Estimating the variability and confidence of land use and imperviousness relationships at a regional scale

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Abstract

Impervious cover is a commonly used metric to help explain or predict anthropogenic impacts on aquatic resources; often it is used as a surrogate for intensity of human impacts when evaluating effects on aquatic resources. The most common way to estimate imperviousness is based on relationships with land use. Few studies have evaluated how the relationship between impervious surface and land use varies among geographies with different levels of development and between types of imagery used to assign land use type. In this study we assess variability in estimates of imperviousness based on two locally available land use data sets: one based on aerial imagery (2-m resolution) and another based on satellite imagery (30-m resolution). The ranges and variability in imperviousness within land use categories were assessed at several spatial scales, including within counties, between counties, and between watersheds. Results indicate that there was considerable variability for all developed land use types. Estimated impervious cover often varied over a range of 20 to 40 percentage points within a land use category. Furthermore, there were clear spatial patterns both between and within counties, with impervious cover for a given land use type being higher near the urban centers and lower at the margins of development. Estimates of imperviousness for twelve study watersheds indicated that variability increased with increasing watershed development, making it difficult to confidently set management or regulatory targets based on impervious cover. This study suggests that locally derived, high resolution satellite or aerial imagery should be used to estimate imperviousness when a high level of accuracy and precision is required for regulatory or management decisions. Furthermore, the error associated with impervious-land use relationships should be accounted for when using impervious cover in runoff or water quality models, or when making management decisions regarding stream health.

Introduction

Regulatory and management programs often use impervious cover as a surrogate for intensity of human impacts when evaluating actual or potential effects on aquatic resources. Numerous studies have related increased impervious cover and urbanization to changes in stream channel geomorphology (Coles *et al*. 2004, Center for Watershed Protection 2003, Roesner and Bledsoe 2003). Water quality models are known to be sensitive to estimates of impervious cover (Endreny *et al*. 2003). More recently, Park and Stenstrom (2006) developed a model that relates impervious cover to water quality, and Dougherty *et al*. (2006) used percent impervious cover as an indicator of pollutant flux from developed landscapes. Increases in impervious cover have also been related to changes in flow patterns that have been shown to have measurable effects on the community composition of stream biota (Konrad and Booth 2005). Morse *et al*. (2003) reported that taxonomic richness of stream insect communities showed an abrupt decline as impervious cover increased above 6%. Similarly, Wang *et al*. (2003 and 2001) reported that the amount of connected impervious surface area in the watersheds was negatively correlated with a fish based cold water index of biotic integrity. Studies of overall stream health suggest that the factor most predictive of variation in stream health ranking is percent impervious cover (Snyder *et al*. 2005, Goetz *et al*. 2003, Schueler 1994).

Impervious cover estimates can vary over several spatial scales based on both the estimation method (i.e., how the impervious cover is calculated) and on actual differences between land use practices. The most common way to estimate impervious cover involves assigning values to specific land use or land cover types generated from aerial photography. Another method that is gaining popularity applies impervious surface coefficients to satellite generated land cover data. Each of these approaches can introduce variability based on the scale of the image used, image quality and consistency, delineation of land use types, image classification, and choice of the impervious cover conversion factors used. Also, variability can be introduced due to heterogeneity in land use practices. For example, the amount of impervious cover associated with a commercial land use will not be consistent between parcels or jurisdictions.

Use of impervious cover estimates for regulatory or management decisions requires an understanding of the variability (and error) associated with these estimates. The Center for Watershed Protection (2003) noted that accurate use of impervious cover models for planning or management requires accurate estimates of impervious cover, otherwise managers' risk making erroneous conclusions. Recently, Moglen and Kim (2007) have questioned the utility of imperviousness as an index of stream health because of varying imperviousness estimates derived from different methodologies. Few studies have attempted to provide regional estimates of variability; hence the low level of confidence associated with impervious cover calculations. Dougherty *et al*. (2004) compared impervious cover estimates for a 127-km^2 watershed in northern Virginia from a satellite imagery/land cover approach with a more traditional aerial photography/land use approach. They found that photo-interpreted estimates of impervious cover were higher than satellite-derived estimates by 100% or more, with the latter being more accurate for planning and management.

This study builds on the work of Dougherty *et al*. (2004) by assessing relationships between land use and imperviousness. The overall goal of this study is to quantify the relationship between imperviousness estimates and land use data while bounding the certainty/confidence of those relationships and assessing the spatial variability or patterns in southern California. Although southern California is the focus of this study, the evaluated data sources and methods used to estimate impervious cover are common across the United States, hence the results may be extended to many other regions.

Methods

Relationships between regional impervious estimates and local land use data were used to quantify variability in land use imperviousness. The 2001 National Land Cover Database (NLCD) was used as the basis to develop imperviousness values based on land use. Two locally available land use data sets, one based on aerial imagery and another based on satellite imagery, were overlaid on the NLCD to develop impervious estimates by for each land use pixel. The relationship between imperviousness and land use were tabulated for each dataset within counties, between counties, and between watersheds. These tabulated relationships were then used to bound the range and variability of estimates of imperviousness at the spatial scales of interest.

Location

The study area encompassed six counties in southern California: Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Riverside (Figure 1). Additionally, twelve watersheds (California Department of Fish and Game 1998), which spanned differing degrees of development, were selected to illustrate the effect of different methods for calculating imperviousness. These watersheds ranged in size from 6 to 1,982 km^2 (Table 1 and Figure 1).

Data Sources

Imperviousness

Remote sensing estimates of impervious cover from the 2001 National Land Cover Database were used as the measure of imperviousness throughout the study area (http://www.mrlc.gov/index.asp). The NLCD (Albers conical equal-area projection) is a commonly used, national data set provided by the US Geological Survey in cooperation with the US Environmental Protection Agency, and provides a consistent standard for conversion of land use to impervious cover. The NLCD classified 20 digital orthophoto quarter-quadrangles across the mapping zone with a nominal spatial resolution of 1 m into either pervious or non-pervious surfaces, and then summed within each 30-meter Landsat pixel cell to obtain percentage of imperviousness. Training data were selected with a Sample Selection Tool developed by Earth Satellite Corporation based on the degree of variance each training data set possesses with regards to Landsat ETM+ imagery used for mapping." (http://www.mrlc.gov/index.asp) The methodology is described in detail by Yang *et al*. (2003).

