Comparison of Digital Elevation Models for Aquatic Data Development

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Abstract
Thirty-meter digital elevation models (DEMs) produced by the U.S. Geological Survey (USGS) are widely available and commonly used in analyzing aquatic systems. However, these DEMs are of relatively coarse resolution, were inconsistently produced (i.e., Level 1 versus Level 2 DEMs), and lack drainage enforcement. Such issues may hamper efforts to accurately model streams, delineate hydrologic units (HUs), and classify slope. Thus, the Coastal Landscape Analysis and Modeling Study (CLAMS) compared streams, HUs, and slope classes generated from sample 10-meter drainage-enforced (DE) DEMs and 30-meter DEMs. We found that (1) drainage enforcement improved the spatial accuracy of streams and HU boundaries more than did increasing resolution from 30 meters to 10 meters, particularly in flatter terrain; (2) streams and HU boundaries were generally more accurate when delineated with Level 2 than with Level 1 30-meter DEMs; and (3) the 10-meter DE-DEMs better represented both higher and lower slope classes. These findings prompted us to have 10-meter DE-DEMs produced for the Coast Range Province of Oregon, increased confidence in CLAMS outputs from the 10-meter DE-DEMs, and should benefit others interested in using DEMs for aquatic analyses.

Introduction
Decision makers and scientists are increasingly planning for and studying aquatic ecosystems over broad spatial extents. The Coastal Landscape Analysis and Modeling Study (CLAMS) (Spies *et al.*, 2002), similar to other scientific assessments that support landscape planning (e.g., Forest Ecosystem Management Assessment Team (FEMAT), 1993; Sierra Nevada Ecosystem Project (SNEP), 1996; and Umpqua Land Exchange Project (ULEP), 2001), is developing broad-scale spatial databases. For the Coast Range Province of Oregon (FEMAT, 1993), we are using these databases in the aquatic component of CLAMS to assemble and apply watershed condition indices and to model instream habitat structure from upslope and streamside attributes (CLAMS, 2002). The value of these indices and models relies heavily on the quality and consistency of the foundation data layers used in their construction.

Some of the foundational data can be derived from digital elevation models (DEMs), i.e., slope, elevation, aspect, channel gradient, hydrologic unit (HU) boundaries (FGDC, 2002), and stream traces (Jenson and Domingue, 1988; Jenson, 1991; Moore *et al.*, 1991; Quinn *et al.*, 1991; Tarboton *et al.*, 1991; Band, 1993; Wang and Yin, 1998). These DEM-generated products have many benefits for broad-scale aquatic analyses. For example, streams created from DEMs are precisely registered to the DEMs (Jenson and Domingue, 1988; Jenson, 1991), which improves the quality of stream-associated topographic information, such as channel gradient and valley floor width. Furthermore, streams created from DEMs always appear as single lines, rather than as braided channels or double-bank streams, and a single line represents water bodies such as lakes and reservoirs. Thus, it is easier to calculate stream order and route stream networks; the latter is necessary prior to georeferencing stream-associated data.

We evaluated the usefulness of DEM data for our specific applications throughout the range of landscape characteristics found in our study area, following the recommendation of many authors that DEM evaluations need to be contextual (Walsh *et al.*, 1987; Weih and Smith, 1990; Shearer, 1991; Carter, 1992, Robinson, 1994; Zhang and Montgomery, 1994). Given that DEM resolution has been demonstrated to affect the accuracy of landform characterization and drainage networks (e.g., Elsheikh and Guercio, 1997; Thieken *et al.*, 1999; Zhang *et al.*, 1999; McMaster, 2002), we wanted to evaluate advantages for aquatic analyses of employing 10-meter drainage-enforced DEMs (DE-DEMs) (Osborn *et al.*, 2001) rather than the more widely available 30-meter DEMs. Specifically, results from 10-meter DE-DEMs and 30-meter DEMs (Level 1 or 2) were compared for deriving (1) a consistent density, positionally accurate, single-line stream layer that corresponded to the topography; (2) hydrologic units delineated at approximately the 6^{th}-field hydrologic unit (HU) level; and (3) a representation of topography to calculate slope. The 10-meter DE-DEMs we used have better horizontal and vertical resolution and were produced with a more consistent process (i.e., by the same contractor and specifications; Averstar Geospatial Services, now Titan Corp.[1]) than were the 30-meter DEMs.

