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Journal
San Francisco Estuary and Watershed Science, 8(3)

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Publication Date
2010

DOI
https://doi.org/10.15447/sfews.2010v8iss3art4

SEPTEMBER 2010

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

Change in Urban Land Use and Associated Attributes in the Upper San Francisco Estuary, 1990 to 2006

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ABSTRACT

Land use is an ultimate driver of many of the stressors on the Upper San Francisco Estuary, but the magnitude and pattern of land use change has not been analyzed. This paper attempts to fill this knowledge gap through a screening-level risk assessment. Urban land use was compared within hydrodynamic sub-regions in 1990, 2000, and 2006. Ancillary data were then used to quantify secondary measures such as impervious cover, housing density, road density and road crossings. Despite the rapid growth of the Bay Area, Sacramento, and Stockton metropolitan areas, the percentage of urban area and rates of change in the sub-regions are generally low to moderate when compared to other estuaries in the United States. The spatial data sets used in this analysis have been posted online to a public repository to be used by other researchers.

KEYWORDS

urban growth, geographic information systems (GIS), hydrodynamic sub-regions, housing density, road-stream crossings, impervious cover

INTRODUCTION

The physical, chemical, and biological conditions of the upper San Francisco Estuary (the Estuary) (Figure 1) have changed dramatically as a result of complex responses to land-use change, contaminants, and regulation of river flows for urban and agricultural uses (Sommer and others 2007). Concern over the effects of these changes on fish populations, water supply, and water quality has led to an extensive program of monitoring and research. Monitoring data collected by the Interagency Ecological Program (IEP) indicated that long-term declines in populations of delta smelt (*Hypomesus transpacificus*), longfin smelt (*Spirinchus thaleichthys*), age-0 striped bass (*Morone saxatilis*), and threadfin shad (*Dorosoma petenense*) began accelerating around 2000 (Sommer and others 2007). A recent analysis of those data confirmed the steep declines in the early 2000s, with a common decline by all four in 2002 (Thomson and others 2010). This pattern has been dubbed the Pelagic Organism Decline (POD). Untangling the potential causes of the POD has become a major research effort, but is complicated by the fact that the four species have distinctive life histories as indicated by differences in their distributions within the Estuary at particular times of the year, what they eat, and their individual vulnerabilities to stressors, such as temperature or contaminants (Brooks and others, in review).

