

# Pollutant export under a new regime of continuous transboundary sewage flow in the Tijuana River

**Alexandra Grant**

San Diego State University

**Trent Biggs**

San Diego State University

**Daniel Sousa**

San Diego State University

**Matthew E. Verbyla**

San Diego State University

**Stephany Garcia**

Tijuana River National Estuarine Research Reserve

**Sneha Korat**

San Diego State University

**Alina Alex**

San Diego State University

**Elise Piazza**

San Diego State University

**Jeffrey Crooks**

Tijuana River National Estuarine Research Reserve

**Douglas Liden**

Institute of the Americas

**Yongping Yuan**

United States Environmental Protection Agency-Office of Chemical Safety and Pollution Prevention

**Natalie Mladenov**

[nmladenov@sdsu.edu](mailto:nmladenov@sdsu.edu)

San Diego State University

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## Abstract

Transboundary rivers worldwide face escalating wastewater pollution, highlighting the need for multinational monitoring and mitigation. The Tijuana River, shared by Mexico and the United States, is contaminated by untreated sewage, industrial waste, trash, and polluted runoff. In December of 2022, damaged wastewater infrastructure and wet weather shifted transboundary flow from intermittent to perennial. Average dry-weather transboundary flows increased from  $3.18 \times 10^4 \text{ m}^3/\text{day}$  during water years (WYs) 2021–2022 to  $19.1 \times 10^4 \text{ m}^3/\text{day}$  for WYs 2023–2024, a 6.3-fold increase. To evaluate the effects of the altered flow regime on pollutant export, over 280 water samples were analyzed for chemical constituents and fecal indicator bacteria. Chronic cross-border flows increased pollutant loading to the Pacific Ocean by an order of magnitude, with annual exports of  $\sim 1.06$  million kg of total dissolved nitrogen (TDN) and 1.15 million kg of dissolved organic carbon (DOC). Chronic dry weather flows averaged  $7.8 \times 10^6 \text{ MPN}/100\text{mL}$  for *Escherichia coli*, equivalent to untreated wastewater, and resulted in continuous beach closures since 2023. Under this continuous transboundary flow regime, dry-weather baseflow had significantly ( $p < 0.01$ ) higher DOC, TDN, and tryptophan-like fluorescence than wet-weather, storm-driven runoff. Attenuation of chemical constituents, microbial source tracking markers, and enteric virus pathogens across the  $\sim 12 \text{ km}$  from border to ocean was essentially absent, likely due to limited photodegradation in highly colored water. These findings establish a baseline for evaluating infrastructure investments, reducing public health and ecosystem risks, and supporting sustained binational monitoring and data sharing.

## 1. INTRODUCTION

Worldwide, 286 transboundary river basins span across 151 countries, and over 70% of those basins suffer from inadequate wastewater treatment (UNEP-DHI and UNEP, 2016). Managing water quality across transboundary basins is made more complex by the additional need for intercountry coordination and agreements compared to basins contained within just one country. ‘Business-as-usual’ projections indicate that pollution and other risks to transboundary waterways are expected to increase in the next 15–30 years with a changing climate, socioeconomic development, and increasing human populations (UNEP-DHI and UNEP, 2016). The Tijuana River is a transboundary river in Mexico (MX) and the United States (U.S.), within the traditional lands of the Kumeyaay people. The Tijuana River has experienced severe pollution from untreated wastewater discharges, resulting from deteriorating and inadequate infrastructure in both MX and the U.S. (California Regional Water Quality Control Board San Diego Region [San Diego Regional Water Board], 2025a).

Tijuana’s wastewater infrastructure maintenance and capacity have not kept pace with its rapid population growth, resulting in wastewater discharges to the Tijuana River from pipeline breaks, aging wastewater treatment systems, poorly maintained manholes and canyon collectors, lack of stormwater drainage systems, and homes without plumbing (EPA, 2024b). Tijuana’s Public Water Commission (CESPT) operates 13 wastewater treatment plants (WWTPs) and the private company SUEZ operates 3 WWTPs throughout Tijuana and Rosarito for a combined population of over two million (Arreola-Serrano et al., 2022). Notably, the San Antonio de los Buenos WWTP (SAB) has the largest capacity of the WWTPs in Tijuana ( $8.2 \times 10^4 \text{ m}^3/\text{day}$  or 18 MGD) but was nonoperational from 2020 to 2025 (North American Development Bank, 2020; San Diego Regional Water Board, 2025a). The network of pumps, collectors, and sewer lines designed to route the city’s wastewater to treatment plants is frequently inundated or inoperable, leading to discharges into the Tijuana River and the Pacific Ocean (International Boundary and Water Commission, 2017). The U.S. International Boundary Water Commission (IBWC)-operated South Bay International Water Treatment Plant (SBIWTP) is meant to receive wastewater flows (up to  $11.4 \times 10^4 \text{ m}^3/\text{day}$  or 25 MGD) that might otherwise flow by gravity into the Tijuana River, but is frequently overwhelmed due to insufficient capacity, aging components, maintenance challenges, and damage from extreme events like Hurricane Hilary (U.S. Environmental Protection Agency, 2024). On 28 December 2022, discharge in the Tijuana River at the international border (IBWC site; Fig. 1) transitioned from an intermittent (seasonally dry) to a perennial flow regime due to a significant increase in dry-weather flow, producing some of the most severe estuarine pollution conditions on record (IBWC, 2020).

The resulting pollution has negatively impacted coastal residents in Tijuana, San Diego, San Ysidro, Imperial Beach, and Coronado. It has also caused detrimental effects on ecosystems within the Tijuana River Estuary (TRE), the largest remaining coastal wetland in southern California (TRNERR, 2024). Human derived pathogens are of particular concern to public health; high fecal indicator bacteria (FIB) concentrations along the Imperial Beach coastline have triggered more than 1,000 continuous days of beach closure from 2023–2025 (California State Water Resources Control Board, 2024). Polluted cross-border flows have been associated with infections and illnesses, including among beachgoers and Navy SEAL trainees (Feddersen et al., 2020; U.S. Department of Defense, 2025) and made conditions unsafe for biologists to conduct in-water surveys (Murga, 2024). In 2024, Tijuana River odors and air pollutants were reported to have adverse health impacts on most Imperial Beach households (CDC, 2024). For thousands of years, Indigenous communities including the Kumeyaay fished in and gathered food resources from the TRE (Safran et al., 2017), but now sewage-derived contamination has led to conditions that threaten safe harvest and consumption of aquatic organisms. Indeed, a 2023 ecological survey revealed that, out of four Southern California wetlands, the TRE had the highest average for sequential hours of hypoxia and had the lowest density and diversity of fish species (Beheshti et al., 2024). There are critical knowledge gaps regarding the pollution magnitude under this new perennial flow regime, which hinders the development of effective multinational contamination management strategies.