DEM Data
Concerns about the vertical and horizontal resolution and inconsistent quality of the 30-meter DEMs prompted preliminary assessment of these data for aquatic analyses. Although the U.S. Geological Survey (USGS) has improved its methods to generate DEMs, some of the 30-meter DEMs in the study area were created with earlier methods, which yielded two classes of quality, Levels 1 and 2. Level 1 DEMs were created by autocorrelation or manual profiling directly from aerial photography. Level 2 DEMs were created from digital line graph (DLG) contours or equivalent (USGS, 1998). The vertical accuracy

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any products or services.

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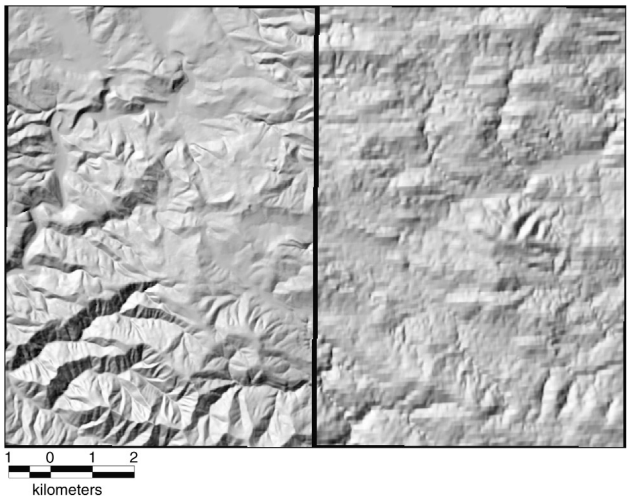

Figure 1. Comparison of hillshades for two adjacent 7.5-minute quadrangles showing the different 30-meter DEM levels: (a) Elsie Quadrangle Level 2, 30-meter DEM; (b) Sunset Springs Quadrangle Level 1, 30-meter DEM.

of each DEM is described by a vertical root-mean-square error (RMSE) (USGS, 1998). The stated maximum permitted RMSE for Level 1 DEMs is 15 meters with 7 meters or less being the desired accuracy. Systematic errors within the stated accuracy standards are tolerated in Level 1 DEMs. For Level 2 DEMs an RMSE of one-half contour interval is the maximum permitted. For both levels, elevation is recorded to the nearest integer (meters or feet).

Approximately 20 percent of the quadrangles in the study area were Level 1 DEMs. A visual inspection of hillshades (a shaded relief of an elevation grid made considering the illumination angle of the sun and shadows) revealed striations on some Level 1 DEMs (Figure 1). Such striations appear only on Level 1 DEMs produced by the manual profiling technique (Garbrecht and Stark, 1995). Preliminary processing of the Level 1 DEMs to create streams, HUs, and slopes suggested unacceptable quality issues.

Three options were considered to address problems ensuing from the Level 1 DEMs. The first option was to filter or smooth the DEM, but such processes further degrade data quality (Garbrecht and Stark, 1995). The second option was to create Level 2 DEMs to replace Level 1 DEM quadrangles. Although Level 2 DEMs may improve hydrologic modeling results, concerns remained about locations of stream channels and HU pour points relative to topography. The third option, and the one we chose to explore in depth, was to drainage enforce DEMs during production (Osborn *et al.*, 2001) and to increase their vertical and horizontal resolution, creating 10-meter DE-DEMs.

The newly obtained 10-meter DE-DEMs exceeded Level 2 USGS specifications and were produced using contour data (hypsography) supplemented with hydrography from 7.5-minute topographic quadrangles for "drainage enforcement." Underwood and Crystal (2002) explain drainage enforcement as adding breaklines (lines, such as stream lines, along which there are abrupt changes in slope) to hypsography data prior to gridding the DEM. Elevation is proportioned along these breaklines between known elevations where contour lines cross a stream. This is particularly useful in areas of sparse elevation data, such as wide floodplains, or along slopes in which contour biasing, or other artifacts produce puddles. Although drainage can be enforced onto an existing DEM, supplementing the hypsography with hydrography data prior to gridding produces a more natural surface. That is, hydrographic flow is depicted as a stream meandering through a valley bottom rather than meandering within an evident channel (Underwood and Crystal, 2002). For the 10-meter DE-DEMs used in this study, drainage was enforced to 1:24,000-scale USGS hydrography DLGs and elevation data were recorded to the nearest decimeter.