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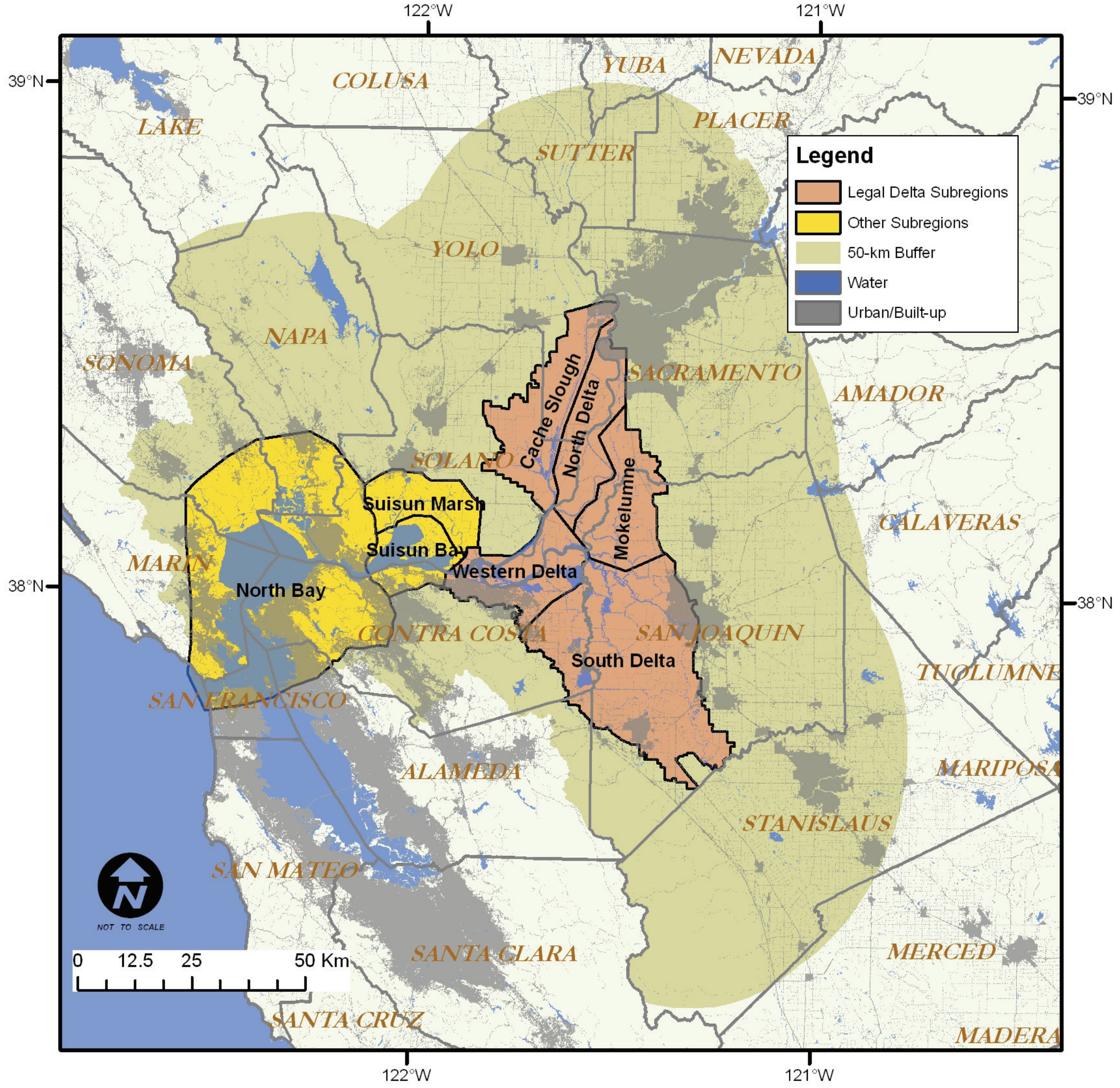

Figure 1 Location map of the upper San Francisco Estuary, showing the hydrodynamic subregions including those in the legal Delta (delineated in section 12220 of the Water Code), and the 50-km (30-mile) buffer upstream from the Estuary

Land use is an ultimate driver of many of the changes in conditions in the Estuary, especially altered hydrologic regimes and loadings of contaminants (Reed and others 2007). Quantifying the extent of developed land over time provides a foundation for understanding the loadings and effects of many classes of contaminants. Urban development can generate many impacts to water quality. For example, urban runoff contains mercury, copper, silver, and other metals (Flegal and others 2005). Urban population growth potentially increases the discharge of ammonia and ammonium-bearing effluent from wastewater treatment plants. Development also increases the proportion of impervious surface in the watershed, which changes the hydrologic response to runoff and accelerates the mobilization of contaminants from urban areas (Schueler and others 2009) and, potentially, the biotic response (Alberti and others 2007). Current construction practices attempt to clear sites of ants by applying pyrethroid insecticides, some of which is transported into urban creeks (Kuivila and Hladik 2008; TDC Environmental 2008).

Despite extensive monitoring data, much is still not known about the spatial and temporal distributions of pesticides and other contaminants in the Estuary (Kuivila and Hladik 2008). If dramatic land-use change were detected for the period immediately prior to the fish decline, this would provide circumstantial evidence of changes in sources of non-point source contaminants and their potential loadings to the Estuary. The Independent Science Advisors to the Bay Delta Conservation Plan (Reed and others 2007) noted that local land-use data were dispersed and inconsistent, which has made Estuary-wide analysis challenging. There has not been an assessment of land-use change in the upper Estuary over the time-period preceding and during the POD at a scale related to the fish populations.

To address this knowledge gap, this paper presents a land-use change assessment based on the time series of maps compiled by the California Farmland Mapping and Monitoring Program (FMMP) summarized within geographic units within the Estuary related to life history stages of the four POD species (Brooks and others in review). The specific objectives of this study are to (1) assess the area of land within the Estuary and surrounding region that was developed between 1990 and 2006, (2) quantify disturbance metrics related to the built environment, and (3) evaluate these results in relation to other estuarine environments across the United States where relationships between urban development drivers, environmental stressors, and biotic responses are better known. The results from these multiple lines of evidence are used to discuss whether urban growth per se is likely to be a major contributor to increases in contaminants and other stressors in the Estuary.

