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EXTENT AND CHANNEL MORPHOLOGY OF UNMAPPED HEADWATER STREAM SEGMENTS OF THE QUABBIN WATERSHED, MASSACHUSETTS[1]

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ABSTRACT: Effective regulatory protection and management of headwater resources depend on consistent and accurate identification and delineation of stream occurrence. Published maps and digital resources fail to represent the true occurrence and extent of headwater streams. This study assessed the accuracy of mapped origins of “blue-line” streams depicted on U.S. Geological Survey topographic maps, and, if present, the morphological characteristics of unmapped stream segments. We identified 170 mapped stream origins on the Quabbin Reservoir watershed, Massachusetts. Of 30 mapped stream origins, we identified and examined 26 unmapped stream segments above 25, with an average length of 502 m. Twenty unmapped tributaries occurred on 10 of the 26 unmapped segments, with an average length of 127 m. Wetland reaches occurred more frequently and were larger on unmapped than on mapped stream segments. A significant and complex stream network occurs above most mapped stream origins. For the Quabbin watershed, we estimate that there are 85.8 km of unmapped stream upgradient of 314.5 km of mapped streams. Reliance on mapped stream networks for regulatory standards allows for the potential disturbance or even destruction of the unmapped stream resources. Jurisdictional regulations and guidelines should be revised so that the occurrence of streams should require field validation.

(KEY TERMS: headwater streams; stream survey; channel morphology; topographic maps; map accuracy.)

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INTRODUCTION

Headwater streams are small, unmapped to low-order (i.e., first-third) streams with ephemeral (associated with storm event), intermittent (seasonal), or perennial (year-round) flow (Peterson, 2001; Gomi *et al.*, 2002; Lowe and Likens, 2005; Svec *et al.*, 2005; MacDonald and Coe, 2007; Fritz *et al.*, 2008). They comprise the vast majority of stream networks and provide a wealth of downstream services including flood mitigation, maintenance of water quantity and quality, nutrient recycling, and habitat creation (Gomi *et al.*, 2002; Lowe and Likens, 2005; Alexander *et al.*, 2007; Freeman *et al.*, 2007; Jensen and Sutton, 2007; MacDonald and Coe, 2007; Nadeau and Rains, 2007a). Headwater streams can also provide habitat unique from downstream systems and contribute to

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total stream network diversity (Richardson and Danehy, 2007).

Following recent decisions by the United States (U.S.) Supreme Court [Solid Waste Agency of Northern Cook County (*SWANCC* 2001), *Rapanos* and *Carabell* (2005)], the accurate and complete delineation of headwater streams and associated wetlands are critical to their effective management (Nadeau and Rains, 2007a,b). The definition and delineation of streams are critical to their protection from disturbance, especially for low-order or headwater streams where their existence or extent in the field could be questioned (Jaeger *et al.*, 2007; Bishop *et al.*, 2008). In a model ordinance for stream buffers, the U.S. Environmental Protection Agency (USEPA) proposes that perennial streams be defined as "those depicted on a U.S. Geological Survey (USGS) map with a solid blue line" and intermittent streams as those "depicted on a USGS map with a dotted blue line" (Svec *et al.*, 2005). This kind of unambiguous definition and delineation of streams is easily determined and clearly understood, but underestimates the true extent of streams and lacks site specificity for the effective application of riparian management practices (Blinn and Kilgore, 2001; Hansen, 2001; Lee *et al.*, 2004; Colson *et al.*, 2008). The application of the USEPA's proposed definition has been shown to be inaccurate for site-specific applications and would exclude many extant headwater streams not shown on topographic maps (Hansen, 2001; Davic and Anderson, 2002; Moore and Richardson, 2003; Svec *et al.*, 2005; Jensen and Sutton, 2007; Vance-Borland *et al.*, 2007; Colson *et al.*, 2008; Roy *et al.*, 2009).

The paucity of research on the spatial distribution and ecology of the uppermost headwater streams precludes the development of effective oversight and regulatory programs, and exposes all lotic systems to the effects of the potential degradation of headwater reaches. To address some of these knowledge gaps, we have initiated a program of study of headwater streams in southern New England. This paper summarizes the results of our initial survey of the extent and morphology of a representative sample of headwater stream networks. The study was intended to assess the accuracy of mapped streams on topographic maps in representing the true origin (channel head) of headwater streams. The surveys were intended to address questions relative to landscape distribution, instream habitat, and hydrology in headwater streams in the Upper Worcester Plateau Ecoregion of north central Massachusetts. These include questions about the structure of headwater streams: if headwater streams follow a logical, longitudinal progression from areas of ephemeral flow, typically associated with overland flow and poorly defined channels; to intermittent, seasonal flow; potentially associated with interrupted channels with areas of subsurface flow; to perennial flow reaches, associated with continuous incised channels.