In comparing outputs from the 10-meter DE-DEMs and 30-meter DEMs, as for any geographic information systems (GIS) data, results may be influenced by two categories of error: inherent and operational (Walsh *et al.*, 1987). Inherent error is present in source documents; operational error arises from data capture and manipulation. We chose not to address inherent error because Level 2 30-meter DEMs and 10-meter DE-DEMs have the same contour source, implying equal inherent error. Inherent error may have affected results from the Level 1 30-meter DEM (derived directly from aerial photography) and 10-meter DE-DEM comparison, but was difficult to isolate from operational error.

The focus of this paper was to compare effects of operational errors, related to data capture, on DEM-derived products. Operational errors associated with producing DEMs from contour data has been extensively discussed (Weibel and Heller, 1991; Wood and Fisher, 1993; Robinson, 1994; McCullaugh, 1998; Wise, 1998; Guth, 1999; Walker and Willgoose, 1999; Hutchinson and Gallant, 2000). Data capture methods differ between the Level 1 and 2 30-meter DEMs. Differences in data capture between the Level 2 DEMs and 10-meter DE-DEMs are a function of horizontal resolution and vertical resolution. Both of these influence the derivatives. Drainage enforcement is an addition to the data capture of the 10-meter DEMs that we used. Accuracy measurements provided by the USGS (1998) do not fully address specific concerns regarding the utility of the two resolutions for our applications. The USGS (1998) admits that artifacts such as benches, striations, or patches will always be present and impart some signature of data capture to the data set. Because of such systematic errors, the sole use of RMSE for error calculation is inadequate (Wood and Fisher, 1993; Brown and Bara, 1994). The reporting of RMSE is geared more to the production process rather than an assessment of the impact of the error (Monckton, 1994; Wise, 1998).

Study Area

The Coast Range Province of Oregon is underlain primarily by marine sandstones and shales, together with basaltic volcanic rocks. Potential natural vegetation is a highly productive coniferous forest consisting mainly of Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), and Sitka spruce (*Picea sitchensis*) along the coast. Most of the current forestland is occupied by relatively young seral stands, and the large flat river valleys have been cleared for agriculture. Except for interior river valleys, and in some places a prominent coastal plain, the area is dominated by mountains with ridges that are often sharp. Elevations range from 0 to 1250 meters. Uplands are highly dissected with drainage densities up to 8.0 km/km^2 (FEMAT, 1993). Mild wet winters, cool dry summers, and heavy precipitation, falling mostly from October to March, describe the climate.

Methods

Differences were evaluated between 10-meter DE-DEMs and 30-meter DEMs for thirteen 7.5-minute topographic quadrangles that represented potential sources of variability. Two 7.5-minute topographic quadrangles were selected in each of the four major ecoregions (Pater *et al.*, 1998) in the Coast

TABLE 1. LEVEL IV ECOREGION AND DEM LEVEL FOR 7.5-MINUTE QUADRANGLES SELECTED FOR COMPARISON

Level IV Ecoregion	Quadrangle Name	USGS 30-Meter DEM Level (Level 2 unless noted otherwise)
Quadrangles selected for ecoregion comparison		
Volcanics	Jordan Creek	
Volcanics	Warnicke Creek	
Coastal Uplands	Olney	
Coastal Uplands	Toldeo North	
Mid-Coastal Sedimentary	Glenbrook	
Mid-Coastal Sedimentary	Norton	
Willapa Hills	Vinemaple	
Willapa Hills	Pittsburgh	
Coastal Lowlands	Tillamook	
Quadrangles selected for DEM Level comparison		
Mid-Coastal Sedimentary	Elk Peak	
Mid-Coastal Sedimentary	Loon Lake	Level 1
Volcanics	Sunset Springs	Level 1
Volcanics	Elsie	