Prior studies of the Tijuana River have identified a host of compounds and microbes known to negatively affect human and ecological health. Metagenomic analysis of microbes in water samples from the Tijuana River detected genetic material from dozens of disease-causing pathogens, including HIV-1, SARS-CoV-2, *Salmonella enterica*, *Neisseria meningitidis*, and *Mycobacterium tuberculosis* (Allsing et al., 2022; Rocha et al., 2022). Non-targeted chemical analysis identified compounds in the Tijuana River with high known levels of toxicity, persistence, and bioaccumulation such as triphenyl phosphate (Laughery, 2023), a carcinogenic, endocrine disrupting organophosphate found in flame retardants and plasticizers (U.S. Environmental Protection Agency, 2025). Marine debris and microplastics are abundant in the Tijuana River (Piñon-Colin et al., 2024), which can clog pumps, degrade wildlife habitat, and leach chemicals such as Di(2-ethylhexyl) phthalate, a chemical included on California’s Proposition 65 list for its potential to cause cancer and reproductive harm (IBWC, 2020; Office of Environmental Health Hazard Assessment, 2003). These studies have examined Tijuana River samples for the presence or absence of the above pollutants, but have not established a baseline from which pollution status could be compared over time.

To characterize wastewater influence and pollution dynamics in the Tijuana River, we measured a suite of chemical, physical, optical, and biological surrogate markers for anthropogenic contamination (Crittenden et al., 2012; Lacalamita et al., 2024), including chemical oxygen demand (COD), dissolved organic carbon (DOC), and total dissolved nitrogen (TDN), optical measurements of chromophoric dissolved organic matter (CDOM) and tryptophan-like fluorescence (TRP), which provide sensitive proxies for dissolved organic matter and amino-acid-rich compounds that correlate with wastewater concentrations (Hudson et al., 2007; Mendoza et al., 2020), and fecal indicator bacteria (FIB; including total coliforms, *E. coli*, and enterococci), and other microbial markers associated with public health risk. These parameters were chosen for this baseline analysis due to their simpler measurement protocols compared to concentrations of specific organic or inorganic compounds that may require more advanced techniques.

The objectives of this study are to 1) analyze and present chemical and FIB monitoring data in the Tijuana River downstream of the US-Mexico border, 2) apply statistical hydrologic analyses to document the flow shift from an intermittent to perennial flow regime in the Tijuana River after December 2022, 3) compare wet-weather and dry-weather concentrations of chemical and microbial wastewater indicators to one another and to untreated wastewater; and 4) apply concentration and flow data to estimate dry-weather loads delivered to the TRE and Pacific Ocean. Our results establish a critical baseline for Tijuana River pollutant concentrations and loadings to the TRE and Pacific Ocean during two years of chronic, cross-border polluted river flow. This “existing water quality baseline” provides information for binational water management, and it can be utilized to assess the effectiveness of future binational infrastructure investments and other efforts seeking to improve water quality in this high-profile river system.

## 2. MATERIALS AND METHODS

### 2.1 Study area and sample collection

#### 2.1.1 Tijuana River

The Tijuana River Watershed covers 4,533 km<sup>2</sup>, one-fourth of which lies in the U.S. and three-fourths of which lies in Mexico (TRNERR, 2024). Dams impound more than 75% of the upper watershed; the contributing watershed drains both sides of the border and is heavily urbanized (Biggs et al., 2022). The Tijuana River is channelized through Tijuana and transitions to largely free-flowing riverbed and estuarine morphology with some flood control infrastructure in the United States (Fig. 1).

Grab samples were collected across sixteen sampling events (from 6 September 2023 to 23 April 2025) at sites throughout the Tijuana River and Estuary and from the South Bay International Wastewater Treatment Plant (Fig. 1), with a total of 280 distinct grab samples collected. Collection methods are described in the Text S1. Table S1 lists sampling locations and distances downstream of the border and Table S2 provides dates, locations, hydrological season, and number of samples collected per event. Untreated wastewater (influent) from the South Bay International Wastewater Treatment Plant (SBIWTP) was also regularly sampled, and collection methods are described in Text S2.

Synoptic sampling occurred on 30 April 2024, with samples collected along the ~ 14 km stretch of the Tijuana River from the border to the coast between 8:15 and 11:30 in the morning. Samples were stored on ice and immediately transported back to the laboratory for same-day analyses or preservation as described for other grab samples of this study (Text S3). Three sites along the Tijuana River were also sampled on a second date, 23 April 2025, between 8:30 and 10:45.

### 2.2 Discharge and Precipitation Data

Data on transboundary discharge in the Tijuana River were obtained from the IBWC Tijuana River Gage (#11013300) near the border, with the data publicly available through the Tijuana River Basin Dashboard (IBWC, 2024). Precipitation data were collected from the National Oceanic and Atmospheric Administration's (NOAA) San Diego, Brown Field Municipal Airport gage. Multiple rain gages would be needed to quantify rainfall over the watershed; our goal here was to identify dry periods with no rainfall using the closest available gage.

### 2.3 Chemical and spectroscopic analyses

All samples were analyzed for electrical conductivity, total dissolved solids, salinity and pH with handheld meters or benchtop instruments. Samples were also analyzed for chemical oxygen demand (COD) using Hach Method TNT 822, dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) using high temperature oxidation with a Shimadzu TOC-L Analyzer. Detailed methods and quality control protocols are described in Text S3.

UV-vis absorbance and three-dimensional excitation emission fluorescence spectra were acquired on filtered water samples with a Horiba Scientific Aqualog Benchtop Fluorometer. Fluorescence intensities were measured for tryptophan-like fluorescence (TRP) with an excitation (ex) and emission (em) peak at ex 280 nm/em 350 nm, which correlate with sewage-derived *E. coli* and other fecal indicator bacteria (Baker et al., 2015; Mladenov et al., 2024b), and chromophoric dissolved organic matter (CDOM) fluorescence with a peak at ex 325 nm/em 470 nm, associated with humic like substances derived from natural and human waste sources (Hudson et al., 2007; Mendoza et al., 2020). Detailed correction protocols and other methods are described in Text S4.

