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Survey design and extent estimates for the Wadeable Streams Assessment

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Abstract. The US Environmental Protection Agency (EPA) conducted a Wadeable Stream Assessment (WSA) of all wadeable streams and rivers in the conterminous US between 1999 and 2005. The assessment was led by the EPA Office of Water, in cooperation with EPA regions, states, tribal nations, and the EPA Office of Research and Development (ORD). The WSA was implemented as 2 large-scale regional surveys of streams and rivers. Both studies used EPA's River Reach File (RF3) as the basis for the sample frame. The Environmental Monitoring and Assessment Program (EMAP) Western Pilot Study, conducted by ORD in cooperation with EPA Regions 8, 9, and 10 and 12 western states, assessed all streams and rivers in the 12 western states (EMAP-West). A stratified, unequal probability survey design (50 sites/state and additional sites in 5 intensive study areas) was used to select sites from all streams and river segments coded as perennial in RF3. The unequal selection depended on Strahler order, aggregated Omernik level III ecoregion, and special study region. The WSA study used the EMAP-West wadeable streams (WSA-West) and implemented a new design for the remaining 36 eastern conterminous states (WSA-East). The WSA-East design was an unequal probability survey design with unequal selection depending on Strahler order, Omernik Level II ecoregion, and EPA region. RF3 includes 5.29 million km of rivers and streams, of which 39% (2.07 million km) are coded as perennial. The WSA sample frame included 2.84 million km of streams (54% of the total length in RF3), of which 2.24 million km were in WSA-East and 0.60 million km were in WSA-West. Each selected site was classified on the basis of wadeability and the presence of flowing water. The estimated length of wadeable streams and rivers in the 48 conterminous states was 1.30 ± 0.025 (SE) million km (45.7 ± 1.1% of the stream length in the sample frame). Of this wadeable stream length, 78.6 ± 1.0% (1.02 million km) was estimated to be appropriate for sampling. Nationally, 11.5 ± 0.8% and 5.2 ± 0.6% of this length could not be sampled because of access denial or physical inaccessibility, respectively. The proportion of length affected by access denial was higher in Southern Plains, Northern Plains, and Xeric West aggregated ecoregions, whereas stream length affected by physical inaccessibility was greatest in the Western Mountains aggregated ecoregion. Improvements in the sample frame (RF3 and its successors National Hydrography Database [NHD] and NHD-Plus) would reduce field costs for national surveys.

Key words: aquatic resource survey, monitoring design, survey design, National Hydrography Database, NHD, River Reach File, RF3, Wadeable Streams Assessment, wadeable streams, extent estimation, EMAP, sample frame.

Lack of comparability among monitoring studies has hampered and, in some cases, curtailed reporting the biological condition of US aquatic resources. For example, the US Environmental Protection Agency (EPA) is required to report on the status and extent of US aquatic resources to fulfill a requirement of the Clean Water Act (section 305[b]). At present, EPA compiles reports prepared by individual states (e.g., USEPA 2002), which use different methods for assessing condition, different methods for selecting streams and rivers, and typically rely on the National Hydrography Dataset (NHD; Dewald 2006) to determine extent. Larsen (1997), Paulsen et al. (1998), Olsen et al. (1999), and others have discussed the limitations of current reporting of aquatic-resource condition. Initial attempts to produce a national environmental report card were constrained by lack of comparability in available data because of differences in monitoring designs and methods (H. John Heinz Center for Science, Economics, and the Environment 2002,

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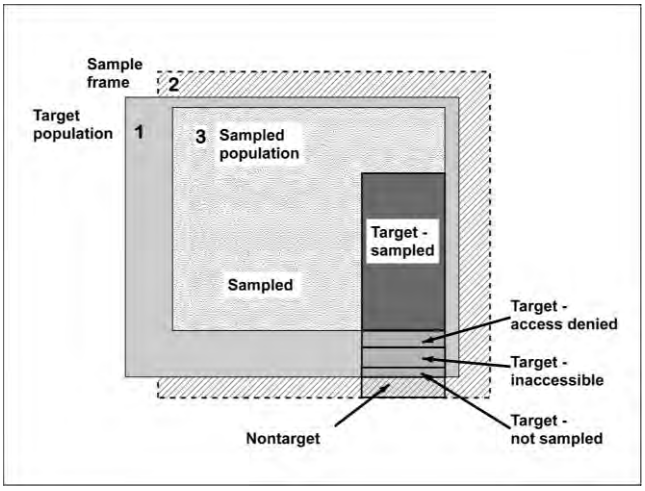

FIG. 1. Conceptual relationships among the target population, sample frame, and sampled population in a probabilistic sampling survey design. The target population (1) is the component of the resource to be assessed. The sample frame (2) is a geographical information system representation of the target population and provides the basis for the selection of sampling sites. The sampled population (3) is the portion of the target population represented by the final set of sampled sites. Ecological condition can be assessed only for the sampled population. Sites selected for sampling include sites in the target population that were sampled; sites in the target population that were not sampled because access was denied, the site was inaccessible, or for other reasons; and sites thought suitable when selected but that were nontarget when sampling was conducted.

USEPA 2003a). In 2004, the EPA Office of Water, in cooperation with state agencies, conducted the Wadeable Streams Assessment (WSA; USEPA 2006) to address some of these issues. The WSA was a probability-based survey of wadeable streams in the conterminous US that provided a means by which to draw statistically valid assessments of the extent and condition of these streams. Our main goal is to describe the design of this probability survey and to provide estimates of the wadeable stream length (extent) for the conterminous US.

Probability-based survey designs provide scientifically rigorous and cost-effective assessments of status and trends in resource condition at large scales (Larsen 1997, Olsen et al. 1999, USEPA 2003b). A probability-based survey design for assessing an aquatic resource, such as streams and rivers, requires objectives that are stated precisely in quantitative terms (Paulsen et al. 1998, Olsen et al. 1999). The objectives determine the *target population*, that component of the resource to be assessed. The target population must be defined explicitly and precisely to be understood easily by data users and field crews. In particular, field crews must be able to determine if sampling points should indeed be sampled. Once the target population is defined, a *sample frame,* based on a geographical information system (GIS) representation of this target population, must be defined. The sample frame provides the basis for the selection of distinct sampling sites, but sample frames are rarely an exact representation of a desired target population (Fig. 1). Some elements of the target population might be missing from the sample frame, and some elements that are not part of the target population might be included in the sample frame. Not all sites selected for sampling actually can be sampled, or some sites that appear appropriate during the selection process might not meet the criteria for inclusion in the target population when they are visited for sampling. These inconsistencies influence the ability to make inferences from the set of sampled sites to the target population. No inferences can be made to any portion of the target population not included in the sample frame, and inferences are restricted to that portion of the target population represented in the final set of sampled sites (*sampled population*).

The best available sample frame for streams and rivers is the River Reach File, version 3 (RF3). RF3 has been used as a sample frame in probability-based survey designs to determine the extent of stream length inhabited by various fish species (Murray 1987, Olsen et al. 1999) and the extent of stream length affected by acidic deposition (Kaufmann et al. 1991, Olsen et al. 1999). RF3 also was used by the Environmental Monitoring and Assessment Program (EMAP) to assess status in ecological condition (e.g., Bradley and Landy 2000, Herlihy et al. 2000, Hughes et al. 2000, USEPA 2000). Attribute information for each stream segment in the RF3 (e.g., intermittent or perennial) can be useful for refining the definition of the sample frame so that it represents the target population more accurately; however, classification errors exist in the stream network represented in these large databases (e.g., Leopold 1994, Fitzpatrick et al. 1998). Monitoring designs based on RF3 must account for these errors in the design and in the statistical analyses. Therefore, we describe our efforts to quantify the effects of attribute errors in RF3 in our final extent estimates.

