. (2014) to estimate accuracy, area, and confidence intervals for each category. We calculated the area estimation error ($\hat{P}_{.k}$, Equation 6) and the pixel precision using the confusion matrix (**Supplementary Appendix**) relative to the confidence intervals using the following equations [$S(\hat{A}_n)$ and \hat{A}_n , Equations 7 and 8].

$$\hat{P}_{.k} = \sum_{i=1}^q W_i \frac{n_{iK}}{n_i} \quad (6)$$

$$S(\hat{A}_n) = S(\hat{P}_{.k}) \times A_{tot} A_{tot} \times z \quad (7)$$

$$\hat{A}_n = \hat{P}_{.k} \times A_{tot} A_{tot} \quad (8)$$

where $S(\hat{A}_n)$ is the error for the estimated area, $z = 1.96$ is the confidence interval at 95%, and $A_{tot} A_{tot}$ is the total of pixels, while \hat{A}_n is the estimated area for the class n .

This procedure was followed for both the total area of the study basin and for each of the sub-basins previously determined, using a confidence interval of 95%.

Estimation of Amount of Nitrogen Used for Main Crops in the Area of Study

The volume of nitrogen from runoff was obtained by multiplying the cultivated area by the average of nitrogen reported (250 kg/ha) and by the percentage of nitrogen in the runoff water according to the values of Riley et al. (2001). In addition, Mexican official recommendations and sowing manuals (SAGARPA, 2015) were used to obtain doses of nitrogen used for the main crops of the area during the periods studied.

Analysis of the Diffuse Attenuation Coefficient $K_d(490)$ Concentration Around the Coastal Entry Points

Satellite images of the diffuse attenuation coefficient at 490 nm $K_d(490)$ L2 OCI were obtained for the two crop cycles from the Moderate Resolution Imaging Spectroradiometer (MODIS-AQUA) from the Ocean Color Data Browser (NASA, 2019b). To obtain the monthly average with a 1 km resolution pixel and to extract the data and for the composed monthly average $K_d(490)$ image for each of the coastal entry points of nutrients previously determined and two control zones (areas where there are no agricultural plots nearby), we used the L2-binnig module of the software seaDAS version 7.5.3 (NASA, 2019a). Each sampling had an area of 19.6 km². This information was used to confirm the amount of nitrogen runoff received by the marine coastal zones through the entry points.

Validation of the Nitrogen Estimation Method

To validate the proposed method to estimate nitrogen inputs in the marine zone, a statistical correlation between the estimated values of nitrogen runoff for each basin and the satellite $K_d(490)$ values around its corresponding outlet point (marine entry point) was performed in R. For this end, we used the 2% nitrogen concentration values.

RESULTS

Hydrological Analysis

The obtained drainage lines, the basins, and the estimated nutrient entry points along the coastal zone and the coastal lagoons are shown in **Figure 3**. Eight basins were obtained within the irrigation district (shown in **Figure 3** with different colors). They allowed a determination of which agricultural parcels drain to the same area. The entry points allow allocation of the affected coastal zone and the coastal lagoons. The results indicate that there are some direct entry points to the Gulf of California, while others are located between mangrove areas and the lagoon of Yavaros and Tóbari.

The results for the two agricultural cycles indicate that rainfall was scarce, and that even during the rainy seasons, there was no total monthly rainfall >130 mm (**Figure 4**) nor maximum daily rainfall >35 mm. Thus, it can be stated that the relative contribution of precipitation during these two

agricultural periods was of low importance regarding the runoff of nutrients into the coastal zone, which depends mainly on the water from the Adolfo Ruiz Cortines dam, together with the various extraction wells used for irrigation.