### 2.4 Microbiological analyses

Total coliforms and *Escherichia coli* (*E. coli*) concentrations were quantified using the IDEXX Colilert-18 method, and enterococci concentrations were quantified using the Enterolert method, as described in Mladenov et al. (2024a) and detailed in Text S5. For samples collected on 30 April 2024, additional analyses of HF183/BacR287, human adenovirus type 40/41 (HAdV), pepper mild mottle virus (PMMoV), and norovirus genogroup II (NoVGII) were conducted (reactions performed in duplicate, and internal amplification controls resulted in non-detects). Detailed protocols are described in the Supplemental Methods, and standard curve efficiencies are reported in Table S3. In brief, sample DNA was analyzed for HF183/BacR287 and human adenovirus type 40/41 (HAdV) via quantitative polymerase chain reaction (qPCR) following previously published assays (Green et al., 2014; Jothikumar et al., 2005); and sample RNA was

analyzed for pepper mild mottle virus (PMMoV) and norovirus genogroup II (NoVGII) via qPCR with reverse transcription (RT-qPCR) following previously published assays (Butot et al., 2010; Haramoto et al., 2013).

## 2.5 Photodegradation and biodegradation experiments

Two exposure experiments were conducted to evaluate the effects of photoirradiation, dark (biodegradation) conditions, and mixing on DOC, TDN, TRP and CDOM fluorescence and total coliforms, *E. coli*, and enterococci concentrations in 100% wastewater from the SBIWTP and a solution of 20% wastewater (SBIWTP) and 80% lake water (Lake Morena, San Diego in the Tijuana River watershed) over a 24-hour period. The experimental setups and detailed protocols are described in Text S6.

## 2.6 Precipitation and discharge analyses

Data analysis and creation of figures for the precipitation, discharge, and flow duration curve analyses was performed using R version 4.5.3,2 (R Core Team, 2026), the open-source programming language, and RStudio Desktop (Posit Team, 2026), an integrated development environment application for R. Linear regression and Mann-Kendall tests were used in R to test significance between parameters (regression) and temporal trends (Mann-Kendall). Daily discharge was divided by daily precipitation to provide daily Q/P data from 2020–2025. Runoff depth (mm) was derived using the IBWC gauge daily discharge values and normalizing by watershed area. The resulting dimensionless ratio represents the fraction of precipitation converted to runoff.

## 2.7 Wet-weather, dry-weather, and wastewater water quality comparisons

Days with > 2.54 mm (0.1 inch) of total daily precipitation were labeled as “wet weather”, consistent with other hydrological studies and regulatory guidelines to filter out trace, non-runoff-producing precipitation like fog, dew, or mist (City of San Diego, 2018; Hathaway et al., 2010). The three days following a date with > 2.54 mm precipitation were classified as “wet weather” according to EPA guidelines to account for delayed runoff or infiltration from previous storms (SDRWQCB, 2013). We acknowledge that other studies (Liden and Giner, 2026) utilize a 14-day recovery period following rain events in the calculation of days per year with wet-weather. Kruskal-Wallis tests were used to evaluate significance of differences in water quality parameters among wet-weather, dry-weather, and untreated wastewater conditions. Description of additional statistical tests for comparisons and to evaluate significance of downstream water quality changes is found in Text S7.

## 2.9 Dry-weather loading estimation

Dry-weather pollutant loads were estimated by pairing instantaneous flow measurements with corresponding water quality concentrations to calculate volume-weighted mean (VWM) concentrations for each sampling event consistent with prior publications (Arreola-Serrano et al., 2022; Gómez-Gutiérrez, et al., 2006; Stein & Ackerman, 2007). VWM concentrations were averaged by water year (WY) and combined with the mean dry-weather discharge observed on days with transboundary flow (> 0 m<sup>3</sup>/day) to estimate mean daily loads. Parameters evaluated included COD, DOC, TDN, fluorescence metrics, microbial indicators, and TDS. Annual dry-weather loads were then calculated by scaling mean daily loads according to the proportion of days within each WY that experienced both dry-weather conditions and measurable flow, thereby accounting for the intermittent nature of transboundary discharge. Detailed methods and equations are provided in Text S8.

Water quality samples collected between 2023 and 2025 were also used to estimate loads for WY2021 and WY2022 by applying average concentrations from the sampled period to historical flow records. This approach assumes relatively stable pollutant concentrations across years and is supported by comparisons with historical monitoring data (IBWC, 2020).

# 3. RESULTS AND DISCUSSION

## 3.1 Hydrologic change and attribution

Average daily dry-weather flow at the IBWC stream gage (Table S4) increased from  $2.54 \times 10^4$  m<sup>3</sup>/day for WYs 2021–2022 (October 2020 to September 2022) to  $1.59 \times 10^4$  m<sup>3</sup>/day for WYs 2023–2024 (October 2022–September 2024), a 6.3-fold increase. Beginning on 28 December 2022, the Tijuana River entered a state of near-continuous daily flow across the border (Fig. 2). Prior to December 2022, no-flow conditions were common during the dry season (Table S5). Between 28 December 2022 and the last sampling event on 23 April 2025, only three days (23–25 July 2023) recorded zero flow (0 m<sup>3</sup>/day). Rather than subsiding with the onset of the dry season in May, as historically observed, the river exhibited record-high dry-season flow frequency and volume during WYs 2023–2024 (Tables S4).

The Mann-Kendall tests indicated no significant trend in precipitation but significant increases in discharge ( $p < 0.001$ ) and the runoff coefficient ( $p = 0.018$ ) over WYs 2021–2024 (Table S6). There was also a statistically significant ( $p < 0.001$ ) increase in dry-weather flow in the Tijuana River during this time.

Additional time series were plotted for WYs 2000–2024 (Figure S1) to examine if the 2020–2024 statistical findings coincided with a more long-term trend. Q and Q/P increased significantly over time while precipitation did not (Fig. 2; Table S6). Indeed, Mosase et al. (2019) describe the current climate conditions to be characterized by decreasing precipitation, at least from 1985 to 2017, rather than increasing precipitation.

