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# Applying SPOT images to study the Colorado River effects on the Upper Gulf of California †

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Academic Editor: name
Received: date; Accepted: date; Published: date

**Abstract:** Sediment discharges from rivers play a key role in downstream ecosystems, both for ecosystem morphology (e.g. deltas) and productivity. However, construction of dams and river regulation dramatically alter sediment transport. Currently, the Colorado River delta is one of the most transformed deltas in the world and no flow reaches the Gulf of California in most of the years. In this study, we used satellite images for the observation and measurement of coastal waters turbidity in the Upper Gulf of California (UGC) and Colorado River Delta (CRD). Specifically, we used SPOT high spatial resolution satellite. We processed images of the wavelength 2 ($S2_{610-680}$) from the period between 2008 and 2013 in the Biosphere Reserve area. Results showed that suspended material and high turbidity predominate in the CRD and intertidal zones of the UGC. High and very high turbidity values were due to two opposite coastal transport components along the Sonora and Baja California coasts. The high spatial resolution of the SPOT sensor effectively allowed locating the sediment transport gradients and the accumulation zones in a highly variable area. This information provided by SPOT images can be very valuable for management decisions such as the amount of ecological flow that needs to be released. This area is the habitat of endangered species, such as totoaba (*Totoaba macdonaldi*) and vaquita (*Phocoena sinus*), that are seriously affected by the loss of estuarine conditions. High resolution satellite images can help in quantifying the true extent of corrective measures.

**Keywords:** remote sensing; turbidity; delta; pulse flow

## 1. Introduction

Regulation of large rivers through dams and diversion projects has caused dramatic changes to many delta ecosystems and receiving waters [1]. The Colorado River (North America) is one of the most transformed rivers in the world. Intensive economic use of the Colorado River water was developed during the twenty century [1, 2]. Before any dam construction, during the period between 1905 and 1936, the average daily discharge into the Gulf of California was 600 $m^3/s$ [1]. Completion of large dams, such as Hoover Dam in 1935 and Glenn Canyon in 1952, greatly reduced discharge [1, 2]. Nowadays, no flow is registered at the Southerly International Boundary (SIB) more than 60% of the time since 2000 [1]. The Colorado River discharges into the Gulf of California only during extraordinary precipitation events (e.g. El Niño) and particularly high tides [2, 3].

The Upper Gulf of California (UGC) is very high marine primary productivity area [4, 5] that maintains its productivity despite the lack of river discharge. This marine area hosts important fisheries such as shrimp and gulf corvine [6, 7]. Despite, there is some disagreement on how the river discharge contribute to this high productivity [7, 8], there are several studies that link Colorado River flow and UGC productivity [7, 9].

Moreover, this area holds several protection figures, like biosphere reserve, the Biosphere Reserve of the Upper Gulf of California and Colorado River Delta. It is the habitat of endangered endemic species, the totoaba (*Totoaba macdonaldi)* and the vaquita marina (*Phocoena sinus)*, which are estuarine-dependent [10]. The decrease in river discharges converted the Colorado River Delta into a negative estuary with hypersaline water, and thus altering the habitat of these species [10, 11].

During spring 2014 a programmed pulse-flow was released under implementation of Minute 319, that get to connect the river with the sea [6, 12]. Minute 319 is a binational agreement (USA and Mexico), which searches to study the ecological benefits of river flow [7]. Freshwater flows can bring nutrients, sediments and detritus which sustain fisheries [7], but other key factor in the UGC is sediment resuspension by strong tidal currents [2].

[3] used satellite images, Landsat 5-TM and Landsat 7, to reconstruct river-sea connectivity and geomorphic processes, and to analyse implications for habitat restoration. In our study, we used high spatial resolution (10 – 20 m) sensor SPOT to study turbidity levels in the UGC. The objective is to locate sediment transport gradients and accumulation zones due to UGC dynamics. This can supply additional information to managers in decisions regarding water allocation.

## 2. Material and methods

### *2.1. Study area*

The study area is represented in Figure 1. It is the Upper Gulf of California (UGC) and the estuary of the Colorado River. It hosts the Biosphere Reserve of the Upper Gulf of California and Colorado River Delta (CRD), and also the Vaquita Marina Refuge. 80% of the refuge is part of the Biosphere Reserve. In this study, this area was covered with SPOT images from year 2008 to 2013. The main transformations for water regulation in the Colorado River, dams and diversions, are indicated in Figure 1 (e.g. Glen Canyon dam, Hoover dam).