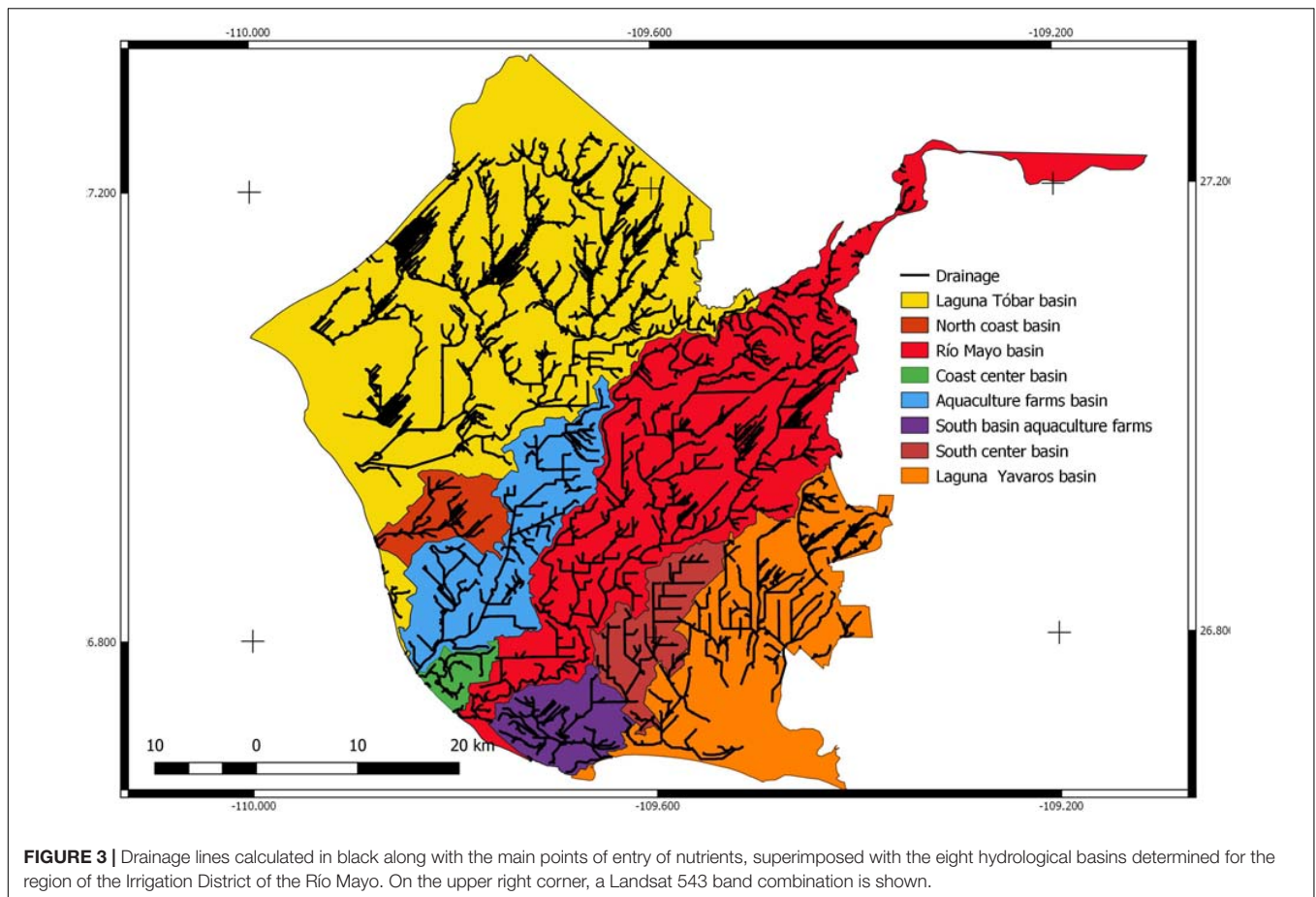
Identification and Estimation of the Agricultural Areas

After image classification, **Table 1** shows the number of classes used, number of samplings, standard error of the estimated overall accuracy, selected accuracy of the allocation that was chosen, and estimated user's accuracy for each class for all selected allocations of each basin. It also shows all the allocation variables selected for each sub-basin. In the case of the autumn–winter cycle, the selection was based on the smallest estimated user's accuracy for the cultivation area and the soil area, while for the spring–summer cycle, priority was given to soil and cultivation area, in that order.

As example, tables showing data of the entire irrigation district are included in **Supplementary Appendix**. As mentioned, these determinations were done for all sub-basins and for the entire district. **Table 1** of the **Supplementary Appendix** shows the standard errors of the user's and overall accuracies for the five possible allocations. We selected allocation 3 for the autumn–winter cycle (February) and allocation 1 for the spring–summer cycle (September), due to their lowest values in the standard error for cultivation area, soil, and selected accuracy. **Table 2** shows the estimator matrix for the total of the Río Mayo irrigation district for February and September, while **Table 4** of the **Supplementary Appendix** shows the error matrix of sample counts of each allocation.