STUDY AREA

The study was implemented on the watershed of the Quabbin Reservoir, located in north central Massachusetts. Waters from the 385-km^2 watershed flow into the 99.5-km^2 reservoir, created by the construction of the Winsor Dam (Long: 72°20′39″, Lat: 42°16′50″) on the Swift River in the 1930s (Figure 1). The Reservoir was constructed to provide a reliable, long-term source of water for metropolitan Boston, Massachusetts. The watershed is principally in public ownership, the majority by the Department of Conservation and Recreation, Division of Water Supply Protection (DCR DWSP; 57%), the lead state land management agency for the property. Other public and private conservation agencies provide protection for an additional 18% of the watershed. The municipal watershed component of the watershed is managed to "assure the availability of pure water for future generations" (Chapter 26 of the Acts of 2003, §290). The municipal watershed is organized into five Management Blocks: Pelham (west), New Salem

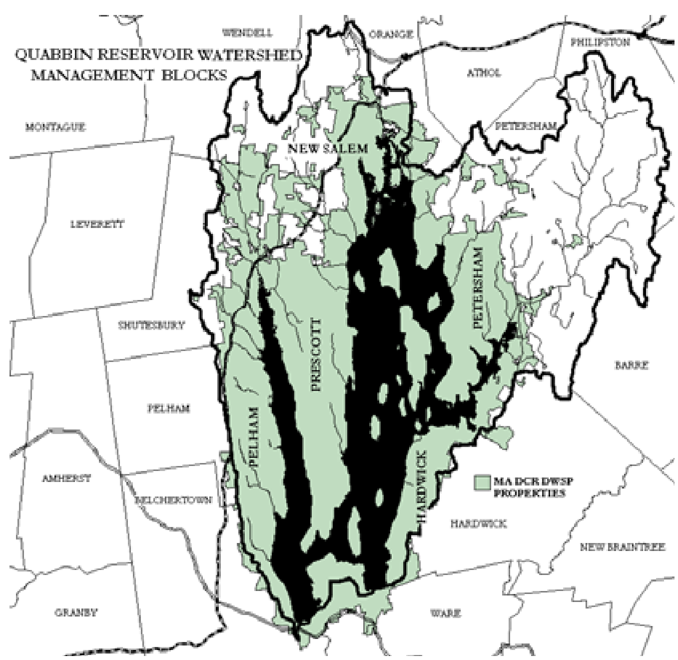

FIGURE 1. Map of the Quabbin Reservoir Watershed (bold line) With Public Watershed Lands in Gray, Central Massachusetts.

(north), Petersham (northeast), Hardwick (southeast), and Prescott (central peninsula). Other major portions of the watershed occur on other state lands (Division of Fisheries and Wildlife, Wildlife Management Areas) and private lands principally in the towns of Petersham, Barre, and Phillipston (Figure 1).

The watershed is principally forested (87%); only 4.1% of the watershed is impacted by human development or use (MADCR, 2007). The remaining lands are in wetlands, open water, or other minor uses. The Reservoir occupies the valleys of the West, Middle, and East Branches of the Swift River (Balk, 1940). There are 258.6 km of mapped perennial and 55.9 km of mapped intermittent streams on the watershed (P. Lamothe, Massachusetts Department of Conservation and Recreation, Belchertown).

The topography of the eastern part of the watershed is irregular with moderate slopes; the western part is defined by two steeply sloped ranges running north-south through the watershed. Elevations range from 161.5 m asl at the Reservoir's surface, when at full capacity, to 421.5 m asl at the highest point. The bedrock geology of west central Massachusetts is dominated by the Bronson Hill anticline, a complex zone of gneiss domes of recumbent folds (Robinson, 1967). The bedrock geology of the uplands of the Quabbin Reservoir watershed is characterized by three domed structures: west of the Reservoir is the West Pelham granitic gneiss; east is a dome of granodiorite gneiss; and the central Prescott is underlain by a belt of metamorphosed, sedimentary, volcanic, and intrusive rocks (Balk, 1940). The surficial geology was formed by the late Wisconsin glaciation, with nearly continuous till deposits covering about 90% of the surface to depths rarely thicker than 30 feet (9.1 m) (Balk, 1940). The soils of the watershed are predominantly mapped as the Shapleigh-Essex-Gloucester association (SCS, 1967). These soils are described as shallow and deep, well-drained soils in sandy glacial till. Annual precipitation averages 117.8 cm per year (MADCR, 2007). Precipitation is fairly evenly distributed throughout the year, with slight increases in late fall and early spring and a slight decrease in late winter (Brooks, 2004).

METHODS

Blue-Line Terminus Inventory and Selection

We examined all full and partial 1-km^2 UTM (Universal Transverse Mercator) grid cells on 1:25,000 metric-scale USGS topographic maps of lands of the Quabbin Reservoir watershed above Winsor Dam for the occurrence of the terminus (head) of mapped (blue line) first-order streams. We used the mapped stream network to assign order; we did not attempt to use map contour crenulations to refine order classification (Hansen, 2001). Based on map symbols, we classified each mapped stream origin as permanent (heavy, solid line) or intermittent (thin or dotted line) and characterized the terminus as simple, wetland, pond, or pond/wetland complex. Each mapped stream origin was identified by UTM cell (easting, northing coordinates), and number within a cell if >1 terminus occurred in a cell. The list of mapped stream origins was stratified by Management Block or, if on the watershed but not managed by DCR DWSP, by Town.