Range Province of Oregon to assess variability associated with landscape features (Table 1). Only one quadrangle was selected from the Coastal Lowlands ecoregion because of its limited geographic distribution. Stream, HU, and slope results from 10-meter DE-DEMs and 30-meter DEMs were compared for each quadrangle. To assess variability associated with different methods of producing 30-meter DEMs, two adjacent 7.5-minute topographic quadrangles were selected in two ecoregions (Table 1). One of each pair was available as a Level 1, 30-meter DEM and the other as a Level 2, 30-meter DEM. The quality of the two selected Level 1 30-meter DEMs differed and affected their utility for aquatic analyses. On one of the chosen quadrangles (Sunset Springs), striations or "corn rows" were obvious on a shaded relief map (Figure 1); on the other quadrangle (Loon Lake), systematic errors were not apparent. Stream, HU, and slope results from 10-meter DE-DEMs and 30-meter DEMs were compared for the Sunset Springs/Elsie quadrangle pair.

We recognize that the question of how well DEMs reflect actual landforms is important for aquatic analyses; however, it was outside the scope of this paper. In defining and describing map accuracy, the only "truth" is the terrain surface itself. Because this cannot be obtained by measurement, accuracy of any field survey data, photogrammetric measurement, or map can be assessed only by comparing it with measurements made to a higher order of accuracy (Shearer, 1991). Consistent with this, we assessed relative accuracy by comparing streams and HUs modeled from DEMs to stream layers and topography from 7.5-minute quadrangles and by comparing slopes modeled from 30-meter DEMs and 10-meter DE-DEMs.

Streams

Perhaps the most critical data layer for aquatic analyses is an accurate portrayal of the stream network, assessed in terms of spatial location and drainage extent. Because streams are the foundation from which other information is georeferenced or derived, the quality of the original stream data influences the quality of subsequent data layers. Biological, physical, and chemical conditions, including fish abundance, habitat types, and dissolved oxygen concentrations, can be georeferenced to a stream layer. Additionally, relationships can be assessed between these instream conditions and stream buffer characteristics, such as percent slope, forest cover type, and road density (Burnett, 2001). The positional accuracy and extent of the stream network influences the extent of these buffers, thereby affecting the quality of buffer characterizations.

Because we wanted to employ a commercially available method, streams were generated from the 10-meter DE-DEMs and 30-meter DEMs with the streamline command in ArcInfo version 7.2, using a 4-hectare drainage area threshold for channel initiation. However, an alternative method was used in the CLAMS project because it more accurately represented the extent of the stream network (see http://www.fsl.orst.edu/clams/prj_wtr_str_indx.html, last accessed 14 August 2003, for details on the method). Streamline uses the output from a flow accumulation grid, applying the method presented in Jenson and Domingue (1988). The 4-hectare threshold produced streams that exceeded the extent of most streams on the 1:24,000-scale USGS hydrography DLGs. However, the channel initiation threshold was chosen to compare the positional accuracy of streams between resolutions rather than to represent the extent of the actual channel network as Tarboton *et al.* (1991) describe. Channel initiation threshold values that are too small can exceed the data resolution and capabilities of the software, thus creating many erroneous parallel lines, commonly termed "feathering."

Streams modeled with the 10-meter DE-DEMs and Level 1 and 2 30-meter DEMs were visually compared with the 1:24,000-scale stream layer for the number and extent of parallel streams, presence of meander bends in flatter terrain, and angles of tributary junctions. The mean length of stream miles produced for each resolution was compared with a paired t-test.

Hydrologic Units

An accurate portrayal of HU boundaries, correctly identifying drainage divides and coalescing at tributary junctions, is important for aquatic analyses. Hydrologic units have been incorporated in regional-scale designs for assessment and monitoring (e.g., Lee *et al.*, 1997; ULEP, 2001; Reeves *et al.*, 2003). Hydrologic units can also be used to model relationships among instream biota, channel conditions, and landscape characteristics and then to extrapolate model predictions. Although 5th-field HUs (FGDC, 2002) were available in a vector format for western Oregon (REO, 2002), these HUs are considered too coarse (i.e., average size in the CLAMS area is 35,485 hectares) for many applications. Thus, smaller 6th- and 7th-field HUs (4000 to 16,000 and 700 to 4000 hectares, respectively) are desirable. Producing these manually by delineating on 7.5-minute topographic quadrangles then digitizing would be time consuming and prove difficult to maintain consistency. However, DEMs are well suited for automated HU delineation, given an input area threshold.