Flow duration curves (Figure S2) indicate a substantial reduction in zero-flow days (0 m<sup>3</sup>/day), decreasing from 63% in WYs 2001–2020 to 59% in 2021–2022 and sharply to 9% in 2023–2024. This shift suggests that the Tijuana River became a more persistent source of contamination for downstream communities and estuarine ecosystems. Additionally, the reduced occurrence of dry periods may limit the estuary's natural capacity to recover between pollution events and diminish opportunities for dilution, potentially exacerbating the effects of continuous pollutant input. High-flow discharge (Q10), defined as the flow exceeded 10% of the time, varied across WYs in the Tijuana River Estuary. Q10 was ~ 215,000 m<sup>3</sup>/day for WY 2001–2020, decreased to ~ 177,000 m<sup>3</sup>/day in

WY 2021–2022, and increased sharply to ~ 586,000 m<sup>3</sup>/day in WY 2023–2024. These results indicate substantial interannual variability in high-flow events, with WY 2023–2024 exhibiting unusually large peak discharges likely driven by storm pulses or changes in upstream inputs.

Several key infrastructure failures coincided with the Tijuana River's December 2022 shift to constant perennial flow documented in the time series and flow duration curves. In December 2021, reports highlighted major deterioration of the International Collector, the wastewater pipeline in Mexico that intercepts Tijuana River flows and either sends them to Pump Station 1 (PB1) or to the South Bay International Wastewater Treatment Plant (San Diego Regional Water Board, 2022a). In July 2022, PB1 lost pumping capacity due to damage of its downstream pipelines, PB1A and PB1B (San Diego Regional Water Board, 2023). When PB1 fails or capacity is reduced, wastewater and intercepted river flow cannot be lifted and conveyed, and flows return to the Tijuana River channel or are diverted to the already overburdened SBIWTP. In addition, the PBCILA diversion structure is designed to intercept river flows only up to approximately 1 m<sup>3</sup>/s, limiting its effectiveness during elevated baseflow or storm conditions (San Diego Regional Water Board, 2022b). Finally, the largest treatment plant in Tijuana, San Antonio de los Buenos WWTP, went offline in 2020 (North American Development Bank, 2020). Together, these infrastructure failures, combined with seasonal precipitation, continuous wastewater discharges to the river, and constrained treatment capacity in Tijuana, resulted in sustained transboundary flows beginning in winter 2022.

## 3.2 Wet-Weather, Dry-Weather, and Wastewater Comparisons

Dry-weather Tijuana River samples had significantly higher DOC, TDN, and TRP than wet-weather Tijuana River samples ( $p < 0.01$ , unadjusted; Table S7). Compared to untreated wastewater, which varies in chemical quality from day to day and across seasons (see photos of SBIWTP water samples on different dates in Figure S3), dry-weather concentrations DOC, TDN, CDOM, TRP, and *E. coli* concentrations Tijuana River samples were not significantly different (Fig. 3). Biggs et al. (2025) also found inverse correlations between Tijuana River discharge and *E. coli* concentrations, suggesting that stormwater dilutes the highly contaminated baseflow. This finding contradicts the typical pattern reported in stormwater literature, where urban runoff is associated with elevated concentrations of sewage-related pollution in receiving waters (Olds et al., 2018; Pinongcos et al., 2022). Moreover, the absence of significant differences between dry-weather Tijuana River samples and untreated wastewater (Table S7) further supports the conclusion that the Tijuana River's baseflow during dry periods is heavily influenced by anthropogenic wastewater.

Although the differences between wet- and dry-weather concentrations of CDOM and *E. coli* were not significant (Table S7), mean concentrations were 38% and 122% higher, respectively, during dry-weather than during wet weather (Table S8). Comparable CDOM levels during wet weather may reflect additional terrestrial dissolved organic matter inputs from stormwater runoff, including soils, leaf litter, and vegetation. Similarly, the lack of a significant difference in *E. coli* may be attributable to suitable growth conditions for bacteria in concentrated wastewater during both wet and dry weather, similar environmental survival rates across hydrologic conditions, or faster travel times during wet weather leading to lower potential for die-off through environmental degradation (Rocha et al., 2022).

In terms of policy implications, dry-weather concentrations of fecal indicator bacteria, including  $6.7 \pm 0.8$  log-MPN/100 mL *E. coli*, and  $5.7 \pm 0.7$  log-MPN/100mL enterococci, greatly exceeded U.S. water quality objectives (Table S9). According to the California Regional Water Quality Control Board, San Diego Region (San Diego Regional Water Board) Basin Plan (2021), beneficial uses for the Tijuana River include non-contact water recreation and preservation of biological habitats of special significance. The fecal coliform objective for non-contact recreation is 2,000 organisms per 100 mL (3.3 log MPN/100 mL), consistent with Mexico's NOM-001-SEMARNAT-1996 standard. Observed *E. coli* concentrations exceeded this threshold by more than three orders of magnitude. The river ultimately discharges to the Tijuana River Estuary, designated for contact recreation with stricter standards (33 CFU/100 mL enterococci; 126 CFU/100 mL *E. coli*). Although MPN and CFU enumeration methods differ, these comparisons illustrate the exceptionally high fecal contamination present in the river.

Dry-weather concentrations of chemical and biological parameters (Table S8) were comparable to or greater than values reported during a 2019 IBWC monitoring campaign (Table S9) that measured COD, DOC, TDN, total coliforms, *E. coli*, and enterococci (IBWC, 2020). Current fecal indicator bacteria concentrations also exceeded those of Tijuana River dry-weather samples reported by Rocha et al. (2022) collected during intermittent flow conditions, from November 2020 to May 2021. Together, these comparisons highlight the persistence and potential intensification of chronic pollution in the Tijuana River, underscoring the need for continued mitigation and binational infrastructure investment. These results establish a current baseline for dry- and wet-weather water quality concentrations in the Tijuana River since the onset of the perennial flow regime, important to ongoing efforts for sewage plume detection with remote sensing (Scrivner et al., 2025) and modeling of Tijuana River pollution transport (Feddersen et al., 2020).