Methods

A survey design requires clear quantitative statements of the study objectives, an explicit definition of the target population and selection of a sample frame, and specification of the site selection process. Study objectives must be stated in the form of a question that

can be addressed quantitatively; e.g., "Estimate the total wadeable stream length (km) within the 48 conterminous United States." The target population is an explicit written definition that identifies the aquatic resource unit of interest. The definition must include criteria for determining whether a specific resource unit is included or excluded. The definition and criteria must be understandable by field crews, which must decide if a unit is part of the target population, and by users of the results of the survey, who need to know what aquatic resource was included in the survey. A GIS data layer that includes all of the target population must be acquired for use as the sample frame. The statistical survey design specifies how the sites are selected from the sample frame. The design includes a definition of the stratification, categories for unequal probability of selection, and sample-size requirements.

EPA sought to answer 2 questions with the WSA: 1) What is the extent of flowing wadeable waters in the conterminous states? 2) What is the condition of these waters? In this study, the target population of flowing wadeable streams was defined operationally as streams with flowing water at the time of the field visit that could be sampled safely by field crews by wading to collect biological samples, water-quality samples, and physical-habitat measurements.

The WSA probability-based survey design consisted of 2 independent survey designs (strata): 1) WSA-West, which was derived from an earlier EMAP Western Pilot Study (EMAP-West) for 12 western states; and 2) WSA-East, which was a wadeable stream design for 36 eastern states (Fig. 2). This combination of designs enabled the WSA study to take advantage of existing data collected by the EMAP-West study.

EMAP-West survey design

From 2000 to 2004, the EPA, in cooperation with various state and federal agencies, conducted EMAP-West, a probability-based survey to assess the ecological status and extent of streams and rivers in the western US (Stoddard et al. 2005). The primary objective of the EMAP-West study was to estimate the total length (extent) of flowing waters and their condition in EPA Regions 8, 9, and 10. The 12 states included were Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming in Region 8; Arizona, California, and Nevada in Region 9; and Oregon, Idaho, and Washington in Region 10. A secondary objective was to investigate the impact of incorrect perennial/nonperennial designations in RF3 when used to identify streams with flowing water during the index period.

The target population was defined as all streams and rivers with flowing water during the index period within the study region. The target population did not include Great Rivers, such as the Columbia River, the Missouri River from its beginning at Three Forks (near the northwest corner of Yellowstone National Park), the Snake River below the Palisades Dam in Idaho (near the Wyoming border south of Grand Teton National Park) to its confluence with the Columbia, and the Colorado River from its confluence with the Eagle River in Colorado (at Dotsero, Colorado) to the Mexico border. The target population for EMAP-West differed from the set of *wadeable* streams that were assessed in WSA. The approach for extracting wadeable streams from the EMAP-West survey is described below.

The sample frame was extracted from RF3, which is based on digitized blue lines from 1:100,000-scale US Geological Survey (USGS) maps (Horn and Grayman 1993). The sample frame was enhanced by the addition of Strahler stream order (Strahler 1957) by an automated process completed by the RF3 development staff. Stream order was used to vary the probability of selecting streams that ranged in size from headwaters to major rivers to ensure that both wadeable and nonwadeable streams were included in the survey design. The EMAP-West study assumed that the sample frame included all stream channels specified by the definition of the target population. That is, stream channels that were not included in RF3 were not included in the study.

The sample frame included all RF3 stream channel segments coded in their attribute tables as regular reach, start/headwater reach, terminal reach, non-networked reach, wide river (one bank only), or unknown. As with the target population, the sample frame excluded all of the Columbia and Missouri rivers and portions of the Snake and Colorado rivers. The sample frame was subdivided into 2 major parts: 1) all stream segments coded as perennial in the RF3, which were used for the EMAP-West survey design; and 2) all stream segments identified as nonperennial, i.e., all other stream segments, which were used for an EMAP-West nonperennial survey design (Stoddard et al. 2005).

Additional attributes were added to the sample frame so that they could be used to vary the probability of selecting a stream segment to meet the survey design requirements. Each segment was assigned to the appropriate state and special study unit. Each stream segment was assigned to an Omernik level III ecoregion (Omernik 1987; revised January