Land use

Land use derived from aerial photography was obtained from the Southern California Association of Governments (SCAG; 2004a, 2004b, 2004c, 2004d,

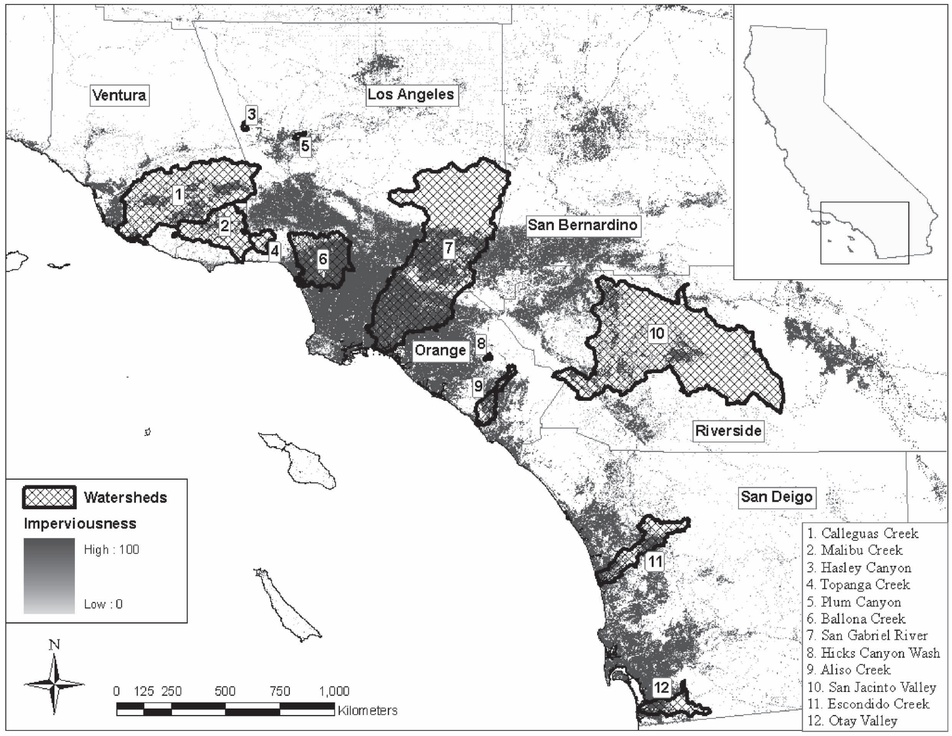

Figure 1. Site map showing imperviousness throughout the study area and the twelve watersheds used to investigate the effect of imperviousness estimation at the watershed scale.

2004e) and the San Diego Association of Governments (SanDAG; 2000). The SCAG vector data used a UTM projection and covered five of the counties in the study area. The data set was developed from aerial surveys from 2000, with a minimum resolution of 2 m (Table 1). The 107 SCAG land use types were aggregated into nine like land use categories as in Ackerman *et al*. (2005; agriculture-AG, commercial-COM, high density residential-HDR, industrial-IND, low density residential-LDR, mixed, open, recreational-REC, and transportation-TRANS). SanDAG data (Lambert conformal conic projection) was used for the sixth county (San Diego). The SanDAG data was compiled in a similar manner as the SCAG data, had 2-m minimum resolution, and was aggregated into the same categories as the SCAG data (Table 2).

Land use derived from satellite imagery was based on seamless region-wide land use raster data obtained from the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Assessment Program (C-CAP; NOAA Coastal Services Center 2006). This regional land cover survey was developed using year 2002 Landsat satellite imagery, which has 30-meter pixel resolution and a Albers conical equal-area projection. The raster C-CAP data provides 39 land types, which were aggregated into six categories for simplification and easier comparison to the SCAG and SanDAG data (Table 3).

Data Processing

Three sources of variability in impervious cover estimates were evaluated. First, we assessed variability within land use categories based on the aggregation of component land use types. Then we assessed spatial variability at three scales, within counties, between counties, and at the watershed scale. Finally, we assessed variability based on the origin of the land-cover data (aerial photo based or satellite based). Raster data (C-CAP and NLCD) were converted to vector data using ArcGIS software (ESRI 2007). The land use datasets were intersected with the NLCD at the 2-m level. The ArcGIS command “Tabulated Area” was used to quantify impervious cover for the various analyses (i.e., by land use category, county, watershed). Cumulative distribution plots of imperviousness for each aggregated land use category (Tables 1, 2, and 3) were calculated and expressed for the 10th, 25th, 50th, 75th, and 90th percentiles.

Spatial variability within the greater Los Angeles

Table 1. Land use aggregation employed for the Southern California Association of Governments (SCAG) data sets.