## 3.3 Spatial analysis

### 3.3.1 Concentration ranges of riverine pollutants

During the two longitudinal sampling events, dry-weather concentrations of COD (200–500 mg/L), *E. coli* ( $10^6$ – $10^7$  MPN/100 mL), and enterococci ( $10^5$ – $10^6$  MPN/100 mL) in the Tijuana River were typical of this sewage-derived river (Fig. 4 and Figure S4; Rocha et al., 2022). DOC and TDN concentrations were comparable to untreated wastewater from the SBIWTP (Fig. 3). Human-associated microbial markers HF183 and PMMoV generally ranged from  $10^3$  to  $10^4$  copies/mL (Fig. 4). Unlike untreated residential wastewater in San Diego, where HF183 is often an order of magnitude higher than PMMoV (Fani et al., 2024), HF183 concentrations in the Tijuana River were consistently lower than PMMoV, suggesting partially treated or aged wastewater. Similar HF183 levels have also been reported in partially treated wastewater in Tijuana (Thulsiraj et al., 2017). Also, fluorescence EEMs of Tijuana River samples were similar to treated effluent samples from the SBIWTP (Figure S5), which also supports some degree of environmental transformation compared to untreated wastewater.

### 3.3.2 Downstream trends

Although these single sampling events represent only a snapshot of water quality conditions, the lack of significant downstream decrease of all concentrations, except for COD, on both dates is notable. Under idealized plug flow conditions in a river system, some attenuation of pollutant concentrations is expected due to photodegradation, biodegradation, and other biogeochemical processes. However, only COD during the April 2024 event showed a significant negative relationship with distance ( $\beta = -19.49$ ,  $p = 0.034$ ,  $R^2 = 0.627$ ). By contrast, TDN ( $\beta = 0.593$ ,  $p = 0.016$ ,  $R^2 = 0.534$ ) and TRP ( $\beta = 12.42$ ,  $p = 0.026$ ,  $R^2 = 0.48$ ) increased significantly with distance. Viral concentrations (HAdV and NoV GII) did have approximately 0.7 log<sub>10</sub> lower concentrations at the Equestrian Trail site (8.35 km from the border) relative to upstream locations.

Dissolved organic carbon, CDOM, and FIB did not exhibit significant relationships with distance. Despite tidal dilution in the estuary (> 10 km), which did affect most constituents, PMMoV and HF183 concentrations at Boca Rio, Sand Bar, and the Tijuana River Mouth were not substantially lower than those measured upstream. Fluorescence EEMs also show no downstream decrease in intensity (Figure S5) their similarity to EEMs of treated effluent samples from the SBIWTP may indicate some transformation of organic constituents under environmental conditions, even if DOC mineralization was not underway.

There are several possible explanations for lack of pollutant decay with distance downstream. For one, sedimentation has substantially decreased the areal extent of the wetlands and tidal prism, decreasing the potential area for ecological pollutant removal to occur within the TRE (Biggs et al., 2022, Safran et al., 2017). Also, the enrichment of the Tijuana River in UV-absorbing and chromophoric compounds can shield contaminants, including pathogens, from sunlight and associated photochemical degradation (Williamson et al., 2017). Therefore, the highly colored river water, with UV<sub>254nm</sub> at 0.42 arbitrary units (AU) in 2024 and 0.72 AU in 2025 being well above values in natural, unpolluted streams (Volk et al., 2002; Izbicki et al., 2004), may have reduced the depth of the photic zone and the effect of photodegradation.

We further investigated how photodegradation affects constituents in 20% and 100% wastewater solutions by exposing stirred solutions to simulated sunlight and dark conditions (Supplemental Methods and Figures S6-S9). Results showed that within 8 h of photoirradiation, DOC and TDN concentrations of 100% wastewater solutions decreased by ~ 25%, fluorescence intensities (TRP and CDOM) decreased by more than 50%, and FIB experienced 3-log to 4-log removal (Fig. 5). In 20% wastewater solutions, sunlight exposure resulted in similar decreases of DOC, fluorescence, and FIB, but TDN remained constant (Figure S6). Based on these results, substantial attenuation of most chemical and microbial constituents would be expected during sunlight-exposed downstream transport. Even under dark conditions, which may be most representative of night-time transport, DOC, TDN, TRP, and CDOM all decreased substantially within 8 h (Fig. 5). Total coliforms, *E. coli*, and enterococci also decreased, although these changes were less apparent on a log scale. These findings suggest that dark conditions and a limited photic zone may partially explain the persistence of FIB; however, they do not explain the limited changes observed in chemical constituents.

Another explanation for the lack of constituent removal with distance downstream relates to the plug flow nature of the Tijuana River channel. Rocha et al. (2022) described a recurring nighttime discharge peak in the Tijuana River that they found to be consistent with the arrival of a pulse of wastewater generated earlier in the day in the City of Tijuana. Peak discharge at the US-Mexico border occurs nightly between ~ 19:00 and 21:00 and a water level peak is observed at the Hollister Bridge site ~ 4 hours later (Figure S10). Based on this travel-time progression and the distance involved, the travel time from the border to the river mouth under dry weather conditions is estimated to be ~ 12.4 h, placing the wastewater peak somewhere near the river mouth by 8:00. Therefore, it is conceivable that a more polluted (or less degraded) parcel of water could occur downstream of a less polluted parcel. Additional research, including 24 h temporal sampling, is needed to characterize the biological and chemical composition of the recurring daily peak in river discharge and better understand its downstream propagation.

### 3.4 Pollutant flux to Pacific Ocean

In the post-December 2022 hydrologic regime, both the magnitude and frequency of dry-weather flow increased, leading to increased loadings, compared to 2021–2022 estimates (Table 1). The average annual loading in the Tijuana River increased five-fold for all pollution indicators between WYs 2021–2022 (intermittent flow regime) and WYs 2023–2025 (perennial daily flow regime). Loads, not just concentrations, must be emphasized when evaluating the severity of pollution impacts, especially under altered flow regimes.