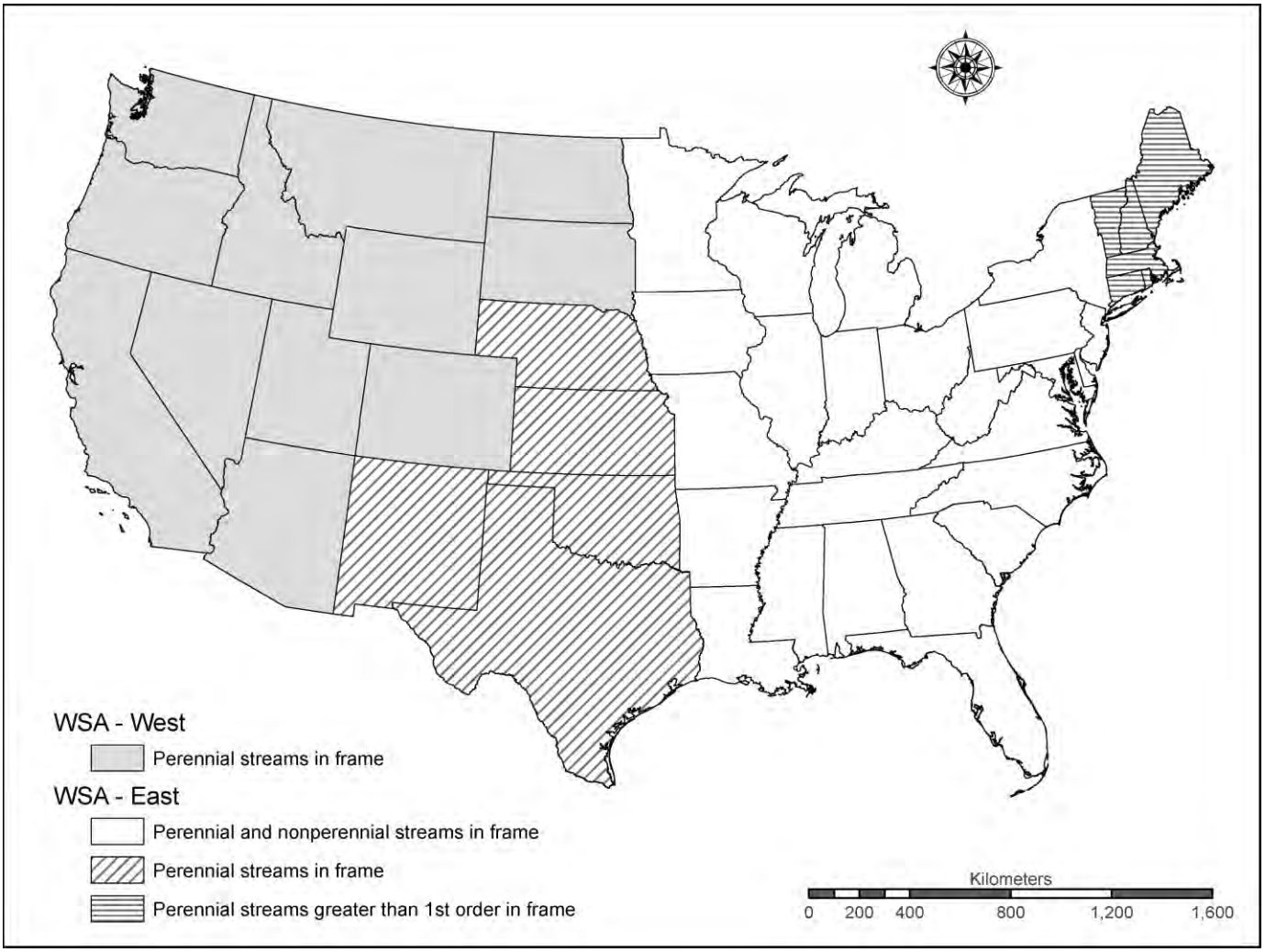

FIG. 2. Two strata in the Wadeable Stream Assessment (WSA). WSA-West was derived from the Environmental Monitoring and Assessment Program Western Pilot Study (EMAP-West) for 12 western states, and WSA-East was a wadeable stream design for 36 eastern states (see Methods for details). Nonperennial streams were not sampled in WSA-West and in 5 states in WSA-East, and 1st-order streams were not sampled in 6 states in WSA-East.

1999). Level III ecoregions were then classified as mountainous/humid or arid and were aggregated into 2 groups. EMAP-West objectives included a focus on nonwadeable rivers. All rivers with drainages >12,950 km^2 (5000 mi^2) were identified, and an attribute (large river) was added to the sample frame to identify these segments. Large-river segments in the sample frame were included in the EMAP-West perennial sample frame.

The study objective required subpopulation estimates for wadeable and nonwadeable streams with flowing water in the EMAP-West study area, each EPA region, and each of the 12 states. Therefore, the survey design was stratified by the 12 states and an unequal probability spatially balanced survey design was used within each stratum. Unequal probability categories were defined by stream-order categories (1st, 2nd, 3rd, 4th+, and large river) and by aggregated ecoregion. An approximately equal number of sites was allocated by stream-order category (1st, 2nd, 3rd, 4th+) within each aggregated ecoregion. For large rivers, the sample size was 120. The expected sample size for the basic survey design was 50 sites/state, for a total of 600 unique sites to be sampled across the study region.

Prior experience in Oregon and elsewhere in the West suggested that miscoding of perennial stream channels in RF3 varied by stream order and ecoregion and that landowners might deny access to ~20% of the sites. For example, in the Central California Valley, Hall et al. (1998) reported ~18% access denial and 33 to 46% no response from landowners. We combined these 2 sources of information to estimate the

TABLE 1. Expected % of probability survey sites that would be available for sampling in the Environmental Monitoring and Assessment Program Western Pilot Study. Availability was estimated based on previous experience with difficulty obtaining permission from landowners for access to sites and with physical inaccessibility. Accessibility was expected to be correlated with Strahler stream order and to differ between sites in humid and arid ecoregions.

	Expected %		Multipliers for selection	
Straher-order category	Humid ecoregions	Arid ecoregions	Humid ecoregions	Arid ecoregions
1^{st}	65	30	1.55	3.33
2^{nd}	75	50	1.33	2.00
3^{rd}	80	50	1.25	2.00
$\geq 4^{th}$	100	90	1.00	1.10
Large rivers	100	100	1.00	1.00

percentage of sites expected to be available for field sampling (Table 1). The final probability of selection was adjusted to incorporate these expected nonaccessibility rates. For example, rather than selecting an equal number of sites by stream-order category, additional sites are selected for lower stream-order categories with the expectation that the final set of sites sampled would be approximately equal among stream-order categories.

The site selection process also included an over-sample of sites that were available for use when the base samples could not be sampled. The over-sample sites ensured that sample size requirements (sites actually sampled in the field) were met. The number of over-sample sites was the same as the expected sample size for each state. If the over-sample sites were insufficient, then additional over-sample sites were selected until sufficient sites that could be sampled were found. Additional over-sample sites were required only in Arizona. Over-sample sites were given in a specified order (reverse hierarchical ordering) to ensure that the spatial balance of the survey design was preserved when they were added (Stevens and Olsen 2004).

Subpopulation estimates for flowing-water streams were required in the following special study areas: 1) the Colorado Plateaus Omernik level III ecoregion, 2) the Upper Missouri River Basin in EPA Region 8, 3) the Northern Glaciated Plains Omernik level III ecoregion in North and South Dakota, 4) the northern California coastal drainages in EPA Region 9, 5) the southern California coastal drainages in EPA Region 9, 6) the Deschutes/John Day River Basins in Oregon, and 7) the Wenatchee hydrologic unit in Washington (Fig. 3). Special study areas were determined by the interests of EPA Regions 8, 9, and 10 in obtaining more information regarding the streams in these areas. The 7 intensive study regions were incorporated by increasing the probability of selection of streams within the study region to achieve the expected sample size for that region. The same unequal probability selection was applied as for the statewide sample. For the Upper Missouri River Basin study, the expected sample size was allocated to each of the 4 states in proportion to the EMAP-West perennial sample frame stream length that occurred in the Upper Missouri River Basin within each state. This allocation was necessary because each state was a separate stratum. The total expected sample size for a state was 50 statewide sites and the additional sites allocated for the 5 special studies (50–160 sites/study) that included parts of a state. Overall sampling was planned at a total of 1035 sites.

WSA survey design

WSA-West stratum.—The major difference between the WSA and EMAP-West was that EMAP-West included both wadeable and nonwadeable streams, whereas WSA included only wadeable streams. This difference resulted in differences in the target populations and the sample frames. Only wadeable sites (sampled sites and sites that could not be sampled) from the EMAP-West perennial survey design were used for the WSA-West stratum. The sample frame for EMAP-West included all stream orders. Therefore, sites on any stream in the sample frame, including those on $\geq 6^{th}$-order or large-river streams, were included if they were wadeable. This process differed from that used in the WSA-East survey design (see below).

WSA-East survey design.—A new survey design was implemented for the 36 conterminous states not included in EMAP-West. The target population was all wadeable streams with flowing water during the index period. It was assumed that $>5^{th}$-order streams were not likely to be wadeable. Thus, the sample frame consisted of stream segments in RF3 that were $\leq 5^{th}$ order. For Kansas, Nebraska, New Mexico, Oklahoma, and Texas, the sample frame also excluded streams that were coded as nonperennial in RF3 because prior