Aggregated Land Use	SCAG Land Use Category
Agriculture (AG)	Dairy, Intensive Livestock, and Associated Facilities; Horse Ranches; Irrigated Cropland and Improved Pasture Land; Non-Irrigated Cropland and Improved Pasture Land; Nurseries; Orchards and Vineyards; Other Agriculture; Poultry Operations
Commercial (COM)	Attended Pay Public Parking Facilities; Base (Built-up Area); Colleges and Universities; Commercial Recreation; Commercial Storage; Correctional Facilities; Elementary Schools; Fire Stations; Government Offices; High-Rise Major Office Use; Hotels and Motels; Junior or Intermediate High Schools; Low- and Medium-Rise Major Office Use; Major Medical Health Care Facilities; Modern Strip Development; Non-Attended Public Parking Facilities; Older Strip Development; Other Public Facilities; Other Special Use Facilities; Police and Sheriff Stations; Pre-Schools/Day Care Centers; Regional Shopping Center; Religious Facilities; Retail Centers (Non-Strip With Contiguous Interconnected Off-Street); Senior High Schools; Skyscrapers; Special Care Facilities; Trade Schools and Professional Training Facilities
High Density Residential (HDR)	Duplexes, Triplexes and 2-or 3-Unit Condominiums and Townhouses; High-Density Single Family Residential; High-Rise Apartments and Condominiums; Low-Rise Apartments, Condominiums, and Townhouses; Medium-Rise Apartments and Condominiums; Mixed Multi-Family Residential; Mixed Residential; Mobile Home Courts and Subdivisions, Low-Density; Trailer Parks and Mobile Home Courts, High-Density
Industrial (IND)	Chemical Processing; Communication Facilities; Electrical Power Facilities; Harbor Facilities; Harbor Water Facilities; Improved Flood Waterways and Structures; Liquid Waste Disposal Facilities; Maintenance Yards; Major Metal Processing; Manufacturing; Manufacturing, Assembly, and Industrial Services; Marina Water Facilities; Mineral Extraction - Oil and Gas; Mixed Utilities; Motion Picture and Television Studio Lots; Natural Gas and Petroleum Facilities; Navigation Aids; Open Storage; Packing Houses and Grain Elevators; Petroleum Refining and Processing; Research and Development; Solid Waste Disposal Facilities; Water Storage Facilities; Water Transfer Facilities; Wholesaling and Warehousing
Low Density Residential (LDR)	Low-Density Single Family Residential; Rural Residential, High-Density; Rural Residential, Low-Density
Mixed (MIX)	Mixed Commercial and Industrial; Mixed Urban
Open (OPEN)	Abandoned Orchards and Vineyards; Air Field; Beach Parks; Beaches (Vacant); Cemeteries; Mineral Extraction - Other Than Oil and Gas; Other Open Space and Recreation; Specimen Gardens and Arboreta; Under Construction; Vacant Area; Vacant Undifferentiated; Vacant With Limited Improvements; Wildlife Preserves and Sanctuaries
Recreational (REC)	Developed Local Parks and Recreation; Developed Regional Parks and Recreation; Golf Courses; Undeveloped Regional Parks and Recreation
Transportation (TRANS)	Airports; Bus Terminals and Yards; Freeways and Major Roads; Mixed Transportation; Mixed Transportation and Utility; Park-and-Ride Lots; Railroads; Truck Terminals
Water	Water Within a Military Installation; Water, Undifferentiated

area was assessed by overlaying a 10-km grid (100 km^2) on impervious cover maps using the utility ET Geo-Wizard (www.ian-ko.com). Land use imperviousness within each grid cell, by land use, was determined by intersecting the grid and SCAG land use layer. The resultant layer was then tabulated against the NLCD layer and plotted to investigate spatial patterns.

The effect of impervious assignment to land use data within a watershed were investigated by comparing calculated and measured impervious cover values in twelve watersheds across the study area. The watersheds were selected to cover a range of sizes (5 - 2,000 km^2), varying degrees of development (1 - 82%) and were spatially distributed throughout the study area (Figure 1 and Table 4). Land use distribution within each watershed was determined for both land use data types using the unaggregated land uses (SCAG/SanDAG and C-CAP). The watersheds ranged from 1 to 52% impervious as calculated by area-weighting the NLCD data (Table 5). Overall imperviousness for each watershed were determined using the 25th, 50th, and 75th percentile estimates of impervious cover to each land use category. The range of estimates based on land use data were compared to overall watershed imperviousness based on the NLCD dataset.

Table 2. Land use aggregation employed for the San Diego Association of Governments (SanDAG) data set.

Aggregated Land Use	SanDAG Land Use Category
Agriculture	Field Crops; Intensive Agriculture; Orchards And Vineyards
Commercial	Airstrips; Automobile Dealerships; Casinos; Commercial Airports; Community Shopping Centers; Convention Center; Elementary Schools; Fire/Police Stations; General Aviation Airports; Gov't Office/Civic Centers; Hospitals-General; Jails/Prisons; Junior Colleges; Junior High Schools And Middle Schools; Libraries; Military Airports; Missions; Neighborhood Shopping Centers; Office-High Rise; Office-Low Rise; Other Health Care; Other Public Services; Other Retail Trade And Strip Commercial; Other Schools; Other Universities And Colleges; Post Offices; Racetracks; Regional Shopping Centers; Religious Facilities; Resort; School District Offices; Schools; Sdsu, Smsu, Ucsd; Senior High Schools; Specialty Commercial; Stadiums/Arenas; Store-Front Commercial; Tourist Attraction; UCSD, VA Hospitals, Balboa Hospital; Wholesale Trade
High Density Residential	Dormitories; Hotel/Motel (Hi-Rise); Hotel/Motel (Lo-Rise); Military Barracks; Mobile Home Parks; Multi-Family Residential; Other Group Quarters Facilities; Residential Under Construction
Industrial	Extractive Industry; Heavy Industry; Industrial Parks; Junkyard/Dump/Landfill; Light Industry-General; Marinas; Military Training; Military Use; Warehousing & Public Storage; Weapons Facilities
Low Density Residential	Monastery; Single Family Residential; Spaced Rural Residential
Open	Beach - Passive; Cemetery; Commercial Under Construction; Industrial Under Construction; Landscape Open Space; Office Under Construction; Open Space Reserves, Preserves; School Under Construction; Undevelopable Natural Areas; Vacant Land
Recreational	Beach - Active; Golf Course Clubhouses; Golf Courses; Olympic Training Center; Other Recreation; Parks - Active; Residential Recreation
Transportation	Communications And Utilities; Freeways; Marine Terminal; Other Transportation; Park And Ride Lots; Parking Lots -Structure; Parking Lots -Surface; Rail Station/Transit Centers; Railroad Right of Ways; Road Right of Ways

Results

There was considerable variability in estimates of imperviousness for all developed land use types, irrespective of the origin of the land use data. The high-density residential (HDR) land use comprised the greatest proportion of the developed area, and its median percentile imperviousness ranged from 37% to 55% in the five counties (Figure 2). By contrast, the median imperviousness for the industrial land use was 0% for Riverside, San Bernardino, Ventura and San Diego Counties; however, the median for Los Angeles and Orange counties was 58% and 70%, respectively.

Table 3. Land use aggregation employed for the NOAA C-CAP data set.

Aggregated Land Use	C-CAP Land Use Category
Agriculture	Row Crop, Orchards
Commercial	Commercial/Industrial
High Density Residential	High Intensity Urban Residential; Urban Residential
Low Density Residential	Suburban Residential; Rural Residential
Open	Unmanaged Grassland Parks; Deciduous Forest; Deciduous Parks; Evergreen Forest; Evergreen Parks; Mixed Forest; Mixed Forest Parks; Scrub/Shrub; Sage; Sage Parks; Chaparral; Chaparral Parks; Scrub/Shrub Parks; Palustrine Forested Wetland; Palustrine Scrub/Shrub Wetland; Palustrine Emergent Wetland (Per; Estuarine Forested Wetland; Estuarine Scrub/Shrub Wetland; Estuarine Emergent Wetland; Unconsolidated Shore (Intertidal; Bare Land; Bare Land Park; Managed Grassland; Pasture; Unmanaged Grassland; Rangeland
Recreational	Golf Courses; Parks / Lawns

Table 4. Watershed characteristics (area and land use distribution) using SCAG/SanDAG data. Watersheds are arranged from north to south. Percent urbanized incorporates all land uses with the exception of agriculture, open, and recreational. Map index refers to the watershed numbers in the legend of Figure 1.