MATERIALS AND METHODS

Land-Use Change

Consistent methods need to be used to classify and develop land-use maps to minimize spurious differences between time-periods, such as was experienced in the earlier land-use change study (Water Plan Land and Water Use Work Team 2007). Because the POD occurred around 2000, it would also be ideal to assess whether land-use changed dramatically between 1990 and 2000. There are two sources of land-use mapping that generally meet this requirement for repeat mapping on these dates. The first source is the FMMP, which produces maps and statistical data every two years beginning in 1984 to assess losses of California's agricultural resources to urban development. The second source is the National Land Cover Database (NLCD) for 1992 and 2001, developed by the Multi-Resolution Land Characteristics (MRLC) Consortium (Homer and others 2004).

FMMP rates agricultural land into four classes (e.g., ”Prime Farmland”). The maps are updated every two years with the use of aerial photographs, a computer mapping system, public review, and field reconnaissance. The minimum mapping unit is 4 hectares (ha) (10 acres). FMMP has a single class of development called “Urban and Built-up Land,” defined by a building density of at least 0.6 structures per acre (http://www.conservation.ca.gov/dlrp/fmmp/Pages/Index.aspx).

The percentage of land area in the Urban and Built-up Land class were summarized for the years 1990, 2000, and 2006.

Land-use change was assessed both within the Estuary and the surrounding upstream landscape. Within the Estuary, the percentage of urban development was summarized within eight hydrodynamic sub-regions (Figure 1). This scale suggests relative direct loadings of contaminants into the distinct habitats of varying salinity. The boundaries of the sub-regions were interpreted from a graphic conceptual model developed by the Delta Regional Ecosystem Restoration Implementation Plan team (J. Burau, U.S. Geological Survey, unpublished data). The legal Delta (delineated in section 12220 of the Water Code) formed primary boundaries that were supplemented by highways and other geographic features as appropriate.

Contaminants can also be imported to the Estuary from upstream sources. As a rule of thumb, water travels approximately 50 km (30 miles) in a day (Mike Johnson, U.C. Davis, pers. comm.). Therefore the same analysis was conducted over a larger region for 50 km beyond the Estuary: the drainage area was delineated by extending 50 km upstream from the boundary of the Estuary (or until reaching the watershed divide where streams drain the western slope of the Coast Ranges directly into San Francisco Bay) (Figure 1). This buffer area (hereafter the 50-km buffer) does not overlap with or include the hydrodynamic sub-regions.

FMMP mapping does not provide information on the intensity of developed use. The NLCD for 1992 and 2001 mapped the levels of development within urban areas, but used incompatible classifications so direct comparison between dates is not recommended by the MRLC (http://www.mrlc.gov/multizone.php). Therefore the NLCD 2001 data were used to identify the proportions of low-, medium-, and high-intensity development of lands identified by FMMP as having been converted to "Urban and Built-up Land" use between 1990 and 2000 within the Estuary plus the 50-km buffer.

Urban Attributes

In addition to the extent of urban change, the configuration of urban land use in a watershed is also important in determining effects on water quality (Alberti and others 2007). In particular, the authors found that variables such as the number of roadstream crossings, road density, housing density, and mean size of urban patches improved the fit of models predicting in-stream biotic integrity in the Puget Sound region in Washington State over models using total impervious surface alone. They also found significant correlation between hydrologic connectivity of impervious cover to surface waters and biotic integrity. Although there are obvious differences in vegetation and topography between Puget Sound and the Estuary, it is likely that these landscape measures could provide a first approximation of the magnitude of urban and road impacts in the Estuary relative to Puget Sound, and a relative comparison of impacts among hydrodynamic sub-regions.