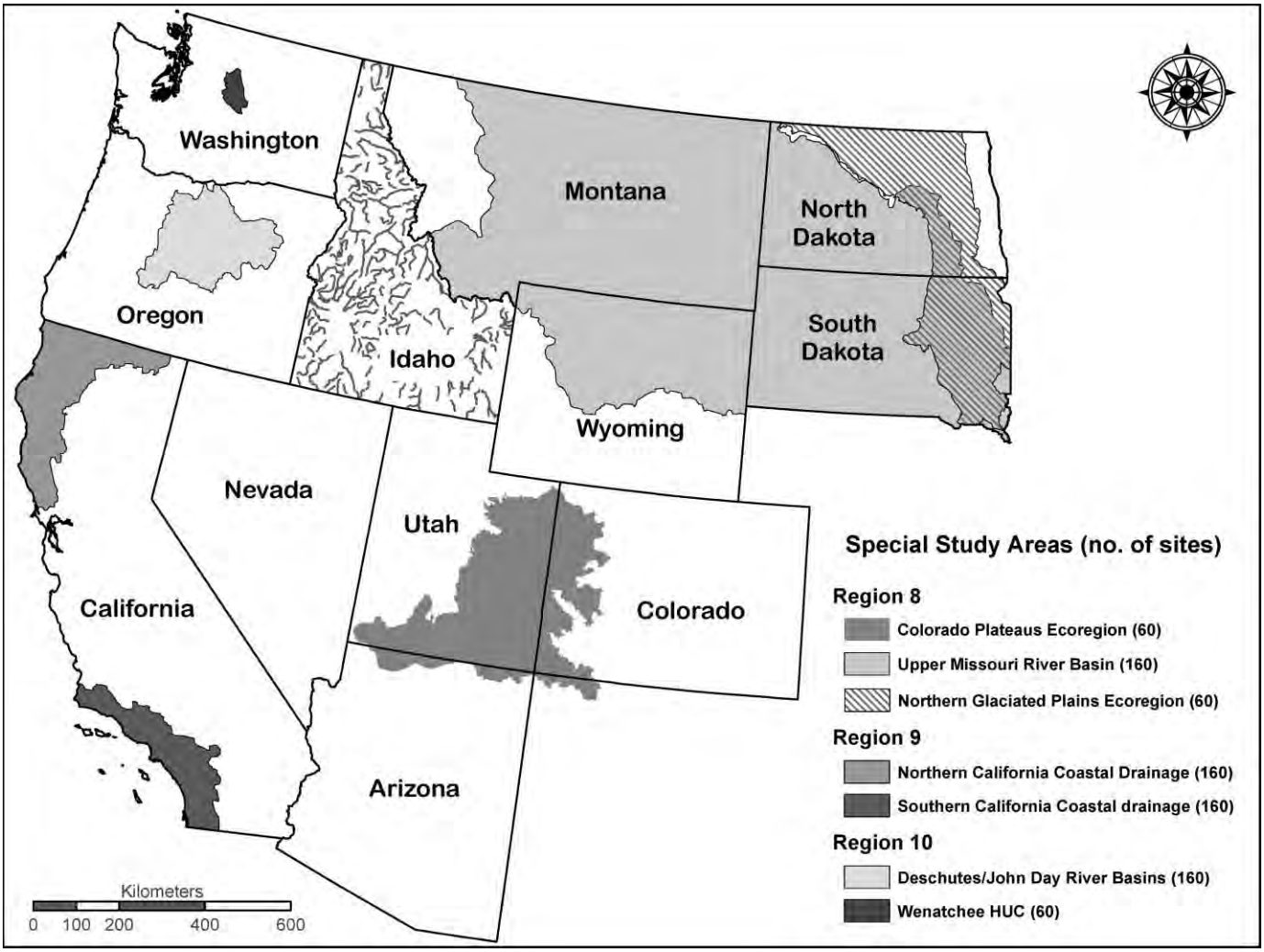

FIG. 3. States and special study regions in the Environmental Monitoring and Assessment Program Western Pilot Study (EMAP-West). Sites were allocated by state (50/state) and for special study areas determined by the interests of Environmental Protection Agency (EPA) Regions 8, 9, and 10. Idaho rivers shown were included in a special study of rivers. Ecoregions are Omernik level III ecoregions. HUC = hydrologic unit code.

experience had shown that almost all streams in Plains states coded as nonperennial in RF3 did not have flowing water during summer index period. The resulting sample frame more closely matched the target population of wadeable flowing-water streams than using RF3 without these exclusions.

A spatially balanced unequal probability survey design was used to obtain a sample size of 500 sites. Omernik level II ecoregions, 7 EPA regions, and 3 stream-order categories (1^{st}, 2^{nd}, and $3^{rd}+$) were used in the unequal probability selection. Over-sample sites were selected to use when base sites could not be sampled because they were not a wadeable stream or could not be accessed. Each state was provided with a list of sites to be sampled. When a site could not be sampled, the replacement was the next site on the list of over-sample sites in the EPA region (not the state). Four separate strata were created during implementation of the WSA-East stratum. Iowa, Virginia, and the New England states requested that they be allowed to use sites from their preexisting probability-based survey designs rather than the WSA-East sites selected within their states. This replacement was implemented after ensuring that the sample frame and target population definitions of the state sites were consistent with those of the WSA.

Site evaluation methods

The process for evaluating sites selected by the survey design for the WSA addressed 3 consecutive questions: 1) Was a stream channel present at the site

location? 2) If a channel was present, did it have flowing water? 3) If flowing water was present, did the stream fit the definition of a stream for the study? The site evaluation was conducted independently of information contained in RF3 and was done with standardized procedures and data recording forms (USEPA 2004). The procedures allowed various approaches to obtain information, including maps, photographs, publications, local contacts, and locally available GIS data. In some cases, a field visit to a site was conducted to acquire or confirm the information. Different individuals or groups conducted site evaluations for each state; each group determined the best approach to use in acquiring the necessary information.

Each site evaluated was classified as: flowing-water wadeable, flowing-water nonwadeable, flowing-water nontarget, nonflowing water, or nonflowing-water nontarget. Flowing-water sites were classified as sampled, inaccessible, or access denied. Sites were confirmed as flowing water or were presumed to be flowing water in the absence of evidence to the contrary (if the site was inaccessible or access was denied). Nontarget sites were sites that were not streams, e.g., impoundments, constructed canals, pipelines, or map errors (no stream channel at the site coordinates).

Extent estimation methods

Information from the site evaluation was used to estimate flowing-water stream length in the study and to estimate the stream length associated with access denial by landowners and physical inaccessibility. Statistical estimation of extent was done by: 1) compiling evaluation status for each site, 2) adjusting survey design weights, and 3) estimating the extent of flowing-water stream length. Each site that was evaluated represented a known stream length (based on the survey design adjusted weights), and these lengths were summed across sites to estimate extent. Statistical analyses were done with R software (version 2.1.0; R Development Core Team 2007) and an R contributed library (spsurvey; available from: http://www.epa.gov/nheerl/arm) that was developed specifically for the statistical analysis of probability survey design data.

Adjusting survey design weights.—The survey design assigned a weight to each site selected for potential sampling. The weights were in units of kilometers of stream length, e.g., a weight of 2.28 meant that the sampled site represented 2.28 km of stream length. The weights differed by state, stream-order category, aggregated ecoregion, and special study regions used in the survey design. The initial weight assignments were based on the assumption that the survey would not require any over-sample sites. To account for use of over-sample sites, adjusted weights were recalculated as:

$$w_{\text{adj}} = w_{\text{init}} \times \frac{L_{\text{RF3}}}{\sum w_{\text{init}}}$$

where w_{adj} is the adjusted site weight, w_{init} is the initial site weight, L_{RF3} is the stream length from the RF3 sample frame, and Σw_{init} is the sum of initial site weights for all evaluated sites. Sums for length and weights included all stream segments in the sample frame and sites within specific combinations of stratum and unequal probability category.