Table 1  
Comparison of annual dry-weather loading of constituents to the Pacific Ocean of WYs 2021–2022 to WYs 2023–2025.

| Water Quality Parameter | Units        | 2021–2022 Estimated    | 2023–2025 Calculated   |
|-------------------------|--------------|------------------------|------------------------|
|                         |              | Average Yearly Loading | Average Yearly Loading |
| COD                     | kg/year      | 2.22 × 10 <sup>6</sup> | 1.10 × 10 <sup>7</sup> |
| DOC                     | kg/year      | 2.32 × 10 <sup>5</sup> | 1.15 × 10 <sup>6</sup> |
| TDN                     | kg/year      | 2.12 × 10 <sup>5</sup> | 1.06 × 10 <sup>6</sup> |
| total coliforms         | log-MPN/year | 18.43                  | 19.12                  |
| <i>E. coli</i>          | log-MPN/year | 17.86                  | 18.56                  |
| enterococci             | log-MPN/year | 17.15                  | 17.84                  |
| TDS                     | kg/year      | 8.72 × 10 <sup>6</sup> | 4.34 × 10 <sup>7</sup> |

As a further comparison, Sutula et al. (2021) estimated that Southern San Diego rivers, including the Tijuana River, delivered an average of 9.11 × 10<sup>5</sup> kg/year of total nitrogen to the Pacific Ocean from 1997–2017. Our annual dry-weather load estimate (1.06 × 10<sup>6</sup> kg TDN/year) from the Tijuana River alone for WYs

2023–2025 exceeds the Sutula et al. 1997–2017 yearly estimate for all rivers in South San Diego by approximately 16%, highlighting the disproportionate influence of the Tijuana River as a nitrogen source to coastal waters, under a continuous cross-border flow regime.

These loading estimates have direct implications for pollution attribution and coastal pollutant transport models. Feddersen et al. (2020) modeled wastewater concentrations in the estuary and ocean for 2017 and identified San Antonio de los Buenos outfall at Punta Banderas (SAB) as the dominant source that leads to regional beach closures. However, the modelled period in Feddersen et al. (2020) occurred before the December 2022 step change in annual loadings to the ocean by the Tijuana River. Future work should simultaneously quantify coastal pollutant loadings in both the Tijuana River and the SAB outfall during perennial flow conditions to better understand the relative contributions of both sources and inform coastal pollution modeling efforts.

## 4. CONCLUSIONS

After 2023, the Tijuana River shifted from intermittent to continuous, cross-border sewage-dominated flow in the Tijuana River. This continuous flow has driven a five-fold increase in pollutant loading to the Pacific Ocean between WYs 2021–2022 and 2023–2024. Typically, estuaries have substantial capacity to buffer pollution through dilution, sedimentation, microbial degradation, and plant uptake (Davis et al., 2001; Kennish, 2002). However, sustained high volumes of wastewater-rich flow reduce the residence time of water in the estuary and limit the effectiveness of natural attenuation processes (Reddy & Delaune, 2008). In addition, the high concentrations of light-absorbing DOM may shield chemical and microbial pollutants from sunlight, reducing the opportunities for photochemical degradation of contaminants. As a result, the river transitions from functioning as a biogeochemical filter to acting primarily as a conduit, transporting pollutants directly to receiving coastal waters, underscoring the urgency of upstream interventions that reduce pollutant loads at the source.

The facts that dry-weather concentrations were significantly higher than wet-weather concentrations and were not significantly different from what is found in untreated wastewater, indicate that baseflow is more polluted than storm-driven runoff. The indicators measured in the present study serve as proxies for the specific wastewater-derived pathogenic microbes, toxic chemicals, and heavy metals previously detected in the Tijuana River through metagenomic sequencing and non-targeted chemical analysis, which may be challenging and time-intensive to measure. Given the substantial increase in overall pollutant loading we observed, it is reasonable to infer that the loadings of these previously detected contaminants have also increased to a similar degree, further elevating risks to human and ecosystem health. In particular, increases in microbial loading to the ocean may heighten the likelihood of acute exposure to pathogenic organisms by people using coastal waters for recreation. The results of this study should support binational efforts by the U.S. and Mexico to inform and prioritize infrastructure improvements, reduce contributing pollution sources, and protect public health in communities affected by the Tijuana River.

## Declarations

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## Credit authorship contribution statement

**Alexandra Grant:** Writing – original draft, conceptualization, formal analysis, investigation, project administration, supervision, visualization. **Trent Biggs:** Writing – review & editing, conceptualization, formal analysis, funding acquisition, methodology, project administration, supervision, visualization. **Daniel Sousa:** Writing – review & editing, conceptualization, funding acquisition, methodology, project administration, supervision. **Matthew Verbyla:** Writing – original draft, formal analysis, methodology, project administration, supervision, visualization. **Stephany Garcia:** Writing – review & editing, investigation, project administration, resources, supervision. **Alina Alex:** Formal analysis, investigation. **Sneha Korat:** Writing – review & editing, investigation, project administration, supervision. **Elise Piazza:** Writing – review & editing, investigation, project administration, supervision. **Jeffrey Crooks:** Writing – review & editing, funding acquisition, investigation, project administration, resources, supervision. **Douglas Liden:** Writing – review & editing, funding acquisition, investigation. **Yongping Yuan:** Writing – review & editing, funding acquisition, conceptualization. **Natalie Mladenov:** Writing – original draft, conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, visualization.

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## Data Availability

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## Figures



Figure 1

a) Map of Tijuana River and Estuary with major sampling sites and photos of b) Tijuana River as a natural channel at Saturn Blvd. in San Diego, USA, showing foam buildup on the water surface and riparian vegetation, and c) channelized portion of the Tijuana River in Tijuana, MX.