We used a random-number table to select candidate stream origins from each Management Block/Town list (Table 1). We rotated through Management Blocks/Towns to insure broad spatial coverage across the watershed. We used StreamStats (Ries, 2002) or a Geographic Information System (GIS) to determine coordinates of the mapped origin of each randomly selected study stream. We used these coordinates with a Global Positioning System (GPS) to locate the mapped stream origin in the field.

For each randomly selected stream origin, we first determined if the stream continued above the mapped blue-line terminus. For mapped stream origins flowing from ponds and/or wetlands, we inspected the full circumference of the pond/wetland for inlet streams. For each "unmapped segment" above a mapped stream origin, we first measured channel and riparian features of the upper 100-m or "mapped segment" of the blue-line stream. We then measured the same features of the upstream, unmapped segment until the true stream origin was reached and of any tributaries (tributary segment) we encountered on the unmapped segment. We were conservative in our determination of true channel heads, basing our decision on the presence of terminal springs, seeps, wetlands, or eroded channels and not simply on topographic depressions (swales); however, we did not attempt to use a quantitative methodology (NCDWQ, 2005). Critical field locations (e.g., junction with unmapped tributaries, channel head) were documented using GPS.

Field Methods

Field surveys included vegetation, topography, flow, and geomorphologic characteristics of the channel, banks, and adjacent low-lying (floodprone)

TABLE 1. Number of First-Order, "Blue-Line" Stream Terminuses (mapped stream heads) on 1:25,000 (7.5′) U.S. Geological Survey Topographic Maps, by Management Block or Town, Permanence, and Terminus Type, Quabbin Reservoir (Swift River) Watershed, Central Massachusetts.

Management Block/Town	Permanence	Terminus Type			
		Simple	Wetland	Pond	Pond/Wetland
Barre	Permanent	2	2		
Hardwick	Permanent	1	2		1
Island	Permanent		1		
New Salem	Permanent	30	1	5	3
Orange	Permanent		1		
Pelham	Permanent	14	9	5	
Petersham	Intermittent	9			
	Permanent	17	9	4	3
Phillipston	Intermittent	3			
	Permanent	6	2		
Prescott	Intermittent	4			
	Permanent	16	7	7	6
All areas	Intermittent	16			
	Permanent	86	34	21	13

topographic areas, as well as a 15-m wide upland riparian zone on each side of the stream. Stream segment surveys included data at three scales: segment, reach, and cross-section.

Stream Segment Data. Stream segments were given unique identifiers, a combination of the Management Block abbreviation and sequential sample number. Unmapped and tributary stream segment lengths were calculated as the sum of the lengths of all reaches occurring in the segment. Surveyed mapped segments were limited to the uppermost 100 m of the blue-line stream. The occurrence and location of tributaries on both mapped and unmapped segments were determined.

Reach Data. Reaches were defined by natural changes in slope, channel type, or other visually distinct characteristics. We recorded the justification for reach identification. Unmapped reaches were numbered sequentially upstream from mapped stream origin location. If the mapped segment was composed of >1 reach, it was also numbered sequentially from the mapped stream head and extending downstream to 100 m. The predominant channel type in each reach was identified. Channel (thalweg) and straight-line reach length were measured in 0.1 m with surveyor's tape. Straight-line slope was measured in percent with clinometer.

Cross-Section Data. One to three cross-sections were measured per reach. If a reach was <20 m in total length, one (<10 m) or two (<20 m) cross-sections were randomly located in each 10-m section of the reach. If a reach was >20 m in total length, we randomly located three cross-sections, one in each third, by length, of the reach. We recorded the distance of the cross-section from the reach origin. A metric tape was stretched across each cross-section, starting at the upland edge of the floodprone zone on the left side of the stream, facing upstream, and ending at the upland boundary of the floodprone zone on the right side of the stream. We recorded morphological data for the floodprone zone, bank, and channel on each cross-section. We classified areas of flat topographic relief without predominance of wetland vegetation or hydric soils between the channel bank and the upland riparian slope as the floodprone zone. We did not attempt to distinguish between floodplain and more elevated terrace features, as these are not geomorphologic features found in the upper reaches of stream systems in the study area (Montgomery and MacDonald, 2002). Areas of cross-sections with saturated soils and dominated by wetland indicator plants were classified as wetland.

We measured the overstory canopy closure at intersection of thalweg and cross-section tapes using a concave (Lemmon) densiometer. This measurement was taken four times at 90° intervals. Finally, we measured slope across a 15-m riparian zone perpendicular to the stream, starting at the distant edge of the floodprone zone, on both the left and right side of the stream. We recorded the dominant overstory, midstory, and understory vegetation species or life form on the riparian zones.

For banks and incised channels, we collected additional point-scale data at 0.1-m intervals. At each point, we recorded the substrate type and in the channel, we estimated bankfull depth, recorded maximum water depth (if present) and flow characteristics, and classified overall embeddedness for entire channel cross-section. For channel or bank points identified as boulders, we recorded the maximum boulder diameter. Point-level data were not summarized for this paper.