Estimation of Nitrogen Runoff

Table 2 shows all data from the validation classification for each sub-basin and the entire irrigation district for the two cycles, and all the basins with their estimation error for each strata. The large difference in the land used in each cycle should be noted. While the autumn–winter had more than 49% of the total areas as cultivated category and the category of soil represents almost 38% of this proportion change, for the spring–summer cycle, the main category is soil, with more than 57% of all the irrigation district and the cultivation category representing just 21.3%. **Table 3** shows the percentages of nitrogen runoff reported by Riley et al. (2001), multiplied by the planted area obtained after classification. The irrigation district Río Mayo basin has its main cultivation period in the autumn–winter cycle, although it also has important nitrogen contributions during the spring–summer cycle. The Tóbari lagoon basin has the most agricultural land cover in both the autumn–winter cycle and spring–summer cycle, and with discharge into the Tóbari lagoon. The Río Mayo basin is second in agricultural production and volume of nitrogen runoff. This basin discharges directly to the Gulf of California. While the Tóbari lagoon basin has a minor agricultural contribution, it also receives input from the shrimp farms that are in the area.



Analysis and Validation of the Nitrogen Estimation Method

Figure 5 shows the $K_d(490)$ values for each of the entry points of nutrients to the coastal zone by month for the two agricultural cycles. We confirmed that the higher clarity of coastal zones water correspond to the control zones, while the lower correspond to the main agricultural areas.

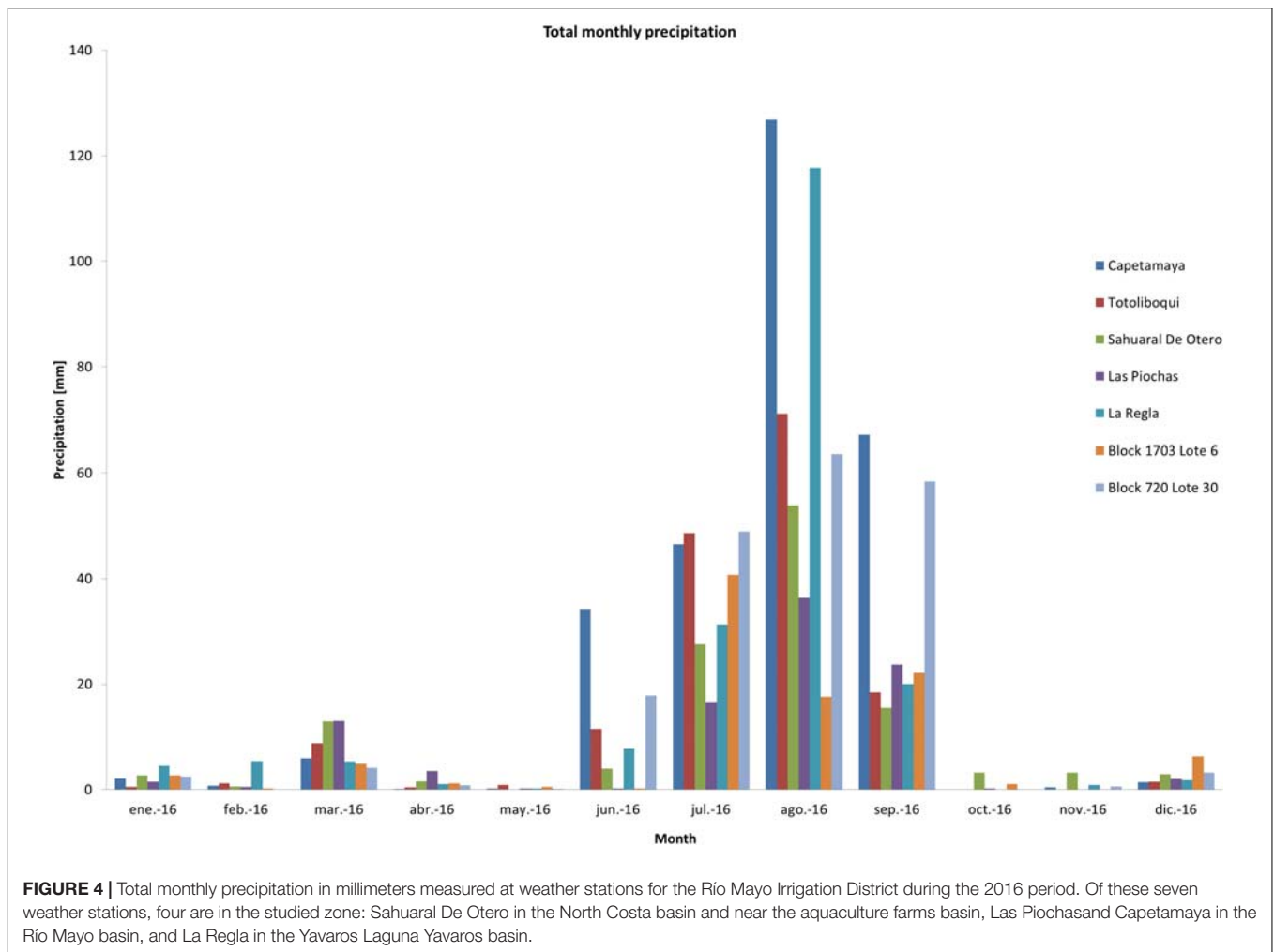
In addition, as the data did not fulfill the assumptions of normality and homoscedasticity, a non-parametric test was used. The Spearman correlation analysis (see Figure 6) indicate a significant correlation (autumn–winter: $r = 0.705$, $p = 0.002$, spring–summer: $r = 0.678$, $p = 0.003$) between the $K_d(490)$ and the nitrogen values. This is very promising for the rapid method proposed here to estimate effects of agriculture farms into the coastal zone. The plots consistently show for both agricultural seasons that the order of the highest and lowest compared values is the same. The controls (basins without agricultural influence) have the lowest values of the compared correlated parameters, and the highest values are registered for the Tóbari lagoon basin.