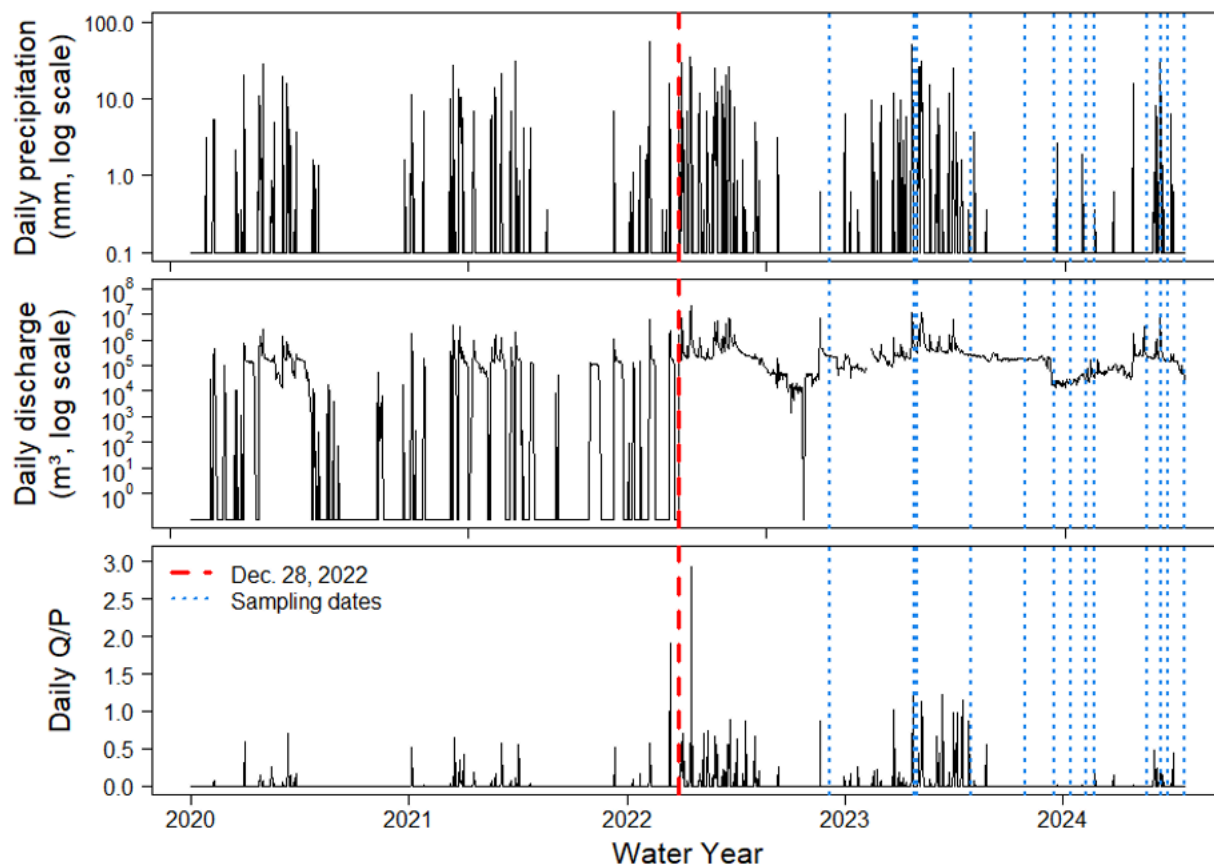


Figure 2

Daily precipitation, discharge, and runoff coefficient time series from 30 September 2021 to 23 April 2025. The red hashed line demarcates the shift from intermittent to perennial flow on 28 December 2022 and the blue hashed lines show sampling dates.

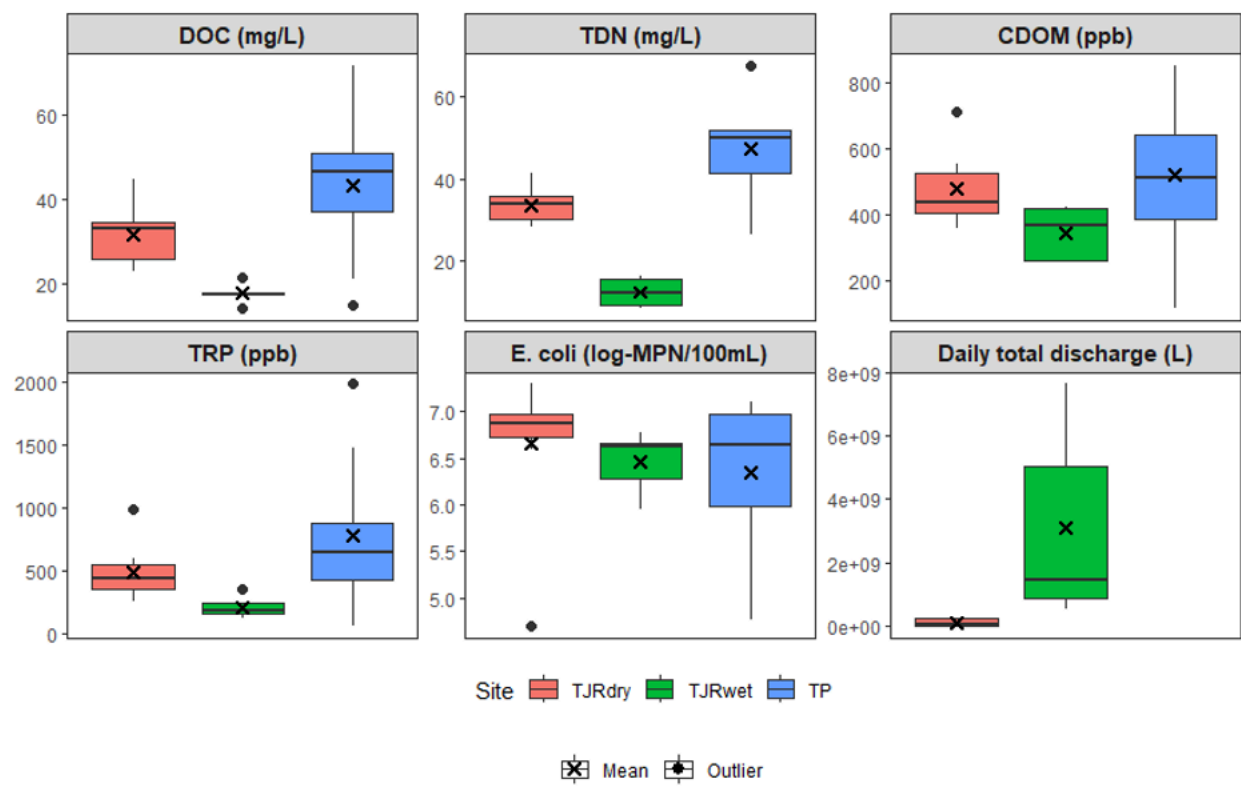


**Figure 3**

Concentrations of water quality parameters in the Tijuana River during wet weather (N = 5), dry weather (N = 9), and untreated wastewater from South Bay International Treatment Plant (TP) (N = 8). Average daily river discharge during wet- and dry-weather sampling periods is shown in the inset. Boxes represent interquartile ranges with medians shown as horizontal lines and means marked by 'X'. Whiskers denote minimum and maximum values, with points beyond representing outliers.