Tributaries. We assigned a sequential number to each tributary we encountered branching off of mapped and unmapped headwater stream segments. We recorded the distance from the mapped stream origin location to the point where the tributary entered the stream segment and recorded UTM coordinates of the location. For tributaries entering unmapped segments, we conducted reach and cross-section surveys as for the main mapped and unmapped segments. We did not conduct surveys of unmapped tributaries branching off the mapped 100-m segments below mapped stream origins.

Analysis

Morphological stream and catchment data were summarized by stream segment and reach. Comparisons among mapped, unmapped, and tributary segments were made using analysis of variance (parametric, morphological data) or chi-square (distributions) tests. Pair-wise comparisons (Tukey's w) were conducted for significant analysis of variance comparisons. Percent data were arcsine transformed prior to summary or analysis.

RESULTS

Segment-Scale Statistics

Five of the 30 randomly selected mapped stream origins (17%), accurately defined the true channel head of the stream (Table 2). Three of the 5 correctly mapped stream origins terminated in large wetlands with no inflow channels. Two mapped stream origins terminated at maintained roads and we were unable to ascertain if the stream may have extended further prior to the long-ago construction of the road.

TABLE 2. Surveyed Headwater Streams by Management Block or Town, Quabbin Reservoir Watershed, Massachusetts.

Management Block/Town	Stream	Total Length (m)	Watershed Area* (ha)	Number of Reaches	Number of Tributaries	Total Length (m)	Number of Reaches
Barre	47	642	41.4	6	0		
Hardwick	26	1,448	41.4	13	3	354	3
New Salem	4E	180	5.34	2	0		
New Salem	7	42	0.5	2	0		
New Salem	8	219	0.8	3	1	15	1
New Salem	14	91	3.9	2	0		
New Salem	21	203	23.2	3	0		
Pelham	6	284	36.3	1	1	93	2
Pelham	15	0					
Pelham	16	530	13.2	9	0		
Pelham	17	161	5.1	3	0		
Pelham	20	363	12.3	8	1	175	1
Pelham	25	0					
Petersham	12	1,561	80.3	7	0		
Petersham	19	506	54.4	5	2	155	2
Petersham	21	201	3.0	1	1	87	1
Petersham	25	308	13.9	3	0		
Petersham	30	0					
Petersham	35	890	82.9	1	6	1,042	8
Petersham	39	28.5	767	8	0		
Phillipston	52	316	2.4	4	0		
Phillipston	55	469	16.1	4	3	465	3
Phillipston	60	1,899	220.0	3	0		
Phillipston	63	300	12.9	1	0		
Prescott	1	376	8.2	12	1	95	3
Prescott	7	62	1.3	2	0		
Prescott	9	0					
Prescott	11E	179	—**	4	0		
Prescott	11S	699	28.5	14	1	65	1
Prescott	13	96	9.2	1	0		
Prescott	30	0					

*Watershed area estimated using StreamStats (Ries, 2002).
**Watershed area of Prescott 11E and 11S combined.

TABLE 3. Mean (±standard error) Segment-Scale Attributes by Segment Type, Quabbin Reservoir Watershed, 2008.

	Stream Segment Type		
Characteristic	**Mapped**	**Unmapped**	**Tributary**
Number of segments	25	26	20
Thalweg length (m)	—*	502 ± 94.5	127 ± 23
Sinuosity (m/m)	1.09 ± 0.01	1.12 ± 0.02	1.13 ± 0.008
Gradient (m/100 m)	5.1 ± 0.01	3.4 ± 0.4	4.5 ± 0.7
Canopy cover (%)	91.9 ± 0.3	91.2 ± 0.3	94.0 ± 0.1
Riparian slope (%)**	6.4 ± 0.04	5.9 ± 0.03	2.5 ± 0.04

*Survey restricted to 100 m downstream of blue-line terminus, length analysis inappropriate.
**Significant ($p \leq 0.05$) differences by segment type.

Unmapped stream segments extended above 25 (83%) of the mapped stream origins; 1 mapped stream origin had 2 unmapped, contributing segments. We found 20 unmapped tributaries on 10 of the unmapped headwater stream segments.

The thalweg length of the 26 unmapped stream segments ranged from 42 to 1,899 m, with an average length of 502 m (Table 3). Thalweg length of the associated tributaries averaged 127 m (range 15-462 m). There was little difference in the average characteristics of entire mapped, unmapped, and tributary stream segments (Table 3). One significant difference was in the average slope of the first 15 m of riparian upland ($F_{\text{d.f.} = 2,68} = 8.196$, $p = 0.001$) due to the significant difference between the riparian slopes of tributary and mapped segments (Tukey's $w = 5.651$, $p = 0.001$) and unmapped segments (Tukey's $w = 5.179$, $p = 0.003$); riparian slopes of mapped and unmapped segments did not differ significantly. The distribution of mapped stream origin types was significantly different from that of the classification of the true origins of the unmapped stream segments ($\chi^2 = 15.3$, d.f. = 5, $p > 0.01$). The majority of mapped stream origins depicted as occurring simply at headwalls or on hillsides while true unmapped stream origins ended predominantly in wetlands or rocky seeps/springs (Figure 2). A few others "petered out" in the upstream direction, appearing to occur where surface drainage accumulated to a sufficient extent to create overland flow. The classification of the origins of unmapped tributaries differed significantly from those of unmapped headwaters ($\chi^2 = 16.6$, d.f. = 5, $p > 0.01$) but not from those of the mapped stream origins ($\chi^2 = 8.4$, d.f. = 5, $0.25 > p > 0.1$).