Hydrologic units for both resolutions of DEMs were delineated with the USGS GIS Weasel (Viger *et al.*, 1998) and an 1100-hectare threshold value. The threshold value was selected to approximate the Federal Geographic Data Committee's guidelines (FGDC, 2002) for 6th-field HUs. For our comparisons, the output from the GIS Weasel was not edited.

We compared the 10-meter DE-DEMs and Level 1 and 2 30-meter DEMs for objectively delineating HUs. The modeled HU outlets were visually compared with tributary junctions on the 1:24,000-scale digital stream coverage, and the percent of correct HU outlets for each resolution was determined for each quadrangle. Boundaries of HUs were visually compared with the ridgelines on 1:24,000-scale topographic quadrangles, and the length of stream that was incorrectly cut off by a HU boundary was calculated.

Slope

The slope of hillsides and channels can directly affect instream conditions, including substrate type, amount of large wood, and channel morphology. Slope can also indirectly

TABLE 2. RATIONALE AND CITATIONS FOR SLOPE CLASS BREAKS

Slope Class Break	Rationale	Citation(s)
3%	Upper extent spawning habitat for chinook and coho salmon	Montgomery *et al.*, 1999
6%	Upper extent spawning habitat for steelhead trout	Montgomery *et al.*, 1999 ULEP, 2001
20%	Upper limit for salmon and steelhead and resident trout	Oregon Department of Forestry, 1997
40%	Lower limit for debris-flow initiation	Oregon Department of Forestry, 1999
65%	Lower limit for high risk sites for destructive mass soil movement	Oregon Department of Forestry, 2000

affect such instream conditions by influencing factors external to channels such as type of land use, degree of stream shade, and probability of debris flow initiation. Measuring and mapping slope in the field is time intensive; DEMs offer an efficient way to determine slope for large areas (Lunetta *et al.*, 1997; Montgomery *et al.*, 1998).

Percent slope grids for both resolutions of DEMs were generated by the slope algorithm in ArcInfo's grid module. This algorithm identifies the rate of maximum change in elevation from each cell. Resulting slope grids were summarized by six classes that reflected potential effects on processes influencing the quality of anadromous salmonid habitat (Table 2).

Slope classes were compared between the 10-meter DE-DEMs and 30-meter DEMs by coincidence matrices. Coincidence matrices indicated the number of pixels in each slope class for both resolutions of DEMs. Amount and direction of deviation can be ascertained from the number and identity of misclassifications. Coincidence matrices were derived using a method similar to that of Isaacson and Ripple (1990), wherein an actual pixel-by-pixel difference was determined by converting the 10-meter DE-DEM to a point coverage. Using an Arc Macro Language script developed by ESRI, the corresponding 30-meter DEM value was obtained for each point. A matrix was constructed that showed the frequency of coincidence of all classes for each quadrangle. Histograms were considered for comparing slope classes between DEM resolutions. However, preliminary analyses revealed that coincidence matrices were more useful because histograms commonly masked differences between resolutions and were unable to identify the direction of the difference.

Results and Discussion

Streams

The 10-meter DE-DEMs produced a more positionally accurate stream layer than either the Level 1 or 2 30-meter DEMs relative to the 1:24,000-scale USGS hydrography DLG. Much of the improvement in positional accuracy probably can be attributed to drainage enforcement, especially for lower gradient, less confined channels. As suggested by Thieken *et al.* (1999) and Hutchinson and Gallant (2000), increased vertical resolution may have also contributed to the more accurate spatial location of channel segments, given that elevation data were recorded to the nearest decimeter in our 10-meter DE-DEMs and to the nearest meter in the 30-meter DEMs.