For the WSA-West stratum, 6 separate adjustment calculations were required for the statewide and special studies (statewide, Upper Missouri River Basin, Northern California, Southern California, Deschutes/John Day River Basins, and Wenatchee hydrologic unit). For the WSA-East stratum, 4 separate adjustment calculations were required (New England, Virginia, Iowa, and the remainder of WSA-East). The standard error (SE) for each extent estimate was calculated based on a local neighborhood variance estimate (Stevens and Olsen 2003). This variance estimator is designed specifically for application to surveys conducted over space and results in better confidence interval coverage than Horvitz–Thompson variance estimators (Horvitz and Thompson 1952).

Results

Sample frame summaries

The total RF3 stream length was 5.29 million km; 39% (2.07 million km) was coded perennial and 61% (3.22 million km) was coded nonperennial (Table 2). Approximately 65% of the total RF3 stream length was coded 1st order. Only 44% of perennial stream length was coded 1st order, whereas 79% nonperennial stream length was coded 1st order. The WSA sample frame included 2.84 million km (54%) of the total RF3 stream length. The WSA sample frame excluded 2.36 million km of RF3 nonperennial stream length in the western states and ~0.08 million km of RF3 perennial 6th- to 10th-order river length (Table 2). The latter is approximate because the EMAP-West sample frame included RF3 perennial rivers that were 6th to 10th order, and most, but not all, of these rivers were nonwadeable.

Most of the excluded RF3 stream length consisted of nonperennial streams in the West reporting region (Table 3) and streams $\geq$6th order in WSA-East. Only ~4% of the total length was excluded in the Eastern Highlands reporting region, whereas ~42% and ~71%

TABLE 2. Lengths (km) of perennial and nonperennial streams by Strahler stream order: 1) in the US Environmental Protection Agency's River Reach File (RF3) database, 2) included in the Wadeable Stream Assessment (WSA) sample frame, and 3) excluded from the WSA sample frame. The WSA consisted of 2 strata. WSA-West was derived from the Environmental Monitoring and Assessment Program Western Pilot Study (EMAP-West) for 12 western states, and WSA-East was a wadeable stream design for 36 eastern states (see Methods for details). WSA-West perennial stream length excluded 6th- to 10th-order rivers that were included in EMAP-West. In some cases, totals might differ from actual sums of lengths because of rounding.

	Perennial			Nonperennial			Total		
Stream order	WSA-East	WSA-West	Total	WSA-East	WSA-West	Total	WSA-East	WSA-West	Total
Total length in RF3									
1st	619,373	298,121	917,494	1,294,091	1,239,091	2,533,182	1,913,463	1,537,212	3,450,676
2nd	328,144	125,122	453,266	205,127	249,054	454,180	533,270	374,176	907,446
3rd	228,761	88,342	317,104	62,542	101,502	164,044	291,303	189,844	481,147
4th	138,232	58,491	196,723	17,352	35,500	52,852	155,584	93,992	249,575
5th	65,005	33,640	98,646	4294	8854	13,148	69,300	42,494	111,793
6th–10th	57,729	24,908	82,637	2509	4200	6709	60,238	29,108	89,346
Total	1,437,244	628,625	2,065,869	1,585,915	1,638,201	3,224,115	3,023,159	2,266,825	5,289,984
Length included in WSA sample frame									
1st	619,373	298,121	917,494	763,185	0	763,185	1,382,558	298,121	1,680,679
2nd	328,144	125,122	453,266	78,495	0	78,495	406,639	125,122	531,761
3rd	228,761	88,342	317,104	13,366	0	13,366	242,127	88,342	330,470
4th	138,232	58,491	196,723	3221	0	3221	141,452	58,491	199,944
5th	65,005	33,640	98,646	1080	0	1080	66,085	33,640	99,725
6th–10th	0	0	0	0	0	0	0	0	0
Total	1,379,515	603,717	1,983,232	859,347	0	859,347	2,238,862	603,717	2,842,579
Length excluded from WSA sample frame									
1st	0	0	0	530,905	1,239,091	1,769,997	530,905	1,239,091	1,769,997
2nd	0	0	0	126,632	249,054	375,685	126,632	249,054	375,685
3rd	0	0	0	49,176	101,502	150,678	49,176	101,502	150,678
4th	0	0	0	14,132	35,500	49,632	14,132	35,500	49,632
5th	0	0	0	3215	8854	12,068	3215	8854	12,068
6th–10th	57,729	24,908	82,637	2509	4200	6709	60,238	29,108	89,346
Total	57,729	24,908	82,637	726,568	1,638,201	2,364,768	784,297	1,663,109	2,447,405

TABLE 3. Lengths (km) of streams coded as nonperennial in the US Environmental Protection Agency's River Reach File (RF3) that were included in or excluded from the Wadeable Stream Assessment (WSA) sample frame for 3 major reporting regions and 9 aggregated Omernik level III ecoregions of the USA.

	Included		Excluded		
Region	Length (km)	%	Length (km)	%	Total length in RF3
Conterminous US	2,842,578	53.7	2,447,405	46.3	5,289,984
Major reporting regions					
Eastern Highlands	868,976	96.5	31,182	3.5	900,158
Plains and Lowlands	1,409,624	57.8	1,028,002	42.2	2,437,626
West	563,979	28.9	1,388,222	71.1	1,952,200
Aggregated ecoregions					
Coastal Plains	615,390	90.7	63,027	9.3	678,417
Northern Appalachians	221,126	98.8	2720	1.2	223,845
Northern Plains	35,841	9.5	341,976	90.5	377,818
Southern Appalachians	647,850	95.8	28,462	4.2	676,312
Southern Plains	74,053	13.2	483,366	86.7	557,419
Temperate Plains	481,050	77.8	137,369	22.2	618,419
Upper Midwest	203,291	98.9	2263	1.1	205,554
Western Mountains	403,791	53.2	355,725	46.8	759,515
Xeric West	160,188	13.4	1,032,497	86.6	1,192,685

TABLE 4. Expected sample size and number of sites requiring evaluation for the Environmental Monitoring and Assessment Program Western Pilot Study in 12 western states. Sites were allocated on a statewide basis and for special study areas determined by the interests of US Environmental Protection Agency Regions 8, 9, and 10.

State	Expected sample size			Sites evaluated	Outcome for evaluated sites at which sampling was attempted				
	State	Special	Total		Total	Sampled	Access denied	Physically inaccessible	Nontarget
Arizona	50	0	50	384	384	47	24	4	309
California	50	100	150	528	475	169	62	49	195
Colorado	50	25	75	203	125	67	22	0	36
Idaho	50	0	50	138	108	48	8	14	38
Montana	50	87	137	198	124	69	19	8	28
Nevada	50	0	50	208	106	51	5	2	48
North Dakota	50	12	62	204	151	63	4	1	83
Oregon	50	100	150	424	329	146	88	2	93
South Dakota	50	24	74	221	99	76	8	0	15
Utah	50	0	50	168	132	55	1	5	71
Washington	50	50	100	290	186	100	18	27	41
Wyoming	50	37	87	262	123	74	13	3	33
Total	600	435	1035	3228	2342	965	272	115	990

of the total length were excluded in the Plains and Lowlands and West reporting regions, respectively. The length excluded in the 9 aggregated ecoregions ranged from ~1% (Northern Appalachians and Upper Midwest) to ~87–91% (Southern Plains, Xeric West, and Northern Plains). The high percentage of excluded streams in some ecoregions was a consequence of excluding nonperennial streams in 17 western states from the sample frame.