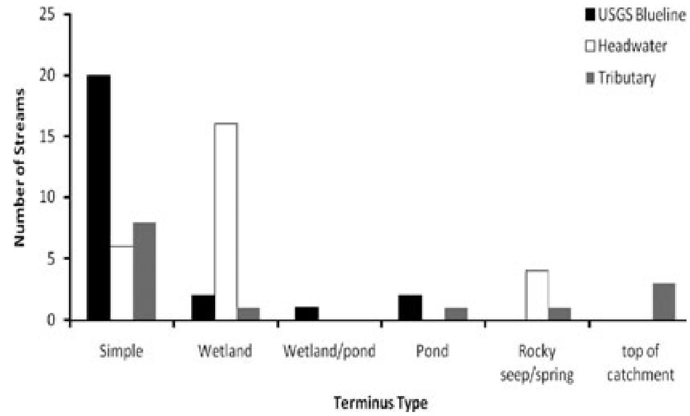

FIGURE 2. Number of Surveyed Mapped (blue line) Stream Origins ($n = 30$) and Unmapped, True Origins of Headwater Stream ($n = 26$) and Tributary ($n = 20$) Segments by Terminus Type, Quabbin Reservoir Watershed, Massachusetts.

Reach-Scale Statistics

Over the 26 unmapped stream segments, we identified 119 natural reaches, 9 culverts, and 2 stone dams, for an average of 5 reaches per stream, with an average reach length of 101.7 m (Table 4). Excluding the culverts and stone dams, the average length of the natural reaches was 135.4 m, with a standard error of 14.3 m. We identified 25 natural reaches on the 20 unmapped tributaries, with an average reach length of 101.8 m, and 39 reaches in the first 100 m of the 25 mapped stream segments. We were unable to calculate average reach lengths for the mapped segments since the survey was restricted to a predetermined distance.

Reaches were most commonly classified as simple-incised channels for all segment types, but especially for mapped segments (Table 4). Interrupted-incised and wetland channels were next most frequently encountered reach classifications. The distribution of channel types differed between mapped and unmapped stream segments ($\chi^2 = 10.0$, d.f. = 5, $0.1 > p > 0.05$). Mapped reaches were more frequently classified as simple-incised channels whereas unmapped reaches were more frequently identified wetland and overland flow channel types. Wetland reaches, while less frequent than incised channel reaches, were, on average, considerably longer and thus accounted for a greater proportion of unmapped stream length (Table 4). Reaches of overland flow were not observed on 100-m mapped stream segments and were more common on tributary than on unmapped segments.

Sinuosity at the reach scale was slightly less for mapped-segment reaches (1.09 m/m) but not significantly ($F_{\text{d.f.} = 2,77} = 0.592$, $p = 0.556$) different from unmapped or tributary-segment reaches (Table 5). Reach gradient differed among stream segment types ($F_{\text{d.f.} = 2,77} = 5.539$, $p = 0.006$). The average gradient of mapped-segment reaches (5.7/100 m) was greater and significantly different than that of unmapped-segment reaches (Tukey's $w = 0.027$, $p = 0.019$) and

TABLE 4. Number and Average (±standard error) Reach (thalweg) Length by Stream Segment and Channel Type Classification, Quabbin Reservoir Watershed, 2008.

	Stream Segment Type				
			Tributary		
Channel Type	**Mapped* Number**	**Unmapped Number**	**Length (m)**	**Number**	**Length (m)**
Beaver pond		1	375		
Simple-incised	24	50	109.5 ± 18.1	10	127.7 ± 28.5
Braided-incised	1	1	284		
Culvert	1	9			
Excavated		1	57.8		
Interruped-incised	7	19	78 ± 11.6	6	113.3 ± 15.9
Mixed	1	1	32		
Overland flow		9	59 ± 11.8	5	54.3 ± 17.5
Stone dam		2	8.5		
Subsurface	3	9	92 ± 37.1	3	47.3 ± 10.8
Wetland	2	28	131.6 ± 50.4	1	175
All channel types	39	130	101.7 ± 13.8	25	101.8 ± 14.2

*Survey restricted to 100 m downstream of blue-line terminus, length analysis inappropriate.

TABLE 5. Average (±standard error) Reach-Scale Occurrence of Zone Types on Channel Cross-Sections and Zone Dimensions by Stream Segment Type, Quabbin Reservoir Watershed, 2008.