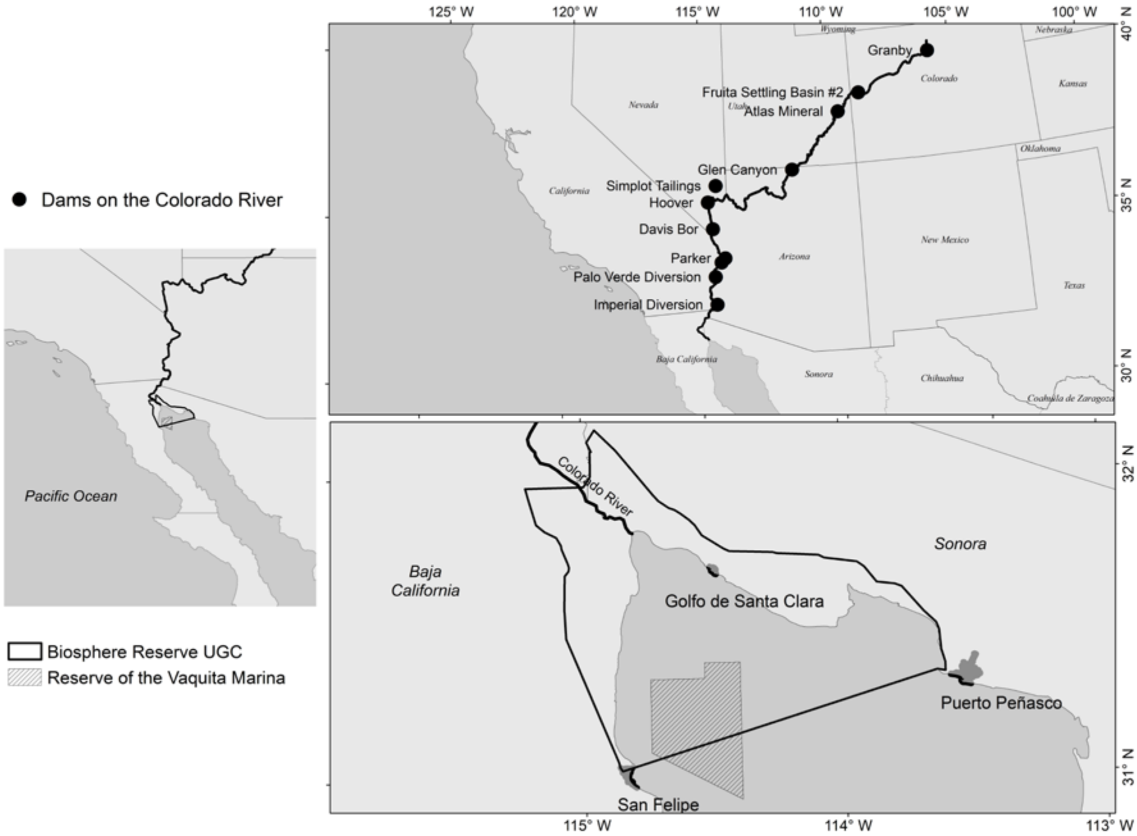


Figure 1. Study area location, Upper Gulf of California and Colorado River Delta (Baja California, Mexico). Tide stations used in this study were located in Golfo de Santa Clara, San Felipe and Puerto Peñasco coastal towns. The Biosphere Reserve and the Vaquita marina refuge polygons are depicted.

### *2.2. Image processing*

In this study we used the SPOT sensor reflectance band 2, $R_{rs}$ $(S2_{610-680})$, to estimate water turbidity. The SPOT images were corrected radiometric, atmospheric and geometrically as described in [13]. A total of 73 SPOT images of the period between 2008 and 2013 were processed. These images were classified according to oceanic conditions at the moment of the scene, in order to be able to study the turbidity in different conditions. Oceanic conditions were determined from the historical records of three tide stations of the UGC (Golfo de Santa Clara, Puerto Peñasco and San Felipe) (Figure 1). The images were grouped as follows [13]:

1) Neap tide (during the first and third quarter moon, when the moon appears "half full", the sun and moon are at right angles to each other, bulge of the ocean caused by the sun partially cancels out the bulge of the ocean caused by the moon) in flow (slow and continuous rise of the waters) or ebb flow (slow and continuous descent of the waters)

2) Spring tide (new and full moon, moon and sun are aligned and their effects are added) in flow or ebb flow

3) Season, warm or cold season.

## **3. Results and discussion**

The next figures show the maps of turbidity in the area of the UGC and CRD for years 2010, 2011 and 2012 (Figure 2, 3 and 4 respectively) both for cold and warm seasons, and different tide conditions. No SPOT image were available for spring tide in ebb flow, so that specific conditions were not assessed. Reflectances obtained from SPOT ranged between very high (white color) to very low (black color).