DISCUSSION

This study provides a robust starting point for the quantification and estimation of total nitrogen from runoffs into the coastal

area, especially in zones where the information is not available or incomplete, unlike others models (McClelland et al., 1997; Valiela et al., 1997; Hofmeister et al., 2016; Sun et al., 2016) that require different layers of information (e.g., type of soil, topography wetness index, floodwater depth, among others) and concede the input of other variables, such as using stable nitrogen isotopes, to distinguish the sources, leaching, and availability (Teichberg et al., 2008; Ochoa-Izaguirre and Soto-Jiménez, 2013; Viana and Bode, 2013; Rivero-Villar et al., 2018).

One of the main advantages of the Olofsson et al. (2014) method to validate land use and land cover classifications is that it considers confidence intervals for the quantification of the cultivated area, allowing a statistical interpretation of the estimates of the nitrogen concentrations from runoff. We believe that, when selecting the data with the largest cultivated area of the season, we obtained data that are closer and more representative of the amount of total cultivated plot found in each basin. One of the main problems for the classification of crops/soils that we experienced was the presence of clouds, since they can mask or increase the classification error for the other class. As shown in Table 3, the estimation error is close to 19% of the total cloud classification, even though this specific class only represents <5% of the overall classification, and the main class cultivated area for February and soil for September only had 4.6 and 4.25% of estimation error, respectively.



Another important result is the geographical location of the drainage entry points. The possible effect of drainage on the ecosystems can be estimated, depending on whether there are buffer zones or nutrient traps, as would be the case of a wetland or a direct entry to the coastal zone (Figure 3). Knowing the location of nutrient entry points allows the implementation of action plans and public policies to address the problem of eutrophication and agricultural pollution. For example, the Tóbari lagoon receives contributions from livestock, urban waste waters, shrimp farms, and two irrigation districts (Valle del Yaqui irrigation district and Río Mayo) (Ahrens et al., 2008; Páez-Osuna et al., 2017). In the same line, Ruiz-Ruiz (2017) describes how the Tóbari lagoon presented a biological stress and even hypoxia during the summer of 2012, while Vargas-González (2018) explains how the discharge waters from the agricultural parcels have an effect on the salinity of the Yavaros lagoon and report the presence of Aldrin and other pesticides in this lagoon.