	Stream Segment Type		
Characteristic	**Mapped**	**Unmapped**	**Tributary**
Number of reaches	38*	119*	25
Sinuosity (m/m)	1.09 ± 0.01	1.12 ± 0.01	1.13 ± 0.02
Gradient (m/100 m)**	5.7 ± 0.9	3.6 ± 0.3	4.9 ± 0.9
Canopy cover (%)	93.1 ± 0.3	89.5 ± 0.09	92.3 ± 0.01
Riparian slope (%)	7.1 ± 0.01	7.1 ± 0.01	2.7 ± 0.03
Floodprone			
%Occ	96.4 ± 0.4	94.8 ± 0.2	94.6 ± 1.0
Sum width (m)	9.0 ± 1.1	12.1 ± 1.0	8.7 ± 1.2
Mean width (m)	5.3 ± 0.7	5.8 ± 0.4	4.8 ± 0.9
Wetland			
%Occ	24.4 ± 0.9	40.0 ± 0.4	7.3 ± 0.6
Sum width (m)**	16.5 ± 2.8	16.7 ± 3.1	10.4 ± 1.9
Mean width (m)**	11.0 ± 1.9	14.0 ± 2.6	7.4 ± 0.8
Bank			
%Occ	77.9 ± 1.0	52.0 ± 0.4	49.8 ± 1.9
Height (cm)	26.3 ± 1.8	24.1 ± 0.8	21.3 ± 1.4
Simple-incised channel			
%Occ	69.2 ± 0.9	34.5 ± 0.3	34.2 ± 1.4
Width (m)	1.6 ± 0.2	2.4 ± 0.4	2.5 ± 0.6
Bankfull depth (cm)	33.5 ± 3.2	27.9 ± 1.7	22.1 ± 1.6
Braided-incised channel			
%Occ	2.2 ± 0.3	12.8 ± 0.1	1.6 ± 0.2
Sum width (m)	2.2 ± 0.1	2.8 ± 0.2	4.5 ± 0.8
Mean width (m)	1.2 ± 0.1	1.3 ± 0.1	1.9 ± 1.4
Bankfull depth (cm)	29.6 ± 1.5	26.8 ± 0.9	23.8 ± 1.9
Overland flow			
%Occ	1.2 ± 0.2	2.7 ± 0.1	8.6 ± 0.9
Sum width (m)	2.4 ± 0.2	4.0 ± 0.5	2.1 ± 0.4
Mean width (m)	2.2 ± 0.2	3.6 ± 0.5	21 ± 0.4

*No cross-sections were taken on culverts or stone dams reaches.
**Significant ($p \leq 0.05$) differences by segment type.

greater, but not significantly different than that of tributary-segment reaches. The gradient of tributary segments was greater but not significantly different than unmapped segments. Variability in gradient was greatest among mapped reaches [coefficient of variation (CV) = 97.4%] compared with unmapped (CV = 86.2%) and tributary reaches (87.4%), but the sample size of mapped reaches was much less than that of unmapped reaches.

Reach-scale sinuosity varied by segment and channel type (Figure 3A). For the predominant channel types, sinuosity was greatest for interrupted-incised and least for wetlands. This was true for all segment types with the exception of wetlands on mapped segments; however, there were only two occurrences of this condition (Table 4), so the results are inconclusive. Reach-scale gradient was least for wetland channel types (Figure 3B), with the exception of the one occurrence on a tributary segment. Gradients on continuous and interrupted-incised channels were similar.

Cross-Section Scale Statistics

Floodprone zones occurred on approximately 90% of all reaches regardless of stream segment type (Table 5). While the average width of individual floodprone units was similar among segment types, at about 5.6 m (Table 5), the average width of the cumulative floodprone zone was greater on unmapped reaches than for mapped or tributary reaches. Simple-incised channels and banks were

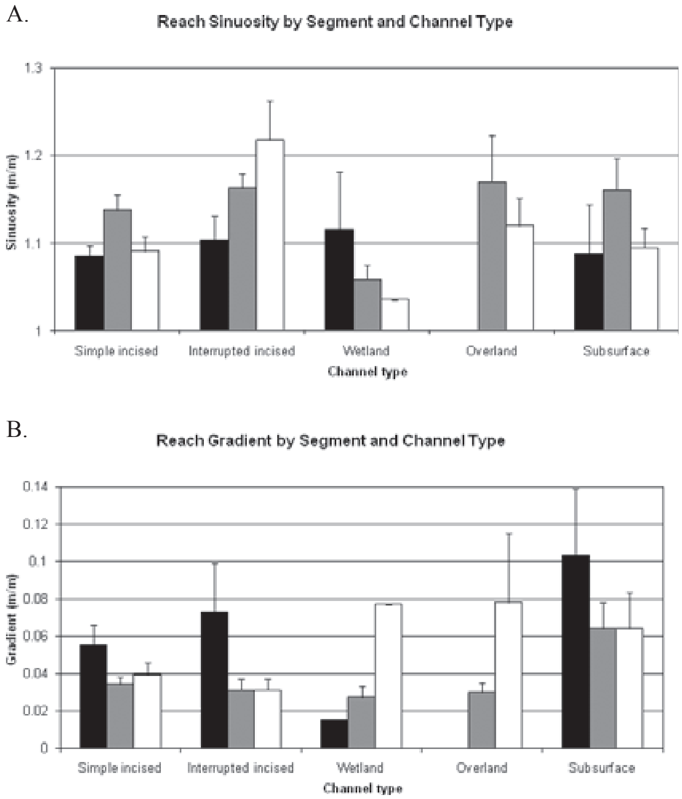

FIGURE 3. Mean, With Positive Standard Error Bar, (A) Sinuosity and (B) Gradient by Reach and Stream Segment Type (solid – mapped, stipple – unmapped, clear – tributary), Quabbin Reservoir Watershed, Massachusetts.