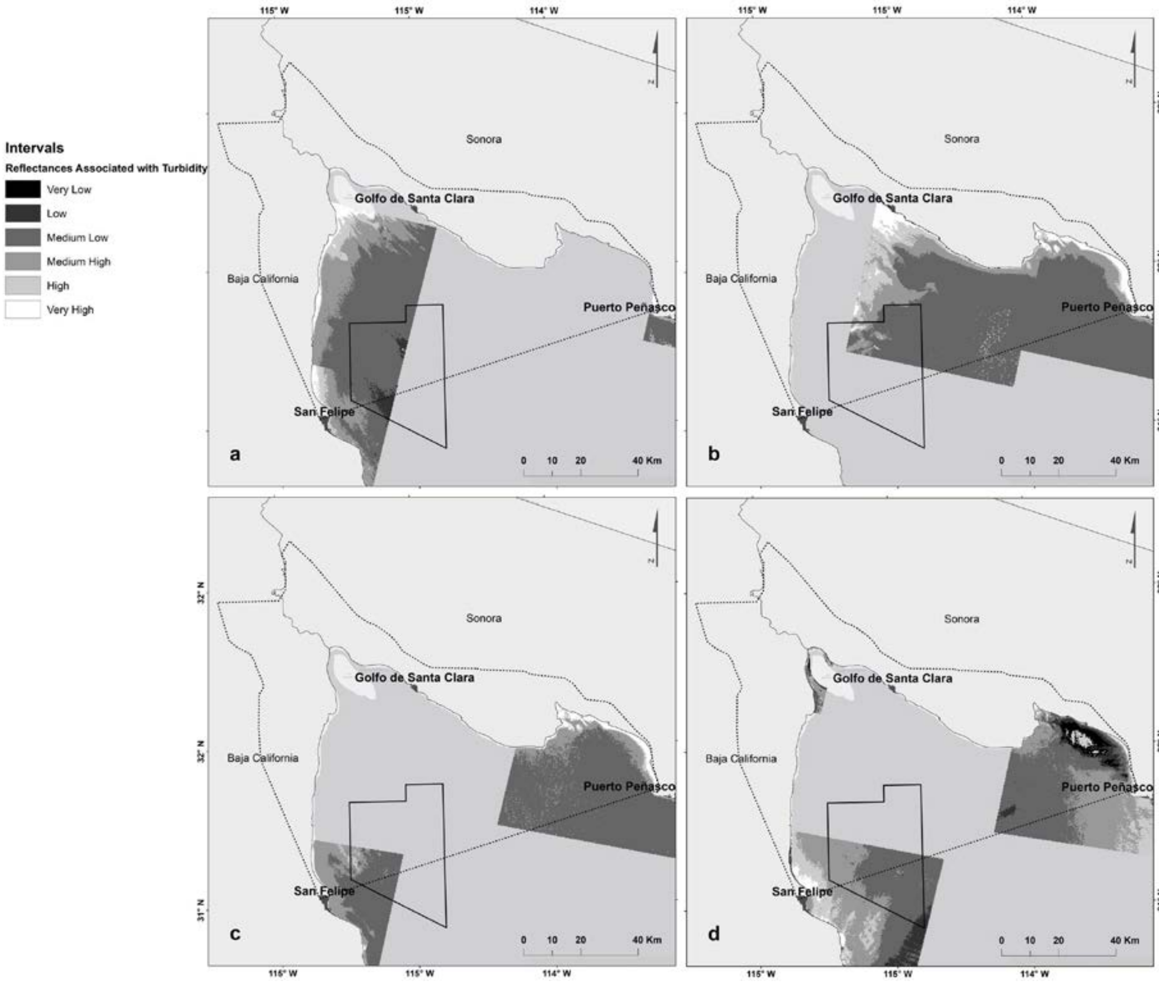


**Figure 2 UGC maps of turbidity for year 2010 in: a) cold season, spring tide in flow, b) cold season, neap tide in ebb flow, c) cold season, neap tide in flow and d) warm season, spring tide in flow. The Biosphere Reserve area and the Vaquita marina refuge polygons are depicted**