Number of sites evaluated and sampled

Excluded streams were designated as nontarget before any site evaluation or field-sampling visit. All sites that were evaluated were used to estimate the extent of wadeable streams for WSA and of wadeable and nonwadeable streams for EMAP-West.

EMAP-West.—Sampling was planned at a total of 1035 sites (Table 4). The total number of sites evaluated was 3228, and sampling was attempted at 2342 of these sites (Table 4). Some states evaluated many more sites than were subsequently required for field sampling. The number of evaluated sites ranged from 138 in Idaho to 528 in California. The number of sites at which sampling was attempted ranged from 99 in South Dakota to 475 in California.

Approximately 42% (990) of the RF3 perennial sites at which sampling was attempted were nontarget sites (Table 4). Most nontarget sites were in streams that lacked flowing water. The remaining nontarget sites were canals, ditches, impoundments, wetlands, tidal streams, or nonexistent stream channels. Approximately 12% (272) of the sites were not sampled because landowners denied access or could not be contacted to acquire access. Approximately 5% (115) of the sites could not be accessed physically, mainly for safety reasons. Sampling was completed at 965 sites (41% of the sites at which sampling was attempted and 71% of the target sites).

WSA.—A total of 3682 sites was evaluated (1495 in WSA-East, 2187 in WSA-West) (Table 5). The 2187 WSA-West sites were the subset of the 3228 EMAP-West sites that were evaluated and wadeable. The number of sites evaluated ranged from 107 in the Upper Midwest aggregated ecoregion to 1055 in the Western Mountains aggregated ecoregion (Table 5). The large number of sites evaluated in the Western Mountains and Xeric West aggregated ecoregions was the result of the special studies conducted in these ecoregions.

Sixty percent (2219) of the evaluated sites were target sites (wadeable streams with flowing water during the summer index period). This total includes sites that were physically inaccessible, where landowner permission was not obtained, where sampling was not completed, or that were not sampled for other reasons, even though on-site evaluation could not be completed for some sites. The 379 sites not sampled for other reasons were from the New England Wadeable Streams project (NEWS; Snook et al. 2007), which was substituted for part of the WSA-East stratum. NEWS excluded 1st-order streams from their sample frame on the assumption that the length of 1st-order streams with flowing waters would be small. Of the non-NEWS target sites (1840 sites), 17% (313) were not sampled because landowners denied access and 7% (134) could not be accessed physically. Sampling was

TABLE 5. Number of sites evaluated and outcomes in 9 aggregated Omernik level III ecoregions in the Wadeable Stream Assessment (WSA). The WSA consisted of 2 strata. WSA-West was derived from the Environmental Monitoring and Assessment Program Western Pilot Study for 12 western states, and WSA-East was a wadeable stream design for 36 eastern states (see Methods for details).

	WSA stratum			Evaluation result					
Aggregated ecoregion	WSA-East	WSA-West	Total	Sampled	Access denied	Physically inaccessible	Not sampled	Nontarget	Not evaluated
Coastal Plains	285	0	285	83	12	4	1	185	0
Northern Appalachians	588	0	588	85	4	13	0	107	379
Northern Plains	1	213	214	98	20	4	0	92	0
Southern Appalachians	276	0	276	184	15	6	0	71	0
Southern Plains	65	62	127	49	23	1	0	54	0
Temperate Plains	143	67	210	132	17	1	2	58	0
Upper Midwest	107	0	107	107	5	5	0	41	0
Western Mountains	17	1038	1055	528	156	90	0	281	0
Xeric West	13	807	820	175	61	10	0	574	0
Total	1495	2187	3682	1390	313	134	3	1463	379

completed at 1390 sites (63% of target sites, 76% of non-NEWS target sites; Fig. 4).

Extent of wadeable streams in the conterminous US

The estimated extent of target streams was 1.30 ± 0.03 million km (Table 6). This extent is 45.7% of the stream length in the WSA sample frame (frame length =←2.84 million km). Intermittent streams or dry channels accounted for most of the nontarget stream length in the WSA sample frame. The remaining nontarget streams were nonwadeable, tidally influenced, wetlands, or impoundments. Estimated target extent in the Eastern Highlands and Plains and Lowlands reporting regions were nearly equal (0.48 million km), whereas target extent in the West reporting region was somewhat lower (0.34 million km). Target extent and frame length were most similar in the West reporting region, where the target extent was ~61% of the frame length. In contrast, target extent was only ~34% of frame length in the Plains and Lowlands reporting region. Among the 9 aggregated ecoregions, the Southern Appalachians (0.32 million km) and the Western Mountains (0.29 million km) had the greatest estimated target extents, and the Northern Plains and the Southern Plains had the smallest target extents (0.03 and 0.05 million km, respectively). Target extents were ≥70% of the frame lengths in 3 aggregated ecoregions (Northern Plains, Northern Appalachians, Western Mountains) and were <40% of frame length in 4 aggregated ecoregions (Coastal Plains, Temperate Plains, Upper Midwest, Xeric West).

Not all target sites could be sampled. Therefore, the percentage of the target population at which landowners would have denied access, sites would have been physically inaccessible, or sites could not have been sampled for other reasons was estimated (Table 6). The portion of the target population for which ecological condition could be assessed (sampled population) was estimated as 1.02 ± 0.3 million km (79 ± 1.0% of the total target extent). The other 21% of the target extent is the portion of the target population for which stream condition could not be estimated. The sampled population ranged from 72% (Plains and Lowlands reporting region) to ~80% (Eastern Highlands, West reporting regions) of the target extent. Among the 9 aggregated ecoregions, the sampled population ranged from ~59% (Northern Appalachians) to ~90% (Temperate Plains, Southern Appalachians) of the target extent. Access denial prevented sampling in >20% of the target extent in the Northern Plains, Southern Plains, and Xeric West aggregated ecoregions. Physical inaccessibility prevented sampling in 5.2% (0.07 million km) of the target extent. Aggregated ecoregions with the greatest percentages of inaccessible streams were the Western Mountains (11.8%), Upper Midwest (8.4%), and Northern Plains (7.8%). Approximately 37% of sites in the Northern Appalachians aggregated ecoregion could not be sampled for other reasons. Most of these nonassessed streams were the result of using NEWS as a replacement for WSA in New England states.