With the results obtained from this study and the analysis of the nutrient entry points to the coast, we have identified that two basins are the most important in terms of agricultural production and the entry of nutrients: Tóbari lagoon and the

basin of Río Mayo. For the purpose of study, the great majority of nutrients that reach these coastal areas arrive during the periods of irrigation, since rainfall is scarce year round (Figure 4). A large contribution of nitrogen was probably during the first irrigation, according to the planting manuals (SAGARPA, 2015). During this period, the crop already has ~60–80% of the total fertilizer to be used during the crop cycle.

As stated by Ahrens et al. (2008); Ruiz-Ruiz (2017), Páez-Osuna et al. (2017), and Vargas-González (2018), the Tóbari lagoon is exposed to a combination of diverse anthropogenic pressures. As one of the main vectors of nitrogen, agricultural runoff can have a significant input to this lagoon, depending on whether there was a previous study of nitrogen soil available. For example, with the lowest estimates of 2% of fertilizer runoff to the Tóbari basin for the autumn–winter cycle, ~680 tons of nitrogen could enter the lagoon in the first months of planting. In the case of the upper estimates, there was not a previous soil–nitrogen study, but the volume of nitrogen that could enter the Tóbari lagoon could even go to the upper limit of 27%. That means more than 4,000 tons would have reached the basin, which highlights the need for more study of the relationship between agricultural and coastal zones.

TABLE 1 | Number of classes by sub-basin, sampling number (n), standard error of the estimated overall accuracy $S(\hat{O}_n)$, selected accuracy $S(\hat{O}_{sa})$ of the allocation that was chosen, and estimated user's accuracy for each class $S\hat{U}_j$.

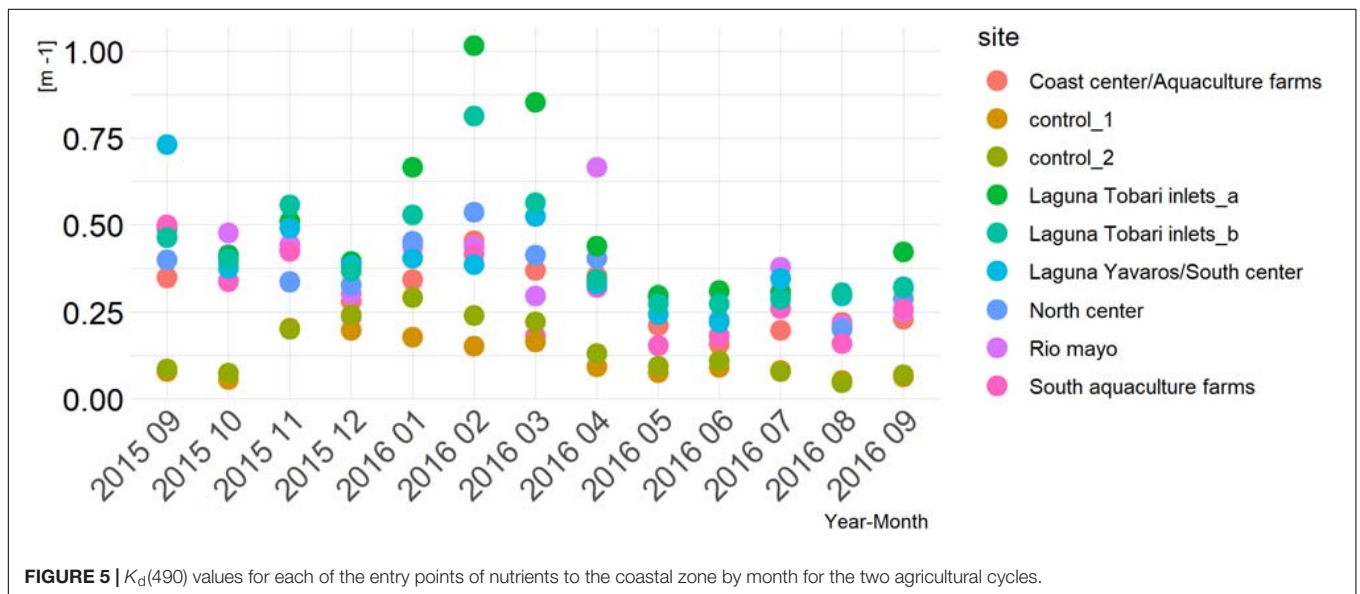
Basin	Class	$S(\hat{O}_n)$	n	$S(\hat{O}_{sa})$	$S(\hat{U}_{ca})$	$S(\hat{U}_s)$	$S(\hat{U}_v)$	$S(\hat{U}_w)$	$S(\hat{U}_c)$
February									
Río Mayo Irrigation District	4	0.015	553	0.016	0.017	0.033	0.094	0.04	–
Tóbari lagoon	4	0.015	528	0.016	0.017	0.033	0.094	0.044	–
Aquaculture farms	4	0.015	596	0.018	0.017	0.033	0.049	0.073	–
Coast center	4	0.015	745	0.016	0.027	0.019	0.062	0.035	–
North center	4	0.015	682	0.021	0.017	0.03	0.079	0.044	–
Río Mayo	4	0.015	556	0.017	0.018	0.033	0.06	0.031	–
South center	4	0.015	530	0.016	0.016	0.035	0.094	0.109	–
South aquaculture farms	4	0.015	753	0.015	0.03	0.018	0.085	0.046	–
Laguna Yavaros	4	0.015	517	0.016	0.017	0.035	0.094	0.034	–
September									
Río Mayo Irrigation District	5	0.015	769	0.016	0.035	0.021	0.042	0.031	0.065
Tóbari lagoon	4	0.015	777	0.015	0.034	0.022	0.035	0.032	0.082
Aquaculture farms	5	0.015	753	0.015	0.071	0.019	0.048	0.037	0.041
Coast center	5	0.015	639	0.017	0.105	0.021	0.038	0.026	0.068
North center	5	0.015	1149	0.014	0.027	0.024	0.027	0.013	0.027
Río Mayo	5	0.015	821	0.015	0.037	0.02	0.035	0.338	0.047
South center	5	0.015	794	0.016	0.038	0.021	0.043	0.025	0.053
South aquaculture farms	5	0.015	736	0.019	0.038	0.022	0.036	0.029	0.065
Laguna Yavaros	5	0.015	685	0.016	0.038	0.021	0.046	0.03	0.085