Watershed	Map Index	Area (km^2)	Percent Land Use									Percent Urbanized
			AG	COM	HDR	IND	LDR	Mixed	Open	Rec	Trans	
Calleguas Creek	1	890	26%	3%	11%	3%	4%	0%	50%	1%	1%	22%
Malibu Creek	2	285	3%	2%	8%	1%	4%	0%	79%	1%	1%	16%
Topanga Creek	3	47	1%	0%	1%	0%	11%	0%	87%	0%	0%	12%
Plum Canyon	4	6	3%	0%	0%	1%	0%	0%	96%	0%	0%	1%
Ballona Creek	5	338	0%	16%	56%	5%	3%	0%	15%	3%	2%	82%
San Gabriel River	6	1,757	1%	8%	28%	7%	2%	0%	48%	3%	2%	47%
Aliso Creek	7	88	0%	9%	38%	2%	2%	0%	43%	4%	2%	53%
Hasley Canyon	8	7	4%	8%	13%	11%	0%	4%	58%	1%	1%	33%
Hicks Canyon Wash	9	8	6%	6%	14%	5%	0%	0%	66%	0%	1%	26%
San Jacinto Valley	10	1,982	16%	2%	6%	1%	5%	0%	66%	1%	0%	14%
Escondido Creek	11	221	10%	3%	3%	2%	25%	0%	47%	1%	7%	40%
Otay Valley	12	120	2%	5%	4%	9%	10%	0%	60%	2%	8%	36%

Differences in imperviousness within individual counties also spanned a wide range. For the 10th and 90th percentiles in Los Angeles County, percent impervious for industrial land uses ranged from 0 to 95% (Figure 2). Even the undeveloped land uses had wide ranges. In Orange County, the open land use had imperviousness values ranging from 0 to 15% for the 10th and 90th percentiles of the distribution, respectively.

Median imperviousness was comparable between the SCAG and the SanDAG data for the majority of the land uses. For example, values from SCAG and SanDAG for commercial, open space,

Table 5. Measured percent imperviousness and calculated percent impervious using the local land use data, C-CAP land use data both aggregated and with the original individual land use categories. Bold values are watersheds whose land use derived imperviousness at the 25th and 75th percentile levels are outside of the NLCD values. Map index refers to the water numbers in the legend of Figure 1.

	Map Index	NLCD	SCAG and SanDAG						C-CAP					
			Aggregated			Individual			Aggregated			Individual		
			25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th
Calleguas Creek	1	10%	6%	9%	13%	6%	9%	13%	6%	9%	11%	7%	8%	10%
Malibu Creek	2	6%	4%	6%	9%	4%	6%	9%	4%	5%	7%	4%	5%	6%
Topanga Creek	3	1%	0%	1%	3%	0%	1%	2%	**1%**	**1%**	**1%**	**0%**	**1%**	**1%**
Plum Canyon	4	2%	**0%**	**0%**	**1%**	0%	0%	4%	**0%**	**0%**	**0%**	**0%**	**0%**	**1%**
Ballona Creek	5	52%	27%	41%	52%	34%	46%	56%	**37%**	**44%**	**51%**	**39%**	**46%**	**51%**
San Gabriel River	6	27%	14%	22%	31%	17%	24%	31%	20%	24%	29%	21%	25%	28%
Aliso Creek	7	28%	18%	27%	33%	20%	28%	35%	18%	22%	28%	**19%**	**22%**	**27%**
Hasley Canyon	8	21%	11%	18%	27%	17%	23%	29%	**13%**	**16%**	**20%**	**13%**	**16%**	**20%**
Hicks Canyon Wash	9	15%	8%	13%	19%	11%	16%	21%	8%	11%	15%	**9%**	**11%**	**15%**
San Jacinto Valley	10	5%	3%	5%	7%	3%	5%	7%	3%	4%	6%	4%	4%	6%
Escondido Creek	11	16%	**7%**	**8%**	**8%**	8%	14%	19%	11%	15%	18%	11%	14%	17%
Otay Valley	12	24%	**7%**	**7%**	**7%**	**0%**	**15%**	**22%**	**16%**	**19%**	**22%**	**16%**	**19%**	**22%**