Discussion

The EMAP-West and WSA studies provided the first estimate of wadeable stream length in the conterminous US and the first opportunity to evaluate the adequacy of the sample frames available for large-scale aquatic resource surveys. RF3 was the sample frame used for the EMAP-West and WSA surveys, but our

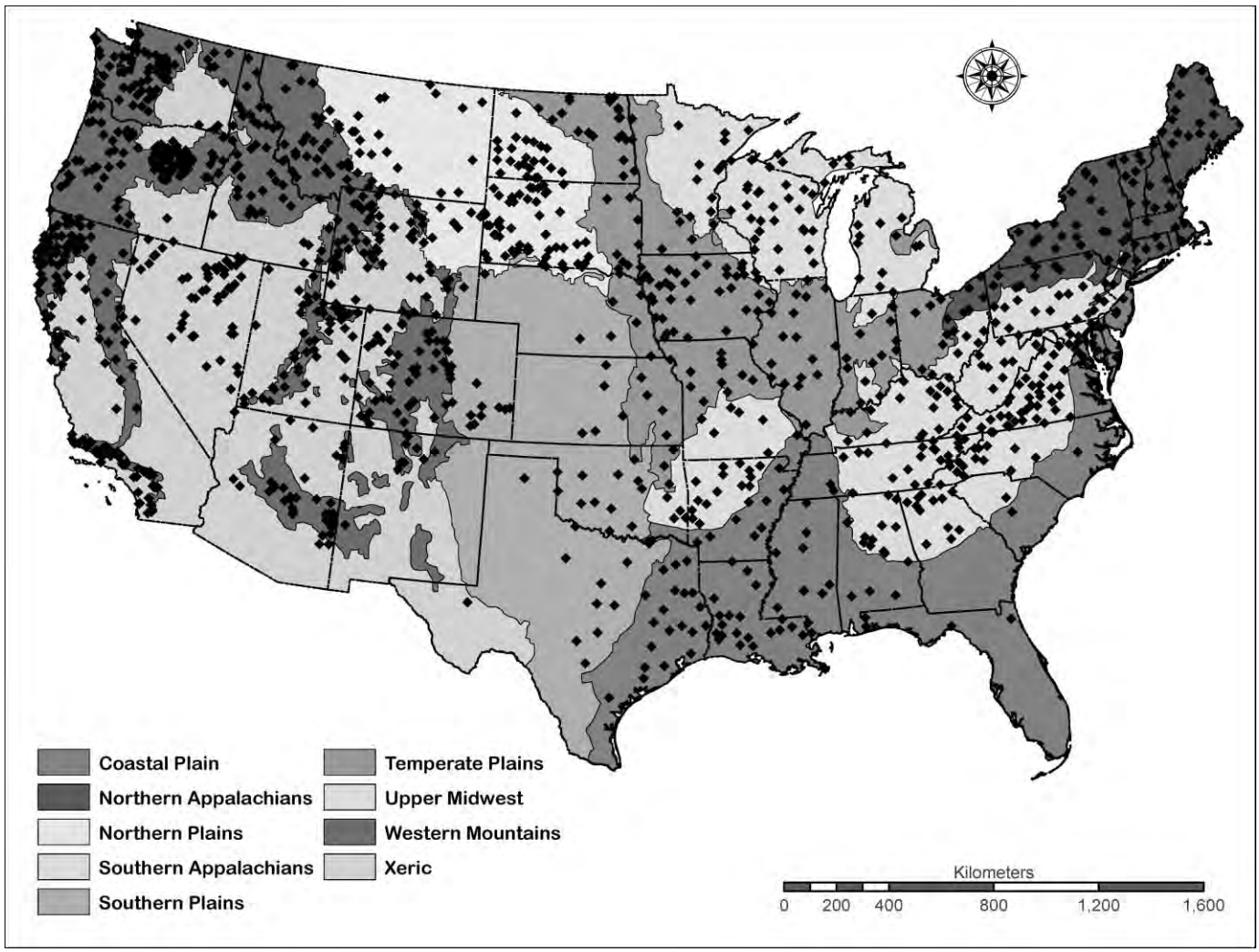

FIG. 4. Sampled sites in the Wadeable Streams Assessment (WSA). Labels are for Omernik level III aggregated ecoregions.

general conclusions also apply to the NHD and NHD-Plus sample frames because the 3 databases are based on the same 1:100,000-scale digital line graphs and the basic attribute information in RF3 is used in NHD and NHD-Plus. The extent of potential errors was estimated in terms of stream length to evaluate their potential impacts on assessment. Study objectives, survey design, and analyses were tightly linked to allow explicit estimates of target extent and the percentage of the target extent for which condition can be inferred.

Matching the sample frame with the target population

The sample frames developed for EMAP-West and WSA from RF3 were not perfect representations of the target populations (Fig. 1). Use of the stream lengths reported in RF3 without consideration of the relationships among the base data set, the target population, and the sample frame will result in overestimates of stream length. In the EMAP-West study, the target extent (wadeable and nonwadeable) was estimated as 67% of the total length of perennial streams represented in the sample frame (0.63 million km; Table 4) (Stoddard et al. 2005). In the WSA study, the target extent (wadeable) was estimated as 46% of the total length of perennial streams represented in the sample frame (Table 6).

Target population not represented in the sample frame

The RF3 sample frame excluded some stream channels because of inconsistencies in construction of 1:100,000 maps, digitization of map blue lines, or inadequacy of photographic information used to develop maps (e.g., heavily forested areas with low-order streams). Our study provides no information on the extent of these exclusions.

Some flowing-water streams miscoded as nonper-

TABLE 6. Estimated extent (total and %) of target streams in the US Environmental Protection Agency's River Reach File database that were included in the Wadeable Stream Assessment (WSA) sample frame for 3 major reporting regions and 9 aggregated Omernik level III ecoregions of the USA and percentages of the estimated flowing-water wadeable length in each evaluation outcome category. "Not sampled other" includes 379 sites from the New England Wadeable Streams Project (NEWS), which was substituted for part of the WSA-East stratum. The NEWS project excluded 1st-order streams from their sample frame. – indicates not applicable in region.

		Target extent				Evaluation result category							
		Length		% sample frame		Sampled		Access denied		Physically inaccessible		Not sampled other	
Region	Sample frame length (km)	Length (km)	SE	%	SE	%	SE	%	SE	%	SE	%	SE
Conterminous US	2,842,578	1,300,361	25,046	45.7	1.1	78.6	1.0	11.5	0.8	5.2	0.6	4.7	0.1
Major reporting region													
Eastern Highlands	868,976	481,656	16,646	55.4	2.1	79.6	1.5	5.0	1.2	3.1	1.0	12.4	0.4
Plains and Lowlands	563,979	343,407	8327	60.9	1.4	71.5	1.7	18.1	1.4	10.3	1.2	–	–
West	1,409,624	475,299	16,351	33.7	1.8	82.7	1.8	13.4	1.6	3.7	1.1	0.3	0.2
Aggregated ecoregion													
Coastal Plains	615,390	146,487	12,451	23.8	3.1	81.2	4.5	13.2	3.6	5.6	3.0	–	–
Northern Appalachians	221,126	163,222	6067	73.8	2.3	58.9	1.9	2.4	1.5	2.1	1.1	36.5	1.1
Northern Plains	35,841	31,375	2050	87.5	3.5	69.0	4.5	23.2	4.2	7.8	3.0	–	–
Southern Appalachians	647,850	318,434	15,498	49.2	2.8	90.2	2.1	6.3	1.6	3.6	1.4	–	–
Southern Plains	74,053	45,749	3629	61.8	5.2	67.7	6.2	30.0	6.1	2.2	1.8	–	–
Temperate Plains	481,050	180,137	7839	37.5	2.8	89.4	2.1	9.9	2.0	0.0	0	0.7	0.4
Upper Midwest	203,291	70,033	4807	34.5	4.0	84.0	4.3	7.7	3.1	8.4	3.1	–	–
Western Mountains	403,791	285,027	7690	70.6	1.8	71.4	1.9	16.8	1.5	11.8	1.4	–	–
Xeric West	160,188	57,838	2908	36.1	1.9	72.1	3.1	24.7	3.0	3.2	1.2	–	–

ennial in RF3 also were not included in the probability sample and, therefore, did not contribute to the assessment. Streams coded as nonperennial were excluded from the WSA sample frame in 17 western states (Fig. 2). Twelve of those states were part of EMAP-West, and data from EMAP-West were used to evaluate the extent of miscoding of nonperennial streams in RF3. Our analysis of those data (ARO, unpublished data) indicated that the length of flowing-water streams excluded from the WSA sample frame because of miscoding was 0.11 million km (7% of the stream length in EMAP-West states that is coded as nonperennial in RF3).