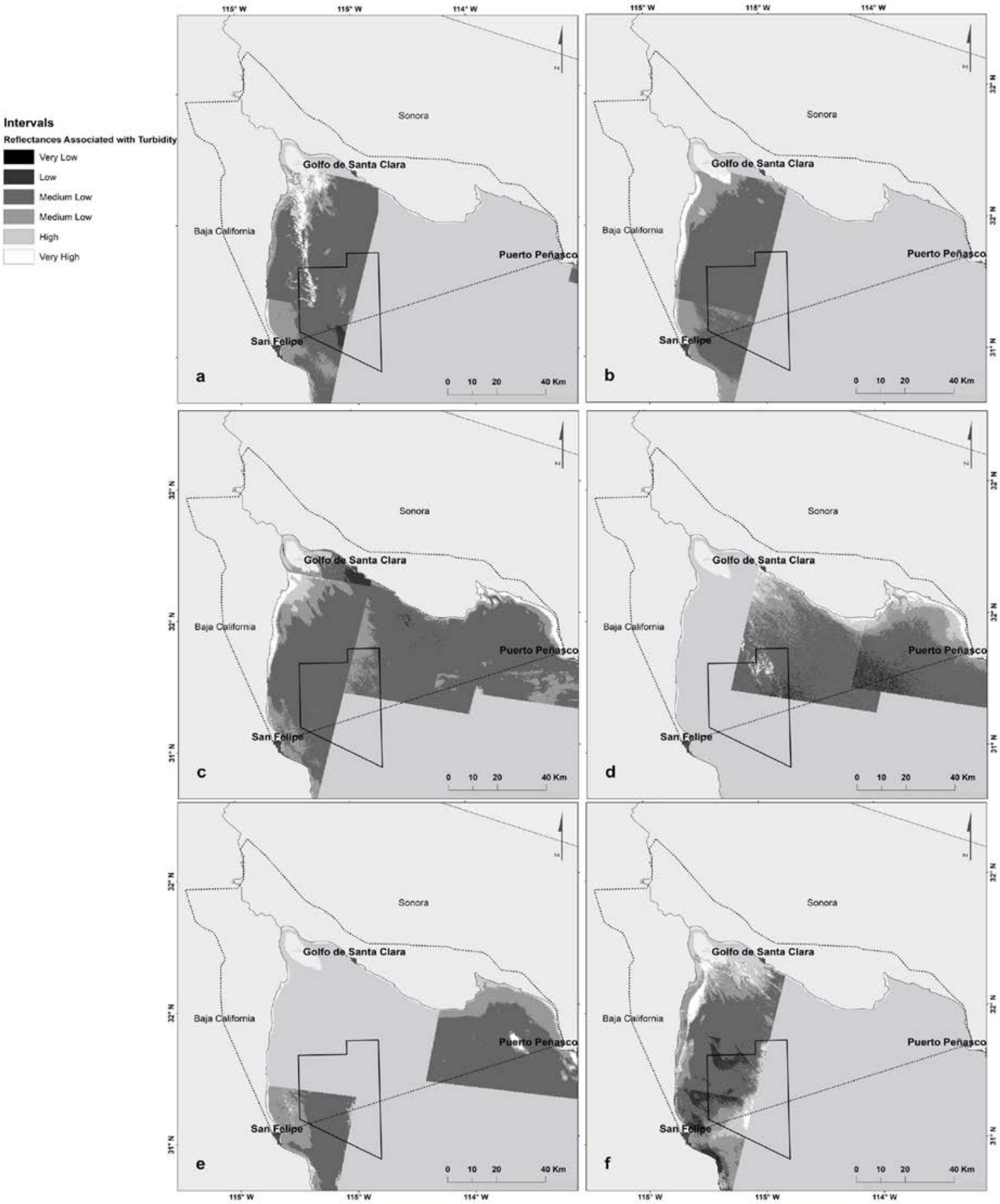


**Figure 3 UGC maps of turbidity for year 2011 in: a) cold season, spring tide in flow, b) cold season, neap tide in ebb flow, c) cold season, neap tide in flow, d) warm season, neap tide in flow, e) warm season, neap tide in ebb flow and f) warm season, spring tide in flow. The Biosphere Reserve area and the Vaquita marina refuge polygons are depicted**