Data for analysis of urban attributes in the Estuary came from several different sources and were analyzed with ArcGIS™. Total impervious cover (Brabec and others 2002) was summarized from NLCD data (Homer and others 2004) as the mean value for the land area in each hydrodynamic subregion. Counts of housing units derived from the 2000 Census were converted to density by hydrodynamic subregion. Following Alberti and others (2007), hydrologic connectivity was calculated as the median distance of urban grid cells from the FMMP 2000 mapping to the nearest surface waters in each subregion. Because the terrain of the Estuary is basically flat, Euclidean distance was assumed to be a reasonable estimate of flow-length distance. Road density is known to be positively correlated with many pollutants and negatively with indicators of water quality (DeCatanzaro and others 2009). The length of each road segment from the U.S. Census 2000 TIGER® files (http://www.census.gov/geo/www/tiger/) was summed with ArcGIS and divided by land area to determine road density by subregion. The roads layer was then overlaid on the streams layer from TIGER® to identify crossings and converted to density by dividing by the total length of streams in each subregion. The absence of data for 1990 (e.g., impervious cover) or inconsistency between 1990 and 2000 data (e.g., roads) precluded a change analysis of urban attributes so only the 2000 results are reported here.

RESULTS

Land-Use Change

Across the Estuary, 1.2% of the land area was converted to "Urban and Built-up Land" areas between 1990 and 2000 (increasing from 15.3% to 16.5%). Between 2000 and 2006, an additional 1.2% of land area was converted to "Urban and Built-up Land" for a total change in urban use from 15.3% to 17.6% between 1990 and 2006 (Table 1). In 1990 the south and north Delta sub-regions had two of the highest percentages of urban area, and they both grew at the highest rates of about an additional 2% in each time-period (Figure 2). Suisun Marsh and especially the North Bay had high initial urban percentages but grew at about half the rate of the north and south Delta. Most urban development present in 2000 in Suisun Marsh and the North Bay already existed before 1990.

The rates of change for the 50-km buffer area were similar to the Estuary in both time-periods (Table 1). The percentage of "Urban and Built-up Land" was about 5% less than in the Estuary, despite the inclusion of metropolitan areas of Sacramento, Stockton,

Table 1 Percent urban and built-up land area and percent change, 1990 to 2006, by land area of hydrodynamic sub-regions and the 50-km buffer

		Year (% of Land Area)			Change (% of Land Area)	
Hydrodynamic Subregion	**Land Area (km^2)**	**1990**	**2000**	**2006**	**1990–2000**	**2000–2006**
South Delta	1,208	8.9	11.0	13.2	2.1	2.2
Mokelumne System	386	3.7	4.0	5.0	0.3	1.0
North Delta	365	20.6	22.6	24.7	2.0	2.0
Cache Slough Complex	483	0.7	1.1	1.3	0.4	0.2
Western Delta	316	6.1	6.9	7.5	0.8	0.6
Suisun Marsh	263	16.0	17.1	17.3	1.1	0.2
Suisun Bay	154	3.9	4.0	4.5	0.1	0.6
North Bay	1,562	30.4	31.4	32.2	1.0	0.8
Estuary Total	**4,737**	**15.3**	**16.5**	**17.6**	**1.2**	**1.2**
50-km Buffer	15,165	10.7[a]	11.3[a]	12.7	0.6	1.4

a Portions of Stanislaus County were not mapped in 1990 and 2000, so this percentage represents only the value of the mapped portion within the 50-km buffer.