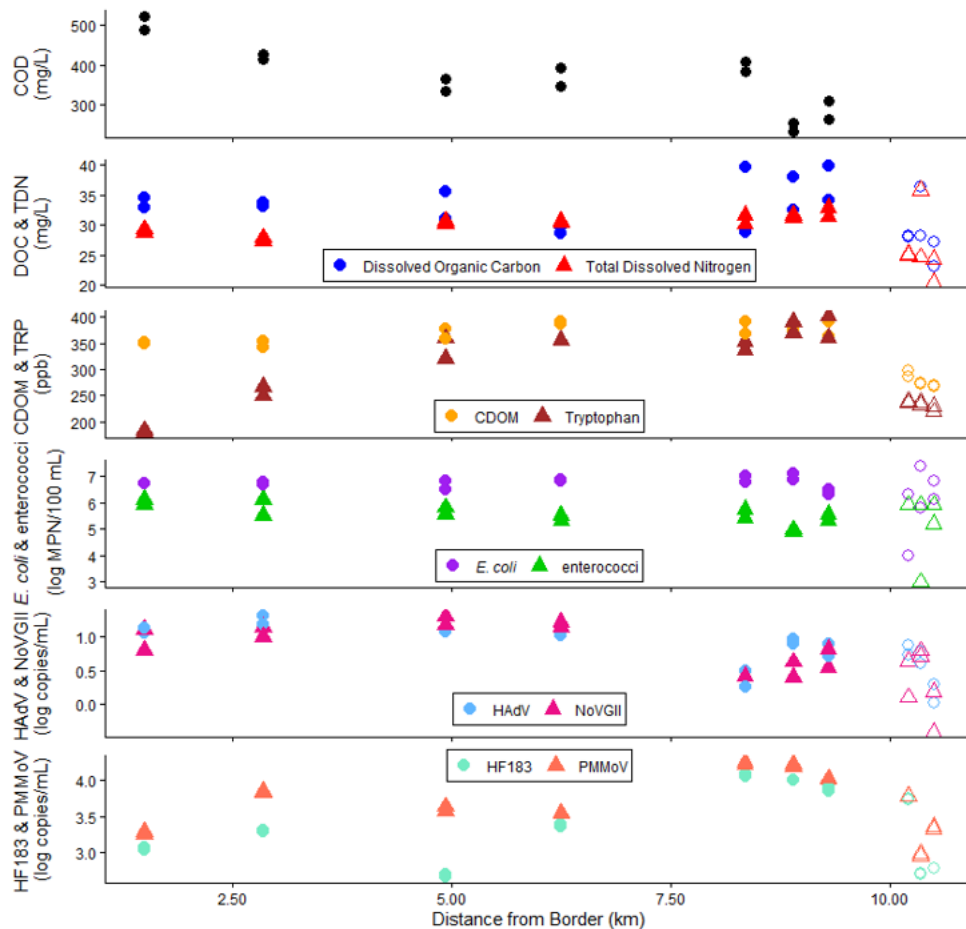


**Figure 4**

Spatial variability in chemical constituents (COD, DOC, and TDN), fluorescence surrogates (CDOM and TRP), microbial source tracking markers (*E. coli*, enterococci, HF183, and PMMoV), and enteric virus pathogens (HAdV and NoVGII) with distance from the U.S.-Mexico border for longitudinal sampling event on 30 April 2024. Duplicate sample results are shown. The empty markers designate estuary locations that are affected by tidal dilution from ocean and river mixing.

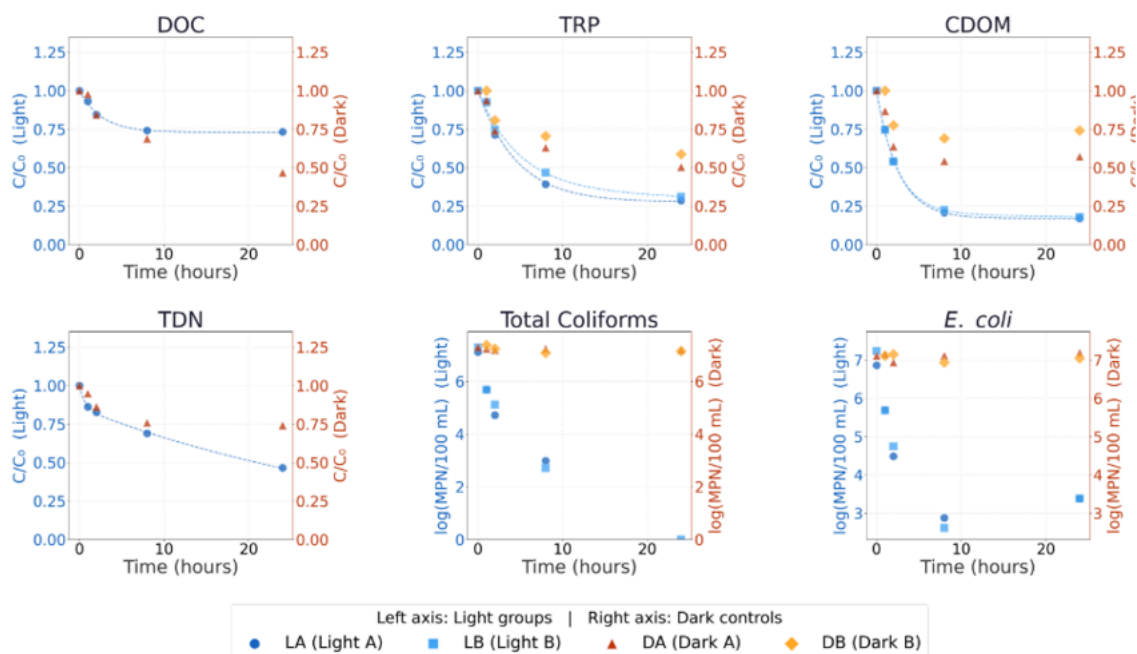


**Figure 5**

Change in DOC and TDN concentrations and fluorescence (CDOM and TRP) as a fraction of initial values, and changes in FIB log concentrations at each time point for solutions of 100% wastewater exposed to simulated sunlight (LA and LB) and dark (DA and DB) with continuous stirring. Decay curves shown only for photoirradiated (light) samples. Experimental results for 20% wastewater solutions and corresponding pH, conductivity, and turbidity shown in Figures S6-S9.

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [TJRPaperSupplementalfinal.docx](#)
- [VisualAbstract.png](#)