TABLE 2 | Area that covers each class, as well as its estimation error.

Basin/Strata	Cultivated area (ha)	±95% (ha)	Soil (ha)	±95% (ha)	Vegetation (ha)	±95% (ha)	Water (ha)	±95% (ha)	Cloud	±95%	Total (ha)
February											
Tóbari lagoon	61,839	2,403	35,178	2,722	7,866	2,372	5,739	752	–	–	110,622
Aquaculture farms	10,562	529	10,083	706	1,957	587	334	249	–	–	22,936
Coast center	336	41	2,213	58	234	50	125	34	–	–	2,907
North center	1,989	104	4,184	236	1,016	245	2	0	–	–	7,191
Río Mayo	37,847	1,929	28,327	1,837	5,051	1,665	711	620	–	–	71,937
South center	6,599	252	3,235	249	544	194	22	43	–	–	10,400
South aquaculture farms	1,246	152	7,172	208	881	198	114	58	–	–	9,414
Laguna Yavaros	15,686	925	13,347	943	3,246	920	7,347	692	–	–	39,626
Total	136,104	6,334	103,739	6,960	20,795	6,231	14,394	2,448	–	–	275,032
Total basins area in percentage	49.49%	2.30	37.72	2.53	7.56%	2.27	5.23	0.89	–	–	100%
El Mayo Irrigation District (DR)	133,835	6,816	98,773	7,946	27,047	6,976	15,538	3,421	–	–	275,192
Total DR area in percentage	48.63%	2.48	35.89	2.89	9.83%	2.54	5.65	1.24	–	–	100%
September											
Tóbari lagoon	30,728	2,356	56,127	2,487	14,259	2,217	7,584	834	2,003	800	110,701
Aquaculture farms	2,217	326	14,215	535	2,350	471	1,396	249	2,771	307	22,948
Coast center	22	16	1,987	72	202	43	505	58	192	22	2,907
North center	512	70	3,398	176	1,174	168	602	43	1,506	81	7,193
Río Mayo	16,261	1,363	39,956	1,708	10,023	1,545	651	420	5,078	827	71,969
South center	1,753	175	6,455	257	1,094	216	98	74	1,000	152	10,400
South aquaculture farms	275	82	5,257	269	1,412	214	929	101	1,544	243	9,417
Laguna Yavaros	6,869	802	19,289	986	6,164	890	6,594	522	660	367	39,575
Total	58,636	5,190	146,683	6,491	36,677	5,763	18,359	2,301	14,755	2,798	275,110
Total basins area in percentage	21.31	1.89	53.32	2.36	13.33%	2.09	6.67	0.84	5.36	1.02	100%
El Mayo Irrigation District (DR)	48,159	3,208	158,665	5,271	36,893	3,844	19,191	2,474	12,301	2,160	275,209
Total DR area in percentage	17.50	1.17	57.65	1.92	13.41%	1.40	6.97	0.90	4.47	0.78	100%