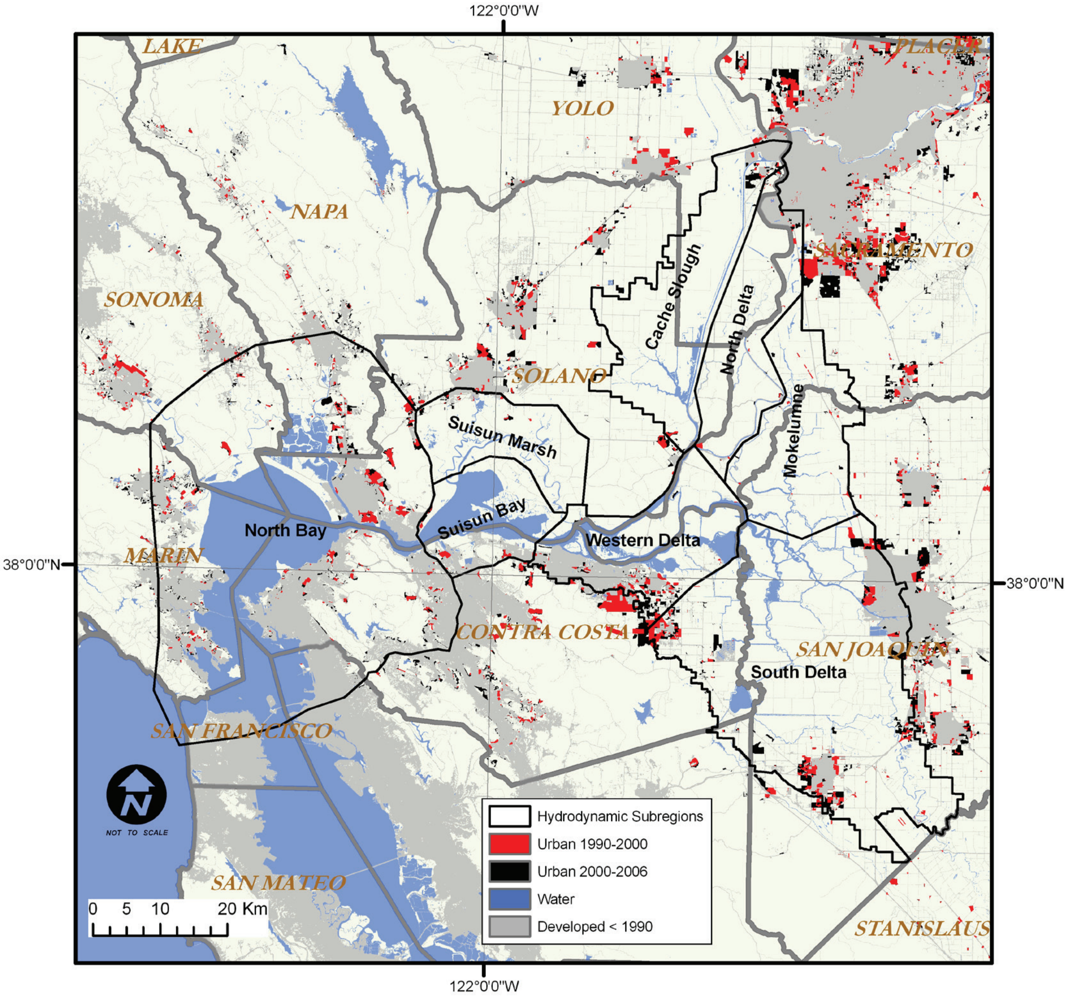

Figure 2 Map of land-use change, 1990 to 2000 and 2000 to 2006, in hydrodynamic sub-regions

Modesto, and interior Contra Costa County. From the perspective of the land-use types, farmland and grazing land each lost about 2% of their initial area to ”Urban and Built-up Land” in both time-periods in the Estuary and 50-km buffer combined.

The FMMP maps identified 30,000 ha of new ”Urban and Built-up Land” between 1990 and 2000 within the combined Estuary and 50-km buffer. The percentage of NLCD 2001 land-use types were calculated within these 30,000 ha (Table 2). The two map sources showed moderately high agreement, with 78% of the FMMP urban change mapped as one of the four developed classes by NLCD. Only 7% was mapped as ”High Intensity” (80% to 100% impervious cover). Another 37% was mapped as ”Medium Intensity” (50% to 79% impervious), and 34% was mapped as either ”Low Intensity” (20% to 49% impervious) or ”Developed Open Space” (less than 20% impervious).

Table 2 Classification of NLCD 2001 land-use types within areas of urban conversion, 1990 to 2000, in FMMP maps for the Estuary and the 50-km buffer, combined

NLCD2001 Class	Name	Area (ha)	% Area Converted to "Urban and Built-up"
11	Open Water	225	0.7
21	Developed, Open Space	6,009	18.2
22	Developed, Low Intensity	5,067	15.3
23	Developed, Medium Intensity	12,323	37.2
24	Developed, High Intensity	2,439	7.4
31	Barren Land (Rock/Sand/Clay)	320	1.0
41	Deciduous Forest	52	0.2
42	Evergreen Forest	66	0.2
43	Mixed Forest	98	0.3
52	Shrub/Scrub	99	0.3
71	Grassland/Herbaceous	2,930	8.9
81	Pasture/Hay	573	1.7
82	Cultivated Crops	2,449	7.4
90	Woody Wetlands	79	0.2
95	Emergent Herbaceous Wetlands	361	1.1