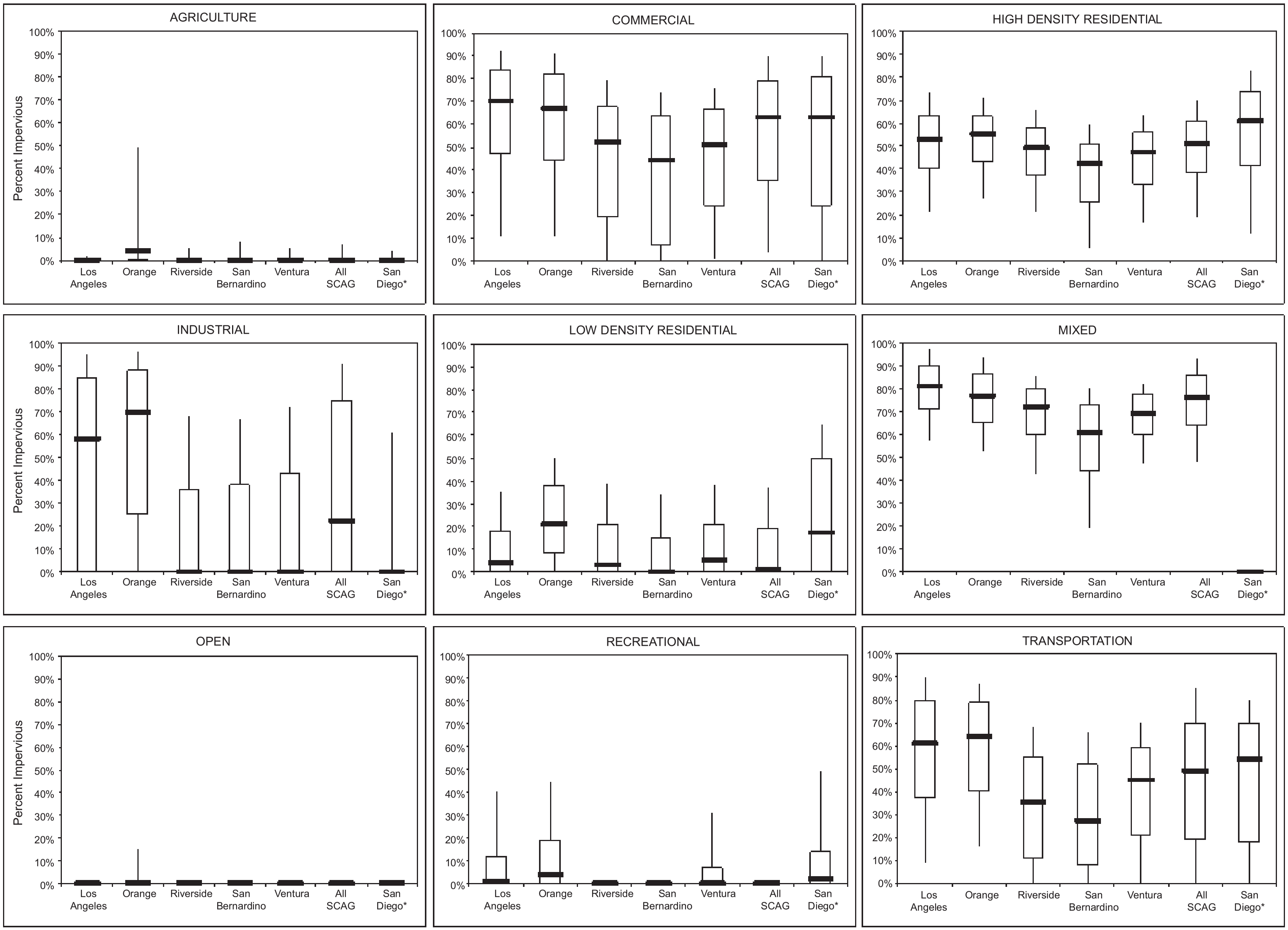

Figure 2. Land use imperviousness, by county and overall region, for the SCAG and SanDAG (shown by an asterisk) datasets. Box ends indicate 25th and 75th percentile; heavy line indicates the median; and whiskers indicate 10th and 90th percentile.

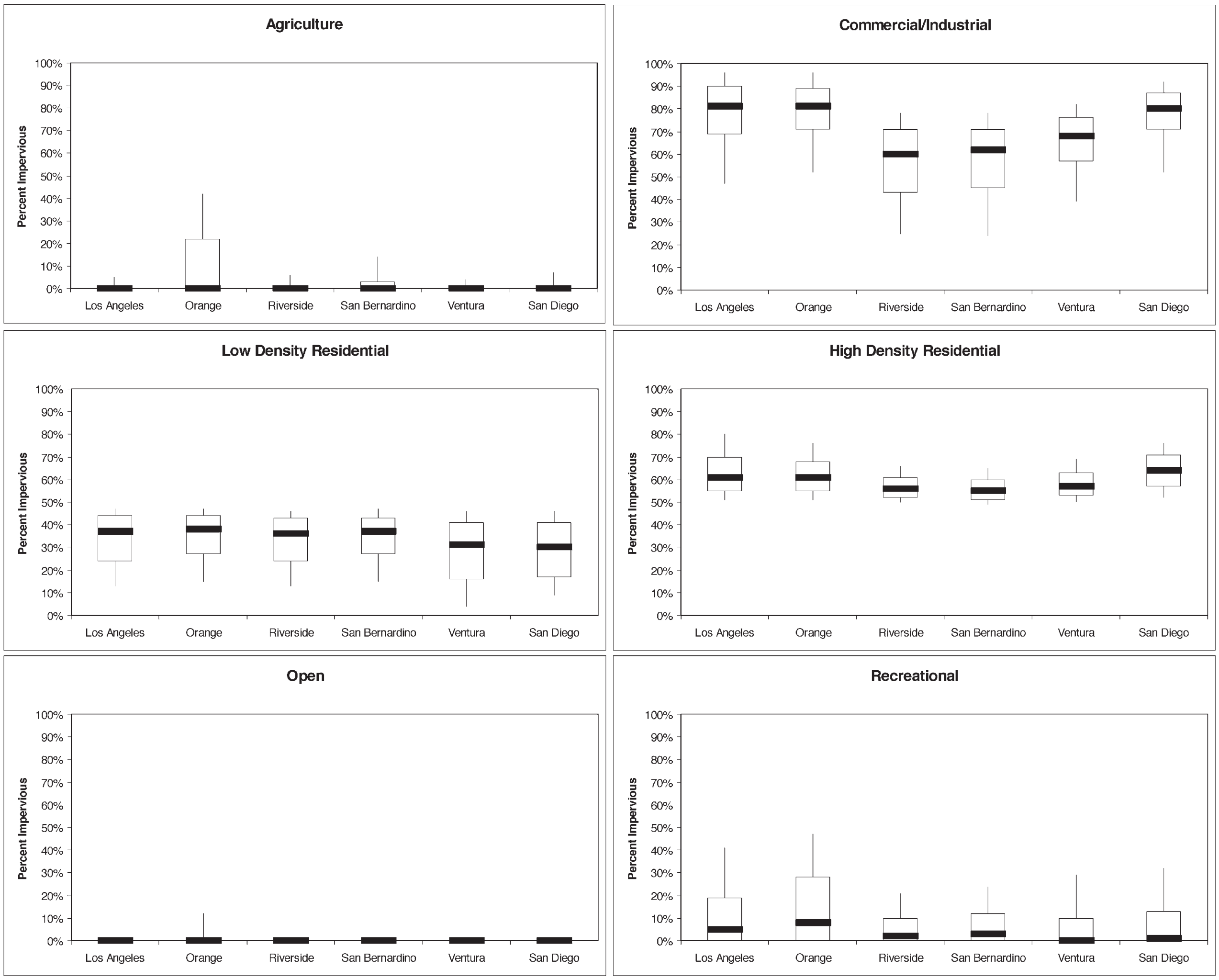

Figure 3. Land use imperviousness, by county and overall region, for the C-CAP dataset. Box ends indicate 25th and 75th percentile; heavy line indicates the median; and whiskers indicate 10th and 90th percentile.

recreation, and transportation land uses were within 5% of each other (Figure 2). The SanDAG derived median imperviousness for the low-density residential and industrial land use categories differed by over 16%, but that variability was also seen among counties covered by the SCAG data.