TABLE 3 | Estimate of nitrogen from runoff according to the average used in the literature of 250 kg/ha, as well as estimates of sweep percentage according to the cited literature.

Río Mayo Irrigation District basins February	Cultivated area (ha)	95% confidence interval in percentage	Riley et al., 2001 (2%) (ton)	Riley et al., 2001 (5%) (ton)	Riley et al., 2001 (17%) (ton)	Riley et al., 2001 (28%) (ton)
February						
Tóbari lagoon	61,838.63	3.89	309.193	772.983	2,628.14	4,328.70
Aquaculture farms	10,561.85	5.01	52.809	132.023	448.878	739.329
Coast center	335.876	12.33	1.679	4.198	14.275	23.511
North center	1,988.90	5.20	9.944	24.861	84.528	139.223
Río Mayo	37,847.06	5.10	189.235	473.088	1,608.50	2,649.29
South center	6,599.24	3.83	32.996	82.491	280.468	461.947
South aquaculture farms	1,246.42	12.16	6.232	15.58	52.973	87.249
Laguna Yavaros	15,686.25	5.90	78.431	196.078	666.666	1,098.04
Total nitrogen swept to the coast	136,104.23		680.52	1,701.30	5,784.43	9,527.30
September						
Tóbari lagoon	30,728.27	7.67	153.641	384.103	1,305.95	2,150.98
Aquaculture farms	2,216.87	14.69	11.084	27.711	94.217	155.181
Coast center	21.719	75.54	0.109	0.271	0.923	1.52
North center	511.984	13.58	2.56	6.4	21.759	35.839
Río Mayo	16,260.78	8.38	81.304	203.26	691.083	1,138.26
South center	1,753.45	9.98	8.767	21.918	74.522	122.741
South aquaculture farms	274.627	29.76	1.373	3.433	11.672	19.224
Laguna Yavaros	6,868.61	11.68	34.343	85.858	291.916	480.803
Total nitrogen swept to the coast	58,636.31		293.182	732.954	2,492.04	4,104.54



Within the values of $K_d(490)$ that we obtained (Figure 5), it is of interest to note that the lower clarity correspond to areas where there is great contribution of nutrients and other compounds from the field. It is important to note that agricultural and aquacultural activities are well reported as a main pathway for organic matter and other compounds to the coastal zones

(Beman et al., 2005; Ahrens et al., 2008; Páez-Osuna et al., 2017). In contrast, the values of the control zone remain with a high transparency, during the two agricultural cycles, having a peak of increased turbidity during the months of December and March.

Reviewing studies such as that of Beman et al. (2005), and the data obtained in this work, allows us to think that agricultural