Increased spatial accuracy of streams derived from 10-meter DE-DEMs was most noticeable in flatter terrain. The number and extent of parallel or "feathered" streams was greatly reduced, especially in the Coastal Lowlands ecoregion. In many of the low-gradient sections of the channel network, streams derived from 30-meter DEMs cut across meander bends (Figure 2), thereby shortening the channel length and potentially causing incorrect stream gradient measurements and stream buffer characterizations (Figure 3). Without drainage enforcement on the 30-meter DEMs, the angle at which tributaries entered many low-gradient sections differed from the 1:24,000-scale stream network (Figure 4). Tributary junction angle is an important variable for modeling debris flow runout (Benda and Dunne, 1987). In highly dissected areas, such as the Volcanics ecoregion, streams produced from the 10-meter DE-DEMs and 30-meter DEMs corresponded closely, having fewer parallel streams and less error in meander bends and tributary junction angles.

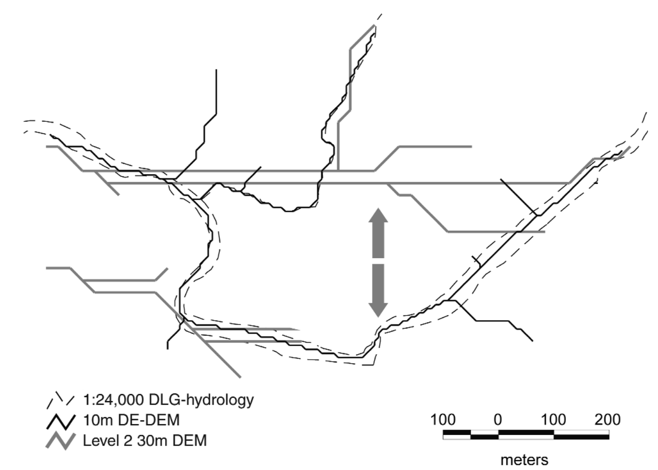

Figure 2. Stream generation comparison for the Tillamook Quadrangle (4-hectare drainage area threshold used for stream initiation). Color version available on ASPRS Web site (www.asprs.org).

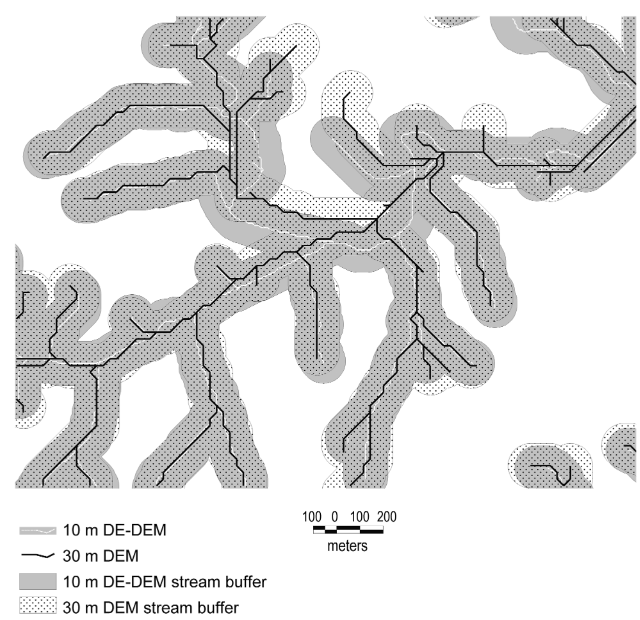

Figure 3. Stream buffer comparison for the Vinemaple Quadrangle, Willapa Hills ecoregion. Color version available on ASPRS Web site (www.asprs.org).