Variability in the range of imperviousness for the C-CAP land use data was less than that of the SCAG and SanDAG data (Figure 3). For example, the 25th and 75th percentile estimates for high density residential were generally within 10% of each other for the C-CAP data. In contrast, there was a 20 - 25% range between the 25th and 75th percentile estimates for high density residential based on the SCAG and SanDAG data. Similarly, for commercial land uses, the C-CAP data produced a range of 20 -30% variability, while the SCAG and SanDAG data produced a range of 30 - 50%. As with the SCAG and SanDAG data, the C-CAP derived commercial and industrial areas had the highest degree of imperviousness followed by high and low density residential land use types.

The general ranges of variability in impervious cover estimates were consistent between counties. However, there were some differences between counties in the levels of impervious cover for a given land use type. For example, Riverside and San Bernardino counties consistently had lower ranges of imperviousness by land use category than the coastal counties, with the differences being most pronounced for the commercial and industrial land use.

There were clear spatial patterns within Los Angles County based on the 10-km grid analysis of the high density single family Residential SCAG and high intensity urban residential C-CAP land use categories (Figure 4). For these individual land use types, the per-

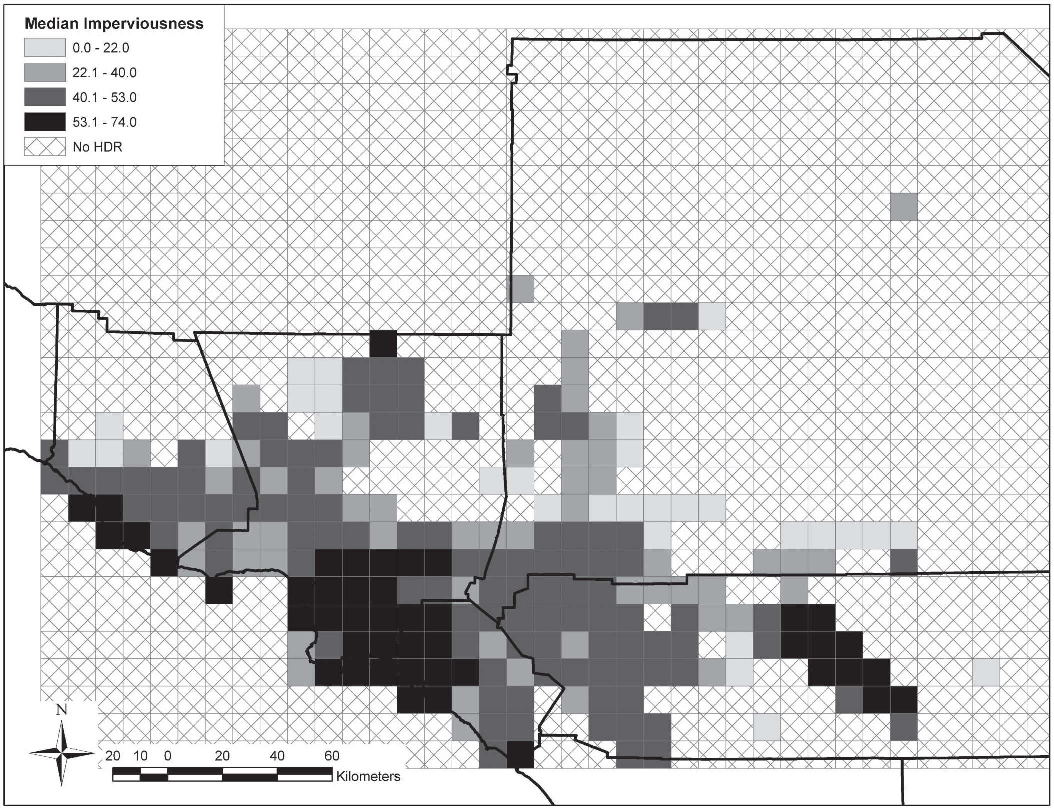

Figure 4. Median imperviousness for High Density Residential land use throughout the study area, using the SCAG land use data. Each square grid cell represents 100 km^2.

cent imperviousness was highest in the area surrounding central and downtown Los Angeles (56 - 74%). However, as the distance between the respective area and the central urban area increased, the percent imperviousness decreased to a low value of 5 - 15% along the mountain foothill development margins even though the mapped designated land used type did not change.

Within the watersheds analyzed, the SCAG/SanDAG and C-CAP data differed in terms of their accuracy and precision relative to the NLCD values that were used as a reference standard. In general, the SCAG/SanDAG data provided more accurate measures of imperviousness for a broader range of watershed sizes, i.e., the majority of the median impervious estimates were within ±5% of the NLCD values using both the individual and aggregated land use imperviousness values. Three watersheds were outside of the 25th and 75th percentile range of the NLCD standard based on aggregated land use categories. Only one watershed (Otay Valley) was outside this range based on the individual land use categories. Imperviousness estimates based on the C-CAP data were less accurate (compared to the NLCD standard) with five watersheds outside of the 25th and 75th percentile range based on aggregated land use values and seven outside this range based on the individual values. In terms of precision, the C-CAP data generally resulted in a narrower range of estimates than the SCAG/SanDAG derived values. Precision of impervious cover estimates (which we used as a measure of the overall range of variability) decreased with increasing development (or impervious cover). Watersheds with the highest amount of impervious cover (e.g., Ballona Creek) had the widest range of values whereas watersheds with the lowest amount of impervious cover (e.g., Topanga and Plum Canyon) had the lowest range of values. This reflects the expected increase in variability with increasing amount of developed land use.

Discussion

There was considerable variability in estimates of imperviousness within the aggregated land use categories for both the C-CAP and SCAG/SanDAG data. Variability in estimates of impervious cover can derive from errors in the image generation and classification (e.g., misclassification of land use or imperviousness pixels), differences in geometric registration, or due to actual spatial variability and heterogeneity of land use. In this study, we focus on bounding the error associated with the latter source of variability because it is an important consideration for managers and regulators when assigning specific impervious cover estimates based on land use type. Image classification errors clearly affect the accuracy of the source data used to make these estimates, but it was not the focus of this study.