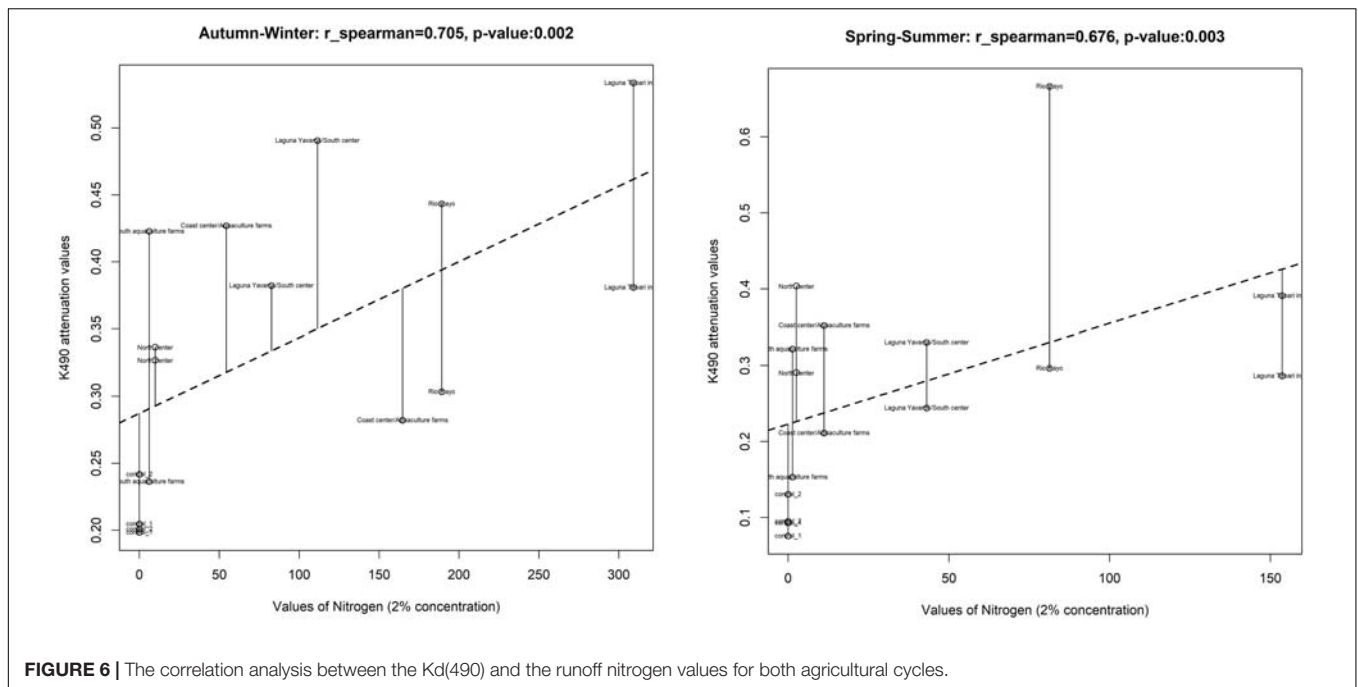


FIGURE 6 | The correlation analysis between the $K_d(490)$ and the runoff nitrogen values for both agricultural cycles.

runoff in the Gulf of California can have a greater influence in this area. Particularly, the results obtained show that the Río Mayo basin is contributing a large amount of agricultural substances directly to the coastal zone into the Gulf of California, since there is not sufficient filtration or retention of nutrients and contaminants. Therefore, its entry and dissemination to the marine area could have several ecological implications.

It is worth noting that there is daily use of high amounts of fertilizers, which are high in nitrogen, within the Sonoran agricultural area, as indicated by Beman et al. (2005) and Christensen et al. (2006). This can also be seen when analyzing the recommendations for the use of nitrogen for the main crops, within the manuals published by SAGARPA (2015) for Sonora.

Additionally, we proved that the methodology can provide a cost-effective, practical approach for estimating nitrogen entries into coastal zones and can be also applied to estimate the runoff of other contaminants. This would allow better decision-making regarding the interaction between agricultural zones and coastal areas.

CONCLUSION

We developed an easy and rapid GIS and remote sensing-based method that uses open access data to estimate nitrogen or any contaminant that changes the optic water properties and that is swept into the coastal zone. The superficial connectivity analysis model used in this study allowed the estimation of nitrogen input to the coastal zones. The developed method allows incorporating field data and extrapolating to any agricultural area.

With the results obtained in this study, we conclude that the quantities of nitrogen fertilizer that enter the coastal zone from the agricultural runoff have an ecological effect by decreasing

the clarity of water in the coastal zone. It is undeniable that there is an input of nutrients and other pollutants from both the irrigation districts of the Río Mayo and other agricultural areas. It is therefore necessary to have tools that allow rapid quantification and analysis to create public policies that will protect the Gulf of California. We propose that these results and this methodology can help to create an easy and quicker agricultural runoff nitrogen inventory for the coastal zone of the Gulf of California and other marine coastal zones worldwide.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

DG-R, FT-S, DR-F, and AO-R significantly contributed to the conception and design of the study. DG-R, FT-S, JB-G, and LB-M organized the databases and the satellite image processing. DG-R, FT-S, and DL-C performed the statistical analysis. DG-R and FT-S contributed to write the first draft of the manuscript. DR-F, FT-S, DR-F, JB-G, LB-M, DL-C, and AO-R wrote specific sections of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2020.00316/full#supplementary-material>

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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