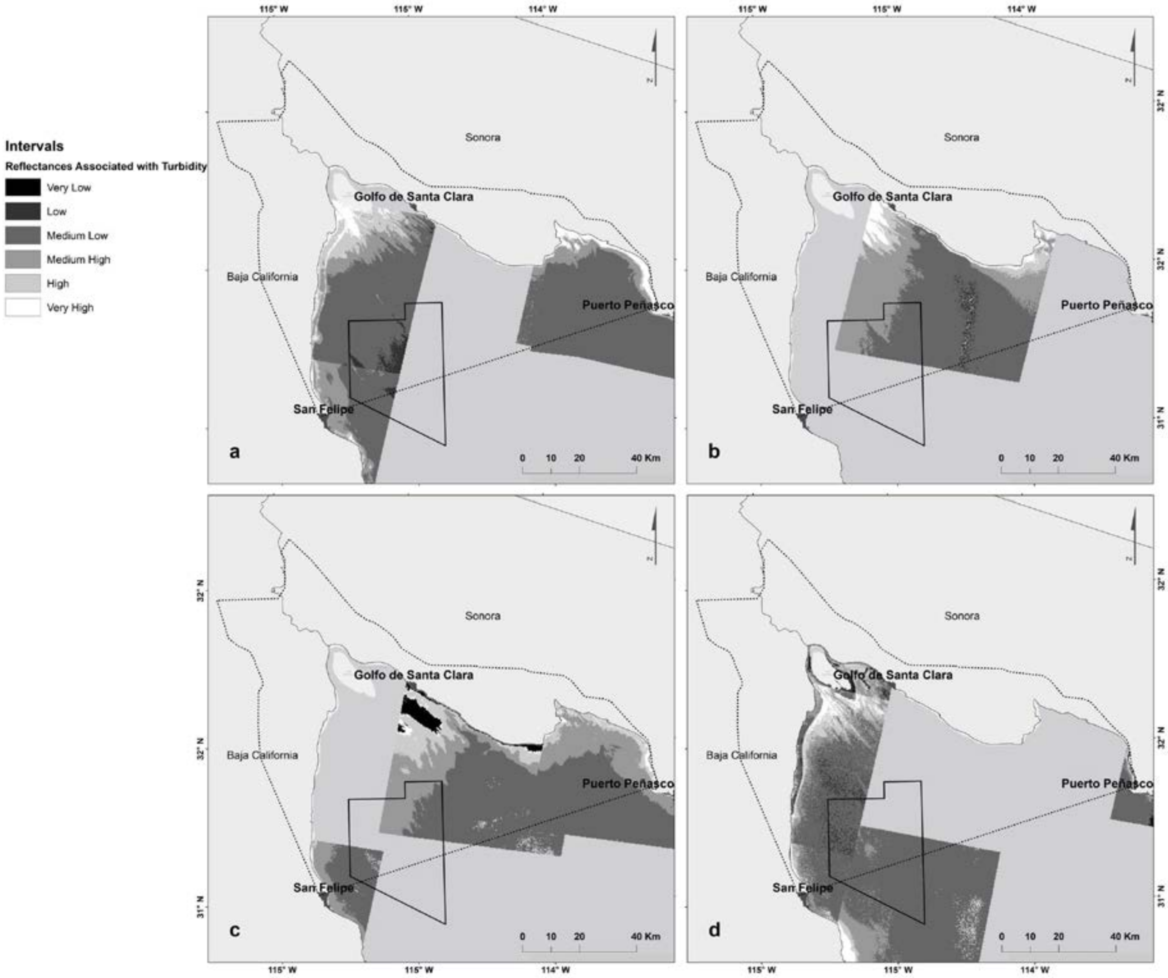


**Figure 4 UGC maps of turbidity for year 2012 in: a) cold season, spring tide in flow, b) cold season, neap tide in flow, c) cold season, neap tide in ebb flow and d) warm season, spring tide in flow. The Biosphere Reserve area and the Vaquita marina refuge polygons are depicted**

Higher reflectance values, and thus higher turbidity, were observed near the coast in the intertidal zone for all the conditions analyzed. More analysis is being done to study other variables such as precipitation, river flow and wind to better interpret the different scenarios. In 2011, a higher influence of the Colorado River was observed during the cold season, in spring tide and flow conditions (Figure 3a). Under other scenarios the high reflectances area was parallel to the Baja California coast (Figure 3b and c), but under these conditions the high turbidity plume gets into the Vaquita marina refuge. Unfortunately, the refuge polygon was not covered by SPOT images in all the scenarios analyzed. However, the variability represented during the period 2010 to 2012 is high, and it suggests that tidal conditions are not enough to explain it.

**Acknowledgments:** The Consejo Nacional de Ciencia y Tecnología (CONACYT, Mexico) provided funding through a PhD scholarship to Jesús-Antonio Aguilar-Maldonado (grant 251025). The Generalitat Valenciana (Spain) provided funding through a scholarship for research staff to María-Teresa Sebastiá-Frasquet (BEST/2017/217)

**Author Contributions:** Jesús A. Aguilar-Maldonado carried out the tests and analyzes developed in the article, and drafted the text of the article. Eduardo Santamaria-del-Ángel provided the data and resources of his research group. Maria-Teresa Sebastiá-Frasquet, organized the text, compiled and wrote data, and formulated new ideas for this article, it was also fundamental in the writing and correction of English.

**Conflicts of Interest:** The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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