Earth-Science Reviews 164 (2017) 1–30

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Invited review

Colorado River flow and biological productivity in the Northern Gulf of California, Mexico

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ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 18 October 2016
Accepted 30 October 2016
Available online 16 November 2016

Keywords:
Gulf of California
Biological oceanography
Fisheries
Colorado River Delta
Vaquita
Totoaba
Gulf corvina
Shrimp

ABSTRACT

A review of published research indicates that the Northern Gulf of California is, historically and currently, one of the most biologically productive marine regions on Earth. This high productivity is driven by a unique mix of factors, including: coastal upwelling, wind-driven mixing, extreme tidal mixing and turbulence, thermohaline circulation that moves intermediate waters into the mixed layer, coastal-trapped waves, regular sediment resuspension, and, to a lesser extent, agricultural runoff, released nutrients from erosion of ancient Colorado River Delta sediments, and perhaps input from decomposing tidal-flat plant debris. It has been suggested that decreased Colorado River flow, due to anthropogenic water impoundments and diversions, has had a negative impact on the health of the Northern Gulf of California ecosystem, particularly by reducing primary productivity and/or stock production of finfish and shellfish. However, there is no evidence that surface flow from the Colorado River is now, nor has ever been an important driver of primary productivity in the Northern Gulf, and nutrient/chlorophyll studies show no relationship to Colorado River flow (or, if anything, reduced nutrient/chlorophyll levels occur during high river-flow periods). And, there is very limited and equivocal evidence to support the claim that reduced river flow has significantly impacted secondary productivity in the Northern Gulf. The marine ecosystem of the Northern Gulf remains rich in nutrients, high in biodiversity and productivity, and appears to continue to be healthy, except for the impacts of historical and current fisheries. Human extraction of shrimp, Gulf corvina, totoaba (largely illegally), and other marine resources, remain very high in this region. There also is no evidence that reduced Colorado River flow has negatively impacted the health of the critically endangered vaquita porpoise, and assertions that it has done so deflect attention from the actual cause of decline—bycatch in legal and illegal gillnet fisheries. A review of Colorado River Delta research confirms that, historically and perhaps as long as the river has reached the Gulf of California, there have been long periods of no flow, or greatly reduced flow to the sea. Thus, the ecosystem is historically adapted to broadly fluctuating river flows and elevated salinities. Although commonly used by recent researchers, measurements of Colorado River water crossing the border into Mexico do not provide a reliable proxy for how much water (if any) actually reaches the Upper Gulf because of the complex nature of internal basins and diversions in the region.

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http://dx.doi.org/10.1016/j.earscirev.2016.10.012

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1. Introduction

The ~60,000 km^2 Northern Gulf of California has long been recognized as a diverse and highly productive ecosystem supporting some of the most important fisheries in Mexico. Despite claims to the contrary, we argue that available evidence does not indicate that the overall level of productivity has diminished significantly due to anthropogenic-driven reduction of freshwater input from the Colorado River.

Ecologists commonly define the Upper Gulf of California as that part of the Northern Gulf north of a line drawn between Puerto Peñasco (Sonora) and San Felipe (Baja California)—corresponding to the Upper Gulf of California and Colorado River Delta Biosphere Reserve (Reserva de la Biósfera del Alto Golfo de California y Delta del Río Colorado) (Brusca et al., 2005; Hendrickx et al., 2005; Brusca, 2007; Hendrickx and Brusca, 2007; Lluch-Cota et al., 2007; see Fig. 1). Oceanographically, it has been suggested that the southern limit of the Upper Gulf can be defined as the region where the vertically well-mixed regime of the water column transitions into stratified conditions; this occurs at ~30-m depth in summer and at ~60-m depth in winter. Or, it may be defined as the latitude of the deeper Wagner Basin (whose overlying waters are stratified year-round). Geographically, these delimitations differ little from one another. In addition to the biosphere reserve designation (which is also part of a UNESCO World Heritage Site that includes about 5% of the area of the Gulf), much of the lower Colorado River Delta is designated a Ramsar Site (Convention on Wetlands of International Importance), an Important Bird Conservation Area (Audubon Society), and a component of the Western Hemispheric Shorebird Reserve Network.

This review is divided into four principal parts. The first part provides an oceanographic overview of the Northern Gulf of California (Midriff Islands northward to the Colorado River Delta), which includes the Upper Gulf region (Fig. 1). Hundreds of papers have been published on the oceanography of the Gulf of California, and evidence consistently indicates that primary productivity remains high and has not been significantly affected by changes in Colorado River flow and that it is instead driven primarily by nutrient input and mixing from a variety of other sources.