The majority of the variability seen in this study likely results from several possible sources. First, errors associated with linking data sources with different resolutions (e.g., NLCD and SCAG); second, error associated with aggregation of different land use type into overall land use categories; third, actual spatial variability associated with differences in land use practices between locations and/or counties; and fourth, different projections of the four data sources.

The first source of variability is that the land use and impervious cover data sources have different resolutions. Detailed land use data used in the study resolves to about 2 m, while the NLCD resolves to 30 m. Therefore, a single pixel representing an impervious value could be assigned to multiple local land uses. As a result the assigned value is not representative of the imperviousness of each land used type, but rather represents an average of the land uses that occupy the pixel. This source of error could be improved by using higher resolution imagery (such as, IKONOS satellite images which resolves to 1 m) as the standard to convert land use to impervious cover. However, for many applications this may be cost prohibitive as most high resolution imagery is substantially more expensive than the LandSat derived NLCD estimates, which are freely available.

Land use aggregation is a second potential source of error. Within a given aggregate land use type (e.g., open space) there may be multiple individual land use types with various amounts of impervious cover. This can lead to some counterintuitive results in the imperviousness estimates for some individual land uses within the aggregate categories. For example, in Orange County the open space land use had 15% impervious at the 90th percentile. This degree of imperviousness was much larger than expected. When the individual land uses were examined, it was seen that the Beaches and Beach Parks (which include parking lots and other impervious surfaces) had median imperviousness of 50 and 64%, respectively (Figure 5). As another example in the same county, the Freeway category (aggregated into transportation) had a median impervious of 62% (Figure 6). One would assume that a Freeway land

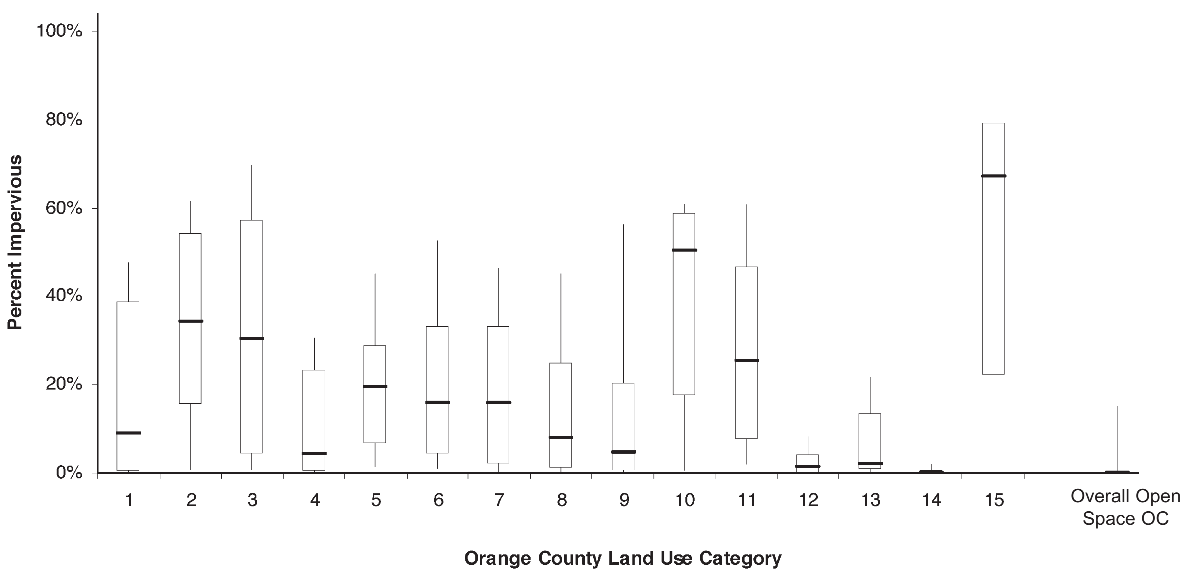

Figure 5. Distribution of imperviousness for individual and aggregated open area land uses within Orange County. Open land use categories include: 1. Vacant Area, 2. Air Field, 3. Former Base (Built-up Area), 4. Former Base (Vacant Area), 5. Former Base Air Field, 6. Mineral Extraction - Other Than Oil and Gas, 7. Under Construction, 8. Cemeteries, 9. Wildlife Preserves and Sanctuaries, 10. Beach Parks, 11. Other Open Space and Recreation, 12. Vacant Undifferentiated, 13. Abandoned Orchards and Vineyards, 14. Vacant with Limited Improvements, and 15. Beaches (Vacant).

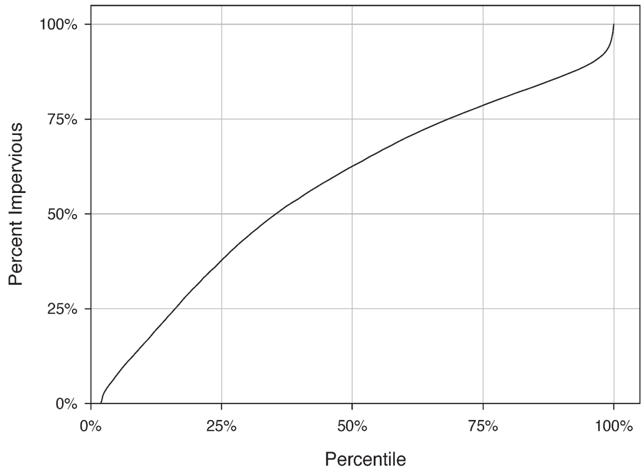

Figure 6. Cumulative distribution of imperviousness for the freeway land use in Orange County. Median = 63% impervious.

use would be at or nearly 100% impervious. Visual inspection of the NLCD pixels at the intersection of two major freeways in Orange County showed that the pixels completely representing the concrete freeway had impervious values near 80%. This suggests that the aggregation error may be compounded by the fact that the optimized training algorithm used to develop the NLCD data doesn't accurately represent all impervious types equally. This error could be mitigated by developing a local coverage imperviousness using high resolution imagery and local algorithm training and calibration. However, this would substantially increase the time and cost to generate and analyze the data when using impervious cover estimates in models or as surrogate indicators of human disturbance. This increase in effort should be weighed against the desired level of confidence (i.e., variability) necessary for application of the data.