more common on mapped-segment reaches than on unmapped or tributary reaches. Where they occurred, average simple-incised channels were wider on unmapped (2.0 m) and tributary (2.3 m) reaches than mapped reaches, but average bankfull depths were greater on mapped reaches (33.5 cm). Wetlands were most frequent and their average width (14.0 m) was greater on unmapped-segment reaches. The width of wetlands differed among segment types, both for mean wetland width ($F_{\text{d.f.} = 2,59} = 5.7$, $p = 0.005$) and for the sum of wetland width ($F_{\text{d.f.} = 2,60} = 5.23$, $p = 0.008$). Braided-incised channels were most frequent on unmapped reaches and overland flow occurred most frequently on tributary reaches. The distribution of zone types differed between mapped- and unmapped-segment reaches ($\chi^2 = 20.0$, d.f. = 5, $0.005 > p > 0.001$). There were fewer simple-incised channel zones and banks on unmapped reaches and more wetland and overland flow zones.

Average forest canopy cover was greater on mapped (93.1%) and tributary (92.3%) segment reaches than on unmapped reaches (89.5%), but these differences were not significant among segment types ($F_{\text{d.f.} = 2,68} = 1.802$, $p = 0.173$). The average slope of the first 15 m of riparian zone was the same for mapped- and unmapped-segment reaches but much less for tributary-segment reaches (2.7%). Again, this difference among segment types was not significant ($F_{\text{d.f.} = 2,68} = 1.946$, $p = 0.151$).

DISCUSSION

Until 2001, the U.S. Army Corps of Engineers (COE) interpreted the federal Clean Water Act to provide regulatory protection to a wide range of "waters of the U.S." including many isolated wetlands and headwater streams. Jurisdiction was substantially curtailed by the 2001 decision by the U.S. Supreme Court in SWANCC *v.* U.S. Army COE that reduced federal jurisdiction over certain isolated wetlands (Downing *et al.*, 2003). In its 2006 decision in the combined cases Carabell *v.* U.S. and Rapanos *v.* U.S. (Rapanos), the Court further limited federal regulatory jurisdiction over isolated and headwater wetlands systems to those with a "significant nexus" to navigable waters (Nadeau and Rains, 2007b; Leibowitz *et al.*, 2008; Sponberg, 2009). Since these decisions, the USEPA and COE, with other federal agencies, state agencies, and the regulated community, have been working to clarify the extent to which headwater stream-wetland complexes may or may not have a "significant nexus" with navigable downstream waters and establish jurisdiction.

Suggested regulations and guidance explicitly link regulatory jurisdiction to "blue-line" streams on USGS topographic maps. In a number of states, including Massachusetts and Vermont in the Northeast and the Carolinas in the Southeast, the depiction of a blue-line stream on a USGS topographic map is a criterion for regulatory jurisdiction under state water-resource law. Some states, notably North Carolina (NCDWQ, 2005) and Ohio (ODSW, 2009), have developed additional field-based criteria for the delineation of unmapped streams. The degree to which the topographic maps accurately depict the location and extent of jurisdictional waters therefore assumes great significance in terms of the ability to protect public interests associated with water quality and streamflow in headwaters.

The uppermost headwaters of river systems, including those that feed into drinking water reservoirs, important fisheries, or other streams that are recognized under the Clean Water Act as being of high quality, are critical to continued maintenance of downstream water quality (Alexander *et al.*, 2007). Such streams contribute seasonal and/or year-round flows and, collectively, account for a high proportion of annual discharge. In addition, particulate and dissolved organic carbon that enters headwaters from adjacent forests and other lands is processed in headwaters and transported downstream where it becomes an integral part of the food web. Biological connections with downstream waters are provided through downstream drift, upstream flight of insects, and seasonal upstream migration of fishes and invertebrates. A large body of research authoritatively shows that losses of ecological integrity and water quality in higher order tributaries are directly tied to degradation of headwaters (Gomi *et al.*, 2002; Alexander *et al.*, 2007; Freeman *et al.*, 2007; MacDonald and Coe, 2007).