Urban Attributes

Because much of the Estuary is unsuitable for development, total impervious cover of land area (not including open water) is relatively low (8.6%), ranging from 0.6% in the Mokelumne System subregion to 16.4% in the North Bay (Table 3). Housing density varies by almost two orders of magnitude from less than 4 units km^{-2} in the Mokelumne System to 292 units in the North Bay. As median distance from urban grid cells to water decreases, potential discharge of contaminants into streams and rivers would be expected to increase. Median distance of developed land is less than 700 meters from open water in the three sub-regions with the least total impervious cover, but is triple that distance in more intensely developed sub-regions. This finding suggests that development began near the shoreline and expanded away from the water over time. Density of roads is highest in the western Delta, Suisun Bay, and the North Bay at the more saline end of the gradient where housing density is also greatest. The south Delta has 1.8 road crossings km^{-1} of stream, while the Estuary as a whole had less than 1.0.

DISCUSSION AND CONCLUSIONS

The amounts and rates of change in land-use attributes vary widely among hydrodynamic sub-regions. Total impervious cover, however, is only loosely related to the percentage of urban land. For instance, the north Delta has the second-highest percentage of urban land at 20.6% but only the fifth-highest impervious cover (3.4%). Suisun Bay, on the other hand, has a low percentage of urban land but the third-highest impervious cover. The rank order of sub-regions is very similar for impervious cover, housing density, and road density. Rankings by road–stream crossings are somewhat different from road density. The one attribute that produces greatly different rankings of sub-regions is the distance from urban to water. The least developed sub-regions typically have development located closest to surface waters relative to the more heavily developed sub-regions.

These results characterize indicators of drivers or stressors in the Estuary, but it is difficult to inter-

Table 3 Landscape indicators of urban stressors on aquatic ecosystems in the Delta by subregion. Density indicators based on land surface area only of subregions.

Hydrodynamic Subregion	2001 Impervious Cover (%)	2000 Housing Density (units km^{-2})	2000 Median Distance Urban to Water (m)	2000 Road Density (km-km^{-2})	2000 Density Road-stream Crossings (#-km^{-1} of stream)
South Delta	5.7	68.1	900	2.3	1.8
Mokelumne System	0.6	3.7	517	1.0	0.5
North Delta	3.4	65.9	676	2.2	0.6
Cache Slough Complex	2.8	18.7	570	1.8	0.7
Western Delta	12.8	151.2	1812	3.2	0.7
Suisun Marsh	2.0	16.4	2732	1.5	1.0
Suisun Bay	9.6	45.5	1888	3.5	0.4
North Bay	16.4	292.4	1894	4.7	1.2
Estuary Total	8.6	133.6	---	3.0	0.8

pret them in relation to water quality or biological response variables of interest (e.g., status and trends of POD species).

As an alternative, we can compare the indicators for the upper Estuary with values found in other bays, estuaries, and river basins where knowledge of the relationships between land use and ecological effects are further advanced. The Neuse River watershed in North Carolina, which has declining surface water quality, has an almost identical percentage of urban land as the Estuary in 2000, but urban land cover has more than tripled in area from 1992 to 2001 (Rothenberger and others 2009). Impervious cover in a sample of 42 basins on a gradient of urbanization in Puget Sound, determined from high-resolution imagery, averages 36% (10% to 61%) (Alberti and others 2007). According to the State of the Sound report, impervious cover in Puget Sound is 7.3%, although the method for calculation was different than that used for the NLCD (Puget Sound Action Team 2007). The small Brunette River watershed in British Columbia has 41% impervious cover (Zandbergen 1998). Chesapeake Bay, another nationally significant watershed with severe ecological impacts from land use, had just 1.5% impervious cover in 1990, although it increased rapidly to 2.1% by 2000 (derived from Jantz and others 2005). Developed land increased from 3.0% to 5.0% in the same period.