Inclusion of all flowing-water streams miscoded as nonperennial in RF3 in the WSA sample frame would have required extensive effort in the field. Extensive ground-truthing might be feasible in certain areas (e.g., southwestern US) where miscoded channels appear to be more common than in other areas (e.g., Valencia et al. 1993). Alternatively, a spatially explicit modeling approach might be developed to predict the probability that a stream segment would having flowing water based on other local or landscape conditions. These predictions could be used to determine which RF3 nonperennial segments should be included in the sample frame.

The sample frame for the WSA-East stratum also might have excluded target sites on streams that were $\geq 6^{th}$ order. These higher-order streams were included in the WSA-West stratum because the EMAP-West survey examined both wadeable and nonwadeable streams. However, exclusion of higher-order streams from WSA-East significantly reduced the effort required for site evaluation and probably excluded only a small number of wadeable high-order streams from the sampling frame.

Target population not included in the sampled population

Estimates of length based on sampled sites apply only to that portion of the target population represented in the sampled population (Fig. 1). Proportional estimates of extent (percentage of total length) can be inferred to the entire target population only if it is assumed that unsampled target sites are missing at random, i.e., sampling is independent of site characteristics. Sites that could not be sampled because of equipment problems can be assumed to be missing at random (unless sampling problems occurred more frequently with certain field crews than with others). Sites that could not be sampled because they were physically inaccessible are unlikely to be missing at random. For example, remote mountain streams are less likely to be influenced by human stressors than streams in lowlands or populous areas. Sites that could not be sampled because landowners refused access are

unlikely to be missing at random. At a minimum, these sites are more likely than others to be influenced by human stressors. For the WSA, 21% of the target stream length (Table 6) could not be sampled and, therefore, its ecological condition was not assessed.

At the national scale, sites for which access was denied made up the largest component of the target population that could not be assessed (11.5%; Table 6). The effect of access denials on assessed length varied by region. The proportion of length that could not be assessed because of access denials was large in the Northern Plains and Southern Plains aggregated ecoregions (Table 6), but the total length of target streams in these regions was relatively small. In the Central Valley in California, 38% of potential sampling sites could not be sampled because of access denial (Hall et al. 1998), and more effort (site evaluation, reconnaissance, and effort to secure permission) than expected was necessary to meet sample size requirements. In a study of Prairie Pothole wetlands in the Northern Plains aggregated ecoregion, ~60% of potential sites could not be sampled because of access denial (Lesser 2001). Denial of access might be reduced by finding and using procedures to obtain permission that have a higher probability of success.

For most aggregated ecoregions in the WSA, inability to sample sites for reasons other than physical accessibility or permission was not an issue (Table 6). However, in the Northern Appalachians aggregated ecoregion, 37% of the estimated target stream length could not be assessed for other reasons. The missing length consisted almost exclusively of 1st-order streams from the NEWS project (Snook et al. 2007) (Table 5). Therefore, the extent of the WSA target population represented by 1st-order streams could not be estimated in the Northern Appalachians aggregated ecoregion. In the remainder of the WSA strata, 1st-order streams were included in the sample frame and made up 44% of the RF3 length coded as perennial (Table 2).

Nontarget streams in the probability sample

The presence of nontarget streams in the set of sampled sites (Fig. 1) can be reduced by correcting obvious coding errors in the sample frame. RF3 consists of data from stream segments, where a segment is a part of stream, and one or more segments typically are defined between successive stream confluences. Potential coding errors for stream segments were assigned when RF3 was constructed and included: 1) designating stream order, 2) distinguishing perennial and intermittent streams, 3) defining natural vs constructed channels (including newly modified channels), and 4) distinguishing irrigation return-flow from irrigation delivery channels. However, the sample frame included stream segments that: 1) had no definable channel, 2) were in a wetland/marsh with no defined channel, or 3) were an impoundment. Incorrect code information will never be eliminated, especially with respect to the flow status of a stream. By necessity, operational definitions of flowing water are used for synoptic surveys because sites are visited only once during a defined sampling period. For the WSA, target sites had flowing water in the channel and were wadeable at the time of the field visit. In many parts of the US, sampling for EMAP-West and WSA was conducted during an extended drought, and sites that typically would have had flowing water might have gone dry either before or after they were visited. Sites that dried before they were visited were classified as nontarget, whereas sites that dried after they were visited were included in the target population. A premise of WSA target extent estimates was that flowing-water status of streams would not change during the index period. Changes in flowing-water status during the study lead to a potential bias of unknown magnitude in the target extent estimates. Interannual differences in climate (e.g., drought) will result in different target extent estimates for surveys conducted in other years.

Considerations for future national aquatic resource assessments

The major lesson learned from large-scale probability surveys is that an accurate and consistent sample frame that can be used by all agencies as part of their monitoring designs is needed. Such a sample frame would make it easier to combine different studies and would provide a consistent basis of stream length from which to estimate extent or assess ecological condition. Such a frame would not eliminate the need for site evaluations or reconnaissance, but would reduce the cost and time associated with these activities and would minimize wasted field visits. NHD is the best current alternative to RF3 for development of such a sample frame.

EPA is cooperating with state and federal agencies to implement a revised strategy to obtain information to answer pertinent water-quality questions at multiple geographic scales (Shapiro et al. 2008, Paulsen et al. 2008). This strategy includes a component to conduct national-scale assessment of condition for aquatic resources. The National River and Stream Assessment (NRSA) is the component of the revised EPA strategy dealing with flowing-water resources. The version of NHD (and NHD-Plus) that is being considered for use

in NRSA, and other surveys of flowing waters, is based on 1:100,000-scale digital line graphs (DLGs), but a high-resolution version of NHD based on a 1:24,000 scale is nearing completion. The USGS is promoting a stewardship program to facilitate updating of the high-resolution version. A sample frame based on higher-resolution DLGs is appealing, especially for local-scale questions, but it also presents challenges. Estimates of stream length probably will change as segments are added, deleted, or modified when states conduct site evaluations and ground-truth segments. Moreover, the length of a given segment estimated from a 1:24,000-scale DLG will not match the length estimated from a 1:100,000-scale DLG.

New probability survey designs, developed specifically for aquatic resources, can be more efficient than the probability survey designs of 10 y ago. These designs can give states and tribal nations enormous flexibility when developing their monitoring programs. If states and tribal nations were to use probability survey designs based on a common sample frame derived from NHD and comparable indicators and methods, then their data could be aggregated to provide a national picture of the condition of aquatic ecosystems. If this practice were continued through time, then changes and trends in aquatic ecosystem conditions could be determined at a national scale. Additional attributes, such as streams on 303(d) or fish advisory lists, could be added so that results could be reported for those attributes. In addition, results from such designs can be used to develop nonpoint-source criteria, to develop predictive or explicit models to develop total maximum daily loads for impaired waters, or to predict probability of impairment for nonmonitored streams (e.g., Baker et al. 2005, Brown et al. 2005).

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