The next section of this paper critically reviews published work that has made a case for reduction in shrimp, finfish and vaquita (*Phocoena sinus*) population size and production due to diminished Colorado River flow. We find that the interpretations and conclusions of that body of work frequently over-extend the actual data and that the underlying assumptions are often questionable. We conclude that there is no, or only equivocal, support for a hypothesis of significantly reduced secondary productivity in the Northern Gulf due to reduced river flow.

The next section provides a brief overview of water flow and distribution across the Colorado River Delta. We agree with many others that much of the Colorado River surface water that historically reached the U.S.-Mexico border was diverted or impounded before ever reaching the Gulf of California, and that many assumptions of surface flow into the Northern Gulf based on measurements below Imperial Dam or at the Southerly International Boundary (SIB) gauging station have probably been far too high. Overall, the marine fauna of the Northern Gulf appears to be highly adapted to a long history of fluctuating (and even absent) Colorado River flows and elevated salinities, at least throughout the Holocene. The final section is a summary of our conclusions and suggestions for future research directions.

2. An overview of Northern Gulf of California oceanography and primary productivity

> "Thus in both inner and outer regions of the Gulf the hydrographical features are conducive to high productivity. These two conditions, upwelling of the outer basin and convection in the inner basin [of the Northern Gulf of California], can fully account for the fertility of the Gulf without the necessity of considering the effect of the Colorado River."
>
> [Gilbert and Allen (1943), based on the first comprehensive study of productivity in the Upper Gulf of California]

The Gulf of California is the only semi-enclosed sea in the Eastern Pacific, and it maintains a high net evaporation rate. Bray (1988) estimated the total annual evaporation for the entire Gulf to be 0.95 m yr^{-1}, Lavín and Organista (1988) estimated the evaporation rate for the Northern Gulf at 0.9 m yr^{-1}, and Lavín et al. (1998) estimated an evaporation rate in the Upper Gulf of 1.1 m yr^{-1}. Annual net evaporation - precipitation - runoff has been estimated at 0.61 m yr^{-1} over the entire Gulf (Beron-Vera and Ripa, 2000). Average annual rainfall in the Northern Gulf is only ~68 mm yr^{-1} and is highly variable (Miranda-Reyes et al., 1990). Unlike some other semi-enclosed seas (e.g., Mediterranean Sea, Red Sea) where tidal mixing is not significant, the Gulf gains heat on an annual average, and it has long been recognized as the only evaporative basin in the Pacific Ocean (Roden, 1958, 1964; Bray, 1988; Lluch-Cota et al., 2007; Paden et al., 1991). Because of heat gain and evaporation, salinities in the Gulf have always been higher than in the adjacent Pacific at the same latitude. In coastal wetlands (*esteros*, or negative estuaries) of the shallow Northern Gulf salinities are even higher. Thus, the flora and fauna of the Gulf, particularly the Northern Gulf, have long been adapted to life at high salinities.

Surface salinity at the mouth of the Colorado River (around the large tidal mud/sand islands of Montague and Pelícano) averages about 38‰, and increases to the northwest, with a seasonal maximum of ~39‰ in August, and a minimum of ~37‰ in December–March (Álvarez-Borrego and Galindo-Bect, 1974; Álvarez-Borrego et al., 1975; Bray and Robles, 1991; Lavín et al., 1995, 1998; Lavín and Sánchez, 1999; Álvarez-Borrego, 2001; Lavín and Marinone, 2003). Álvarez-Borrego and Schwartzlose (1979) used March 1973 data to describe a winter convection with high salinity and low temperature water moving close to the bottom from the Upper Gulf southward to near Ángel de la Guarda Island, reaching depths of >200 m and characterized by high dissolved oxygen. Cintra-Buenrostro et al. (2012) used oxygen isotopes in the shells of the clam *Mulinia modesta* (cited as *Mulinia coloradoensis*, a junior synonym) to estimate salinities prior to the construction of dams on the Colorado River and found that it might have ranged from as low as 22–33‰ at the river's mouth (Montague Island) to 30–38‰ 40 km southward down the Baja California coast, suggesting at least a periodic, localized river dilution effect.

Surface waters in the Gulf change in response to seasonal (i.e., monsoonal) and long-term (i.e., El Niño-Southern Oscillation, ENSO) climatic events (Kahru et al., 2004; Lluch-Cota et al., 2007). Predominately northerly winter winds are replaced at the onset of the summer monsoon season (variously called the "Mexican monsoon," "North American monsoon," and "Southwest monsoon") with southerly winds that, in the Northern Gulf, create an along-Gulf flow (Bordoni and