Numbers for different ecosystems are a bit difficult to compare because of differences in methods and the resolution of imagery used to estimate impervious cover and the scale of watersheds evaluated. The impervious cover of the Estuary is slightly higher than the whole Puget Sound watershed, and four times greater than that of Chesapeake Bay. Note that the Chesapeake data are for the entire watershed. No doubt the totals would be much less for the entire Sacramento–San Joaquin river basins, which include the less-developed Sierra Nevada, Coast Ranges, and agricultural portions of the San Joaquin Valley. None of the sub-regions in the Estuary, however, approaches the percentages of the most developed sub-basins in Puget Sound or the Brunette River. In a meta-analysis of watershed studies, Schueler and others (2009) found that sub-watersheds with impervious cover below 10% could be categorized as “sensitive” with generally good to excellent stream quality. They consider impervious cover between 10% to 25% as “impacted” and usually associated with fair stream quality. However, the authors reported wide variability in stream quality at any given level of impervious cover. Using Schueler and others’ Impervious Cover Model (2009), the Estuary as a whole would be placed in the transition between ”sensitive” and ”impacted” categories. The western Delta and North Bay subregions in the Estuary would be classed as ”impacted,” and Suisun Bay lies on the cusp of this category.

These three sub-regions all lie at the more saline end of the gradient. Schueler and others (2009) also found that at impervious cover below 10%, other indicators (e.g., road density, riparian cover) are often better at explaining variability in water quality. Similarly, Brabec and others (2002) note that total impervious surface is less relevant than effective impervious area that is restricted to impervious surface directly connected to streams. Non-effective impervious area is mediated by intervening pervious cover such as riparian forest. Accounting for this hydrological connectivity was beyond the scope of this study but would be a useful adjunct for future research.

Little information is published on road density and stream crossings in other watersheds with known biological impacts. One exception is the Puget Sound region. Alberti and others (2007) found road densities in 42 sub-basins average 6.61 km-km^{-2} and ranged from 0.62 to 13.26. Sub-regions in the Estuary are all lower than the average in Puget Sound, and the whole Estuary has a density half that of Puget Sound. The number of road crossings-km^{-1} of stream is also higher in Puget Sound (mean = 2.1, range 0.6 to 3.8, Alberti and others 2007) compared to the Estuary (0.8, 0.4 to 1.8). Alberti and others (2007) reported that biological integrity became poor at densities greater than 2.0 crossings-km^{-1}. Only the south Delta subregion approaches that density of crossings.

This assessment of land-use change determined the location and timing of urban development and its attributes as an initial screening of its possible role in the POD. In general, the magnitude of urban land use and its attributes in the Estuary reported here do not in themselves create an expectation of a dramatic decline in fish populations. Nor does it seem likely that the urban development in the 1990s would precipitate the declines. Several additional avenues of research are recommended to seek other explanations related to land use. For instance, this study omitted agricultural aspects of land use, such as change in crop patterns and practices over time in response to markets, weather, policies, and agronomic or technological advances. These changes in crop patterns could be associated with substantial shifts in pesticide and fertilizer applications that might correspond to changes in water quality or fish abundance. We did not analyze changes in crops within the agricultural lands here because the FMMP data does not record crops, only soil categories and general use. Mapping the annual pattern of crops and application of pesticides with data from the California Department of Pesticide Regulation would be a valuable contribution. Future urban growth and its potential effects could also be analyzed, using maps from the ReEnvisioning the Delta report that modeled spatial variation in probability of future urban development (Eisenstein and others 2007) or other growth-modeling efforts. In addition to further analysis of land use, the extensive database of water quality and fish monitoring data should be analyzed in relation to spatial patterns of urban development reported in this study. Biologists could also examine the spatial urban patterns against the movements of the POD species by life-history stages to correlate exposures related to their vulnerabilities (Brooks and others, in review). We have only begun to unpack the complexities of the spatial and temporal dynamics of the biota of the Estuary.

ACKNOWLEDGEMENTS

This work was conducted as part of the "Potential Role of Contaminants in Declines of Pelagic Organisms in the Upper San Francisco Estuary, California, USA" Working Group supported by the National Center for Ecological Analysis and Synthesis, funded by the National Science Foundation (Grant #DEB–0553768), the University of California, Santa Barbara, the State of California, and the U.S. Fish and Wildlife Service (task order #81332 7 J002). Patrick Jantz processed the housing count data and provided valuable advice. I am grateful to the members of the Contaminants working group for their suggestions, and particularly to Larry Brown and Erica Fleishman for encouraging this study and providing many useful comments on a previous draft. To assist with future research on land-use stressors in the Estuary, I have posted GIS products from this study (i.e., the hydrodynamic subregions and the 50-km buffer as well as data Tables 1 and 3) and metadata on the Knowledge Network for Biocomplexity (KNB) website (http://knb.ecoinformatics.org/index.jsp) for open access.

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