The results of our baseline study of mapped blue-line streams in the Quabbin watershed show that USGS topographic maps do not completely depict the entire extent of headwater streams. We examined 30 mapped, blue-line stream terminuses, randomly selected from 170 terminuses occurring on 1:25,000 topographic maps of the Quabbin Reservoir watershed. The maps failed to depict more than 15 km of headwater streams, draining 745 ha of watershed (Table 2), on 25 of the 30 streams. If unmapped headwaters are distributed comparably across the rest of the watershed, this translates to nearly 85 km of unmapped headwater streams, potentially exempt from protection through state or federal regulatory review of proposed development, changes in land use, or alterations of the stream channel. This amount is conservative as unmapped tributaries to the blue-line stream network were not sampled. Our study looked only at mapped blue-line headwaters and did not address whether there are other streams that do not appear at all on the topographic maps. Studies elsewhere suggest the likelihood that there may be many other small streams that contribute directly to the reservoir and to its tributaries but are not depicted on topographic maps (Leopold *et al.*, 1964; Darling *et al.*, 2002; James *et al.*, 2007; Colson *et al.*, 2008).

Headwaters in the Swift River watershed exhibit a "deranged" or "contorted" pattern (Howard, 1967) comprised channel sections that are periodically and irregularly interrupted by wetlands or ponds. Some of the ponds were created or enhanced by human activity, including 18th and 19th Century agriculture and water-powered mills. Other ponds and wetlands are the product of beaver (*Castor canadensis*) activity (Langlois, 1999; Chandler *et al.*, 2009). Active and abandoned beaver impoundments alter stream channel morphology and affect water quality and transport of nutrients downstream (Naiman *et al.*, 1986; Naiman and Pinay, 1994). The stream profiles illustrate how the last episode of Pleistocene glaciation created a fine-scale landscape pattern of slopes and terraces. The slopes are boulder-covered and often overlain by root mat, moss, and organic litter that create interrupted reaches with subsurface flow (viz. Collins *et al.*, 2007). The terraces range from small, shallow, mineral-soil wetlands covering a few hundred square meters (minimum wetland reach length was 11 m; minimum wetland zone width 1.1 m), to many-ha basins containing ponds or large wetlands (maximum wetland reach length 1,400 m, maximum wetland zone width 271 m) with extensive underlying peat deposits.

Because water from the Quabbin Reservoir is currently exempt from USEPA filtration requirements, headwater stream protection is a serious concern for water-resource managers. Our data on the extent of unmapped headwater segments upstream of mapped stream origins suggest that there may be a need for increased evaluation of land-use activities in headwater portions of the watershed, particularly in areas with more development such as the upper East Branch of the Swift River. Road networks that parallel and cross the stream channels are further legacies of past land use. Roads created during the agricultural period remain today as main routes of travel and as woods roads within the forests. Five of the 26 unmapped stream segments flowed through at least one culvert, with the potential for associated downstream sedimentation (Lane and Sheridan, 2002; Khan and Colbo, 2008). In addition, late-20th and early-21st Century expansion of residential development into the hill towns has created new roads and driveway crossings. Thirty percent of unmapped headwater stream segments located outside of protected public lands had houses nearby, and one study stream had new construction including a driveway crossing and culvert.

The unmapped headwater segments we identified had fewer classic incised channels and more wetland and overland flow channels than the first 100 m of the mapped stream segments. In some instances, these may contain critical habitats for specific plants and animals (Collins *et al.*, 2007). For the most part, zone dimensions were similar among the segment types with the exception of wetland widths, which were greater on unmapped reaches. Many segments had incised channel reaches alternating with reaches of wetland and/or subsurface flow zones such as those described by Collins *et al.* (2007). Under Massachusetts wetlands regulations, it is unclear whether reaches of incised channel upgradient of areas without a visible surface channel are classified as "streams" subject to the Massachusetts Wetlands Protection Act (MGL Ch 132 Sect 40) and its regulations. The ability to regulate activities that have the potential to degrade its headwaters is critical to the ability to protect water quality. Headwater protection is critical to maintaining existing high water quality in other waters of the state and of the U.S. in accordance with the anti-degradation provisions of the Clean Water Act.

CONCLUSIONS AND RECOMMENDATIONS

Headwater streams constitute a major component of stream-river networks. The protection of these systems, especially those with less than permanent flow regimes, is often dependent upon their presence being represented on standard topographic maps. The occurrence and physical character of unmapped, headwater stream segments were examined in a stratified, random fashion on the Quabbin Reservoir watershed in central Massachusetts, USA.

Unmapped stream segments were found to occur on over 80% of the mapped stream terminuses we examined. On average, these segments were nearly 0.5 km in length; nearly 40% had one or more unmapped tributaries, with an average length of 130 m. Unmapped headwater streams were characterized by lower gradients and higher frequencies and spatial extents of wetlands than mapped blue-line streams, with the unmapped stream flowing diffusely through some wetland reaches and in a distinct channel through others. In contrast, unmapped tributaries did not differ from mapped blue-line streams in gradient or frequency of wetlands.

Our survey of mapped stream origins confirms the findings of other researchers in other regions of the U.S. that USGS topographic maps do not accurately depict the location and extent of headwater streams in forested landscapes. Our findings argue strongly against the use of topographic maps for the sole determination of jurisdiction under federal, state, or local laws and regulations. Site-specific evaluation by those specifically trained or experienced in recognizing headwater channel indicators is critical due to the variation that can be expected. Given the critical roles played by headwater segments of river-stream networks, we urge the proper and effective protection of entire riverine systems by the recognition of the existence of the very upper reaches of unmapped headwater streams.

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