A third source of error appears to be associated with actual spatial variability associated with differences in land use practices within and between counties. There were consistent spatial patterns in the results for aggregated land use categories between the five counties analyzed. The most notable example would be for the industrial land use category, where three of the counties had a median imperviousness of 0% (Figure 2). In addition, ranges of impervious values across all land use categories were consistently lower in the inland Riverside and San Bernardino counties than they were in the coastal counties, regardless of the data source used to derive the estimates. Furthermore, within Los Angeles County, impervious cover associated with a specific land use type (high density residential) decreased with increasing distance from the center of the city. This suggests that zoning, land use, and construction practices differ within and between counties even within a given aggregate land use category. This spatial variability is perhaps the most important consideration from a management perspective because it suggests that within a given land use category, impervious cover estimates should be assigned intra-regionally. Alternatively, managers could use NLCD (or other impervious cover data sets) directly, rather than trying to translate land use type to impervious cover.

Another source of error derives from using spatial data with different projections. This error would be most prevalent between the coarser resolution C-CAP and NLCD raster data. The SCAG and SanDAG land use datasets are in vector format and have a finer resolution, thus the error associated with different projections would have less of an impact. When looking at the relative error between the C-CAP and SCAG/SanDAG land use impervious estimates (Figures 2 and 3), the more detailed SCAG/SanDAG have larger ranges than the C-CAP data. This is because the C-CAP and NLCD have the same projection and resolution; therefore, their comparison provides a more direct relationship between imperviousness and land use since their pixels align. When using the SCAG/SanDAG data, multiple land uses are assigned the same impervious value within a NLDC pixel; therefore, the effects of different data formats are amplified. Reprojecting the data to a common resolution could minimize some errors. However, some errors will persist, particularly when the source data sets have different resolutions.

As would be expected, uncertainty in estimates of imperviousness increases with increasing amount of watershed development. Watersheds with less than 15 - 20% overall development had the least variability in estimated imperviousness, with overall error increasing with increasing development, or imperviousness (Figure 7). Consequently, when using impervious cover as a surrogate for intensity of human impacts, it is important to consider that the variability (and error) associated with the imperviousness estimates may be equal to or greater than the differences being used to indicate environmental effect. For example, if an impact designation or a management response is associated with 10% change in impervious cover, the error in the estimate of imperviousness may exceed the ability to accurately detect such a change.

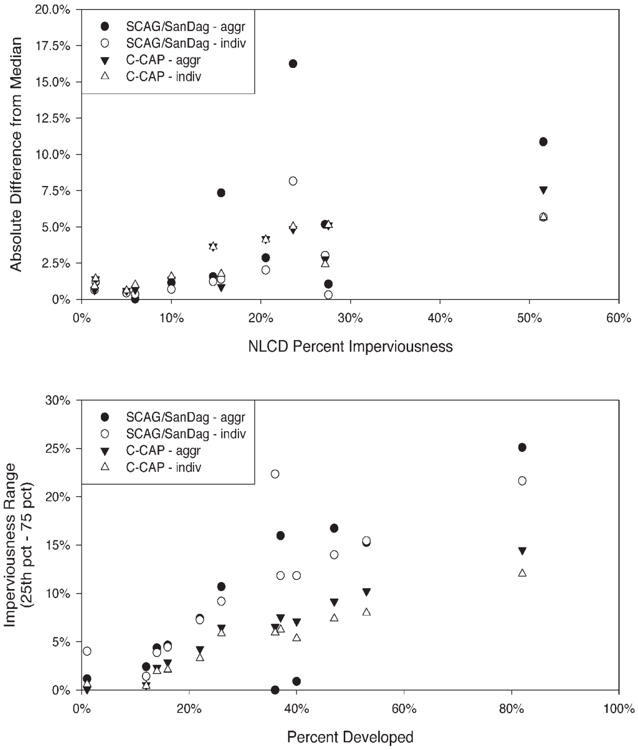

Figure 7. Effect of watershed development on accuracy and precision of impervious estimates. Top graph relates accuracy to percent impervious cover; bottom graph relates precision to percent development. aggr = aggregated land uses; indiv = individual land use.

Watershed managers are mostly concerned with changes in imperviousness of a few percentage points in developing watersheds with little to no imperviousness. For example, Schiff and Benoit (2007) recently reported 5% impervious cover as a critical level above which stream health declined. This study has shown that variability on that order can be seen simply within like land use categories and spatially across a county or region. In addition, the accuracy of the land use-imperviousness relationships is limited by the spatial resolution of the datasets (the 2-m detailed land use data provided a more accurate estimate for watershed imperviousness than the 30-meter C-CAP data). Therefore, using land use to estimate percent imperviousness, where a high degree of accuracy is necessary, can lead to a poor representation of the actual imperviousness. Where a few percentage points can make a significant difference in a management decision, local impervious data should be collected at a resolution comparable to the size of the area of interest. Baring collecting high resolution impervious data, we recommend that relationships between imperviousness and land use be developed using disaggregated land use data rather than the coarser aggregated categories.

Although this study was done in southern California, the data sources (i.e., local land use data, C-CAP, NLCD) are commonly used across the United States; therefore, it is reasonable to expect that similar variability would be observed in other areas. Numerous studies have related impervious cover to changes in the biological and physical health of streams (Paul and Meyer 2001, Morse *et al*. 2003, Konrad and Booth 2005). There is often disagreement in the literature over the scale at which impervious cover is the best predictor of environmental effects, i.e., is impervious cover most predictive at the reach, local drainage area, or watershed scale? Based on this analysis, some of the differences observed between previous studies may be due to spatial variability and error in impervious cover estimates between study locations (in addition to actual mechanistic differences in ecological response). Such variability supports the need to take a multidimensional approach to assessing effects of land use on stream or wetland integrity (Booth *et al*. 2004). Similarly, water quality models that predict changes in runoff or water quality associated with impervious cover, e.g., HSPF (Bicknell *et al*. 2001) and SWMM (Huber and Dickinson 1988), should account for variability in impervious estimates when estimating overall model confidence. No matter what the application, it is important that the variability and confidence intervals associated with estimates of impervious cover be considered to ensure that the reliability of the impervious estimate is represented in the results of any analysis.

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