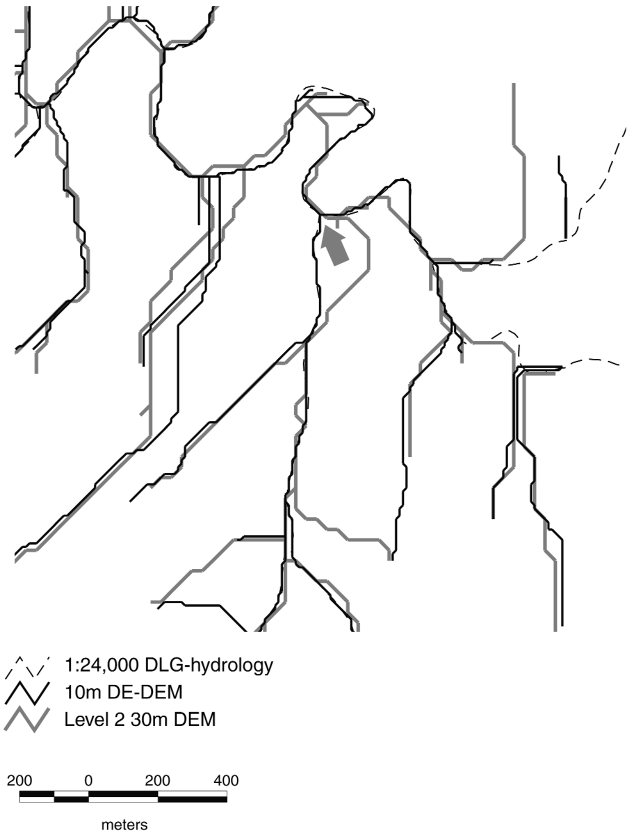

Figure 4. Tributary junction angles for the Olney Quadrangle, Coastal Uplands ecoregion. Color version available on ASPRS Web site (www.asprs.org).

Wang and Yin (1998) identified DEM scale and drainage density as the two major factors affecting the accuracy of stream networks derived from DEMs. Similar to our findings, they noted that neither 1:250,000- nor 1:24,000-scale DEMs produced accurate stream networks if the terrain complexity was low. At high terrain complexity, both scales produced equally representative drainage networks. Shearer (1991) credited the improved ability to delineate streams in areas of steeper slopes to the density and distribution of input data. In steeper slopes contours are closer together on the source map, resulting in more data points.

Although stream length differed between 10-meter DE-DEMs and 30-meter DEMs, we attributed this primarily to a difference in drainage enforcement rather than resolution. Wang and Yin (1998) found that 3-arc-second DEM data significantly underrepresented the total stream length generated from 30-meter DEM data. They used a drainage area threshold value for stream initiation that best represented the extent of the 1:100,000-scale stream network. Similarly, we found that mean stream length differed between DEM resolutions (paired t-test, $P = 0.02$, $df = 9$) (Table 3). However, unlike Wang and Yin (1998), we found longer stream length was usually associated with streams produced from coarser resolution DEMs. This was likely a consequence of increased "feathering" for streams delineated from the non-drainage enforced 30-meter DEM in flatter terrain. This assumption was supported given that we observed the greatest stream length difference (59 kilometers) for the Tillamook quadrangle located in the Coastal Lowlands ecoregion and the least stream length differences for the Toledo North quadrangle located in the Coastal

Table 3. Comparison of Stream Length between 10-Meter DE-DEMs and Level 2 30-Meter DEMs

Quadrangle Name	10-Meter DE-DEM (km)	30-Meter DEM (km)
Tillamook	465	524
Olney	436	451
Toldeo North	405	401
Vinemaple	400	430
Pittsburgh	415	427
Jordan Creek	429	426
Warnicke Creek	394	396
Norton	335	353
Glenbrook	386	402
Elsie	383	398
Mean	404.8	420.8
Standard Deviation	35.2	44.6

Uplands ecoregion (−4 kilometers) and the two quadrangles of the Volcanics ecoregion, Jordan Creek and Warnicke Creek (−3 and +2 kilometers).

The extent and location of small headwater streams appeared unaffected by DEM resolution or drainage enforcement. Headwater streams usually ended at the same location, although occasionally streams from one or the other resolution extended a short distance farther. Few headwater streams were mapped on the 1:24,000-scale USGS hydrography DLG used for drainage enforcement; thus, 10-meter DE-DEMs were not drainage-enforced in these upland areas. This lack of drainage enforcement did not seem to be an issue, given that headwater streams coincided for the two resolutions and appeared to be in valley bottoms on shaded relief maps. Both resolutions produced a drainage network with consistent stream density across the landscape (i.e., did not change at ownership or quadrangle boundaries).

For the Level 1 30-meter DEM (Sunset Spring quadrangle), striations had a noticeable influence on streams (Figure 5). More of the streamlines produced by the Level 1 30-meter DEM were straight, appearing to follow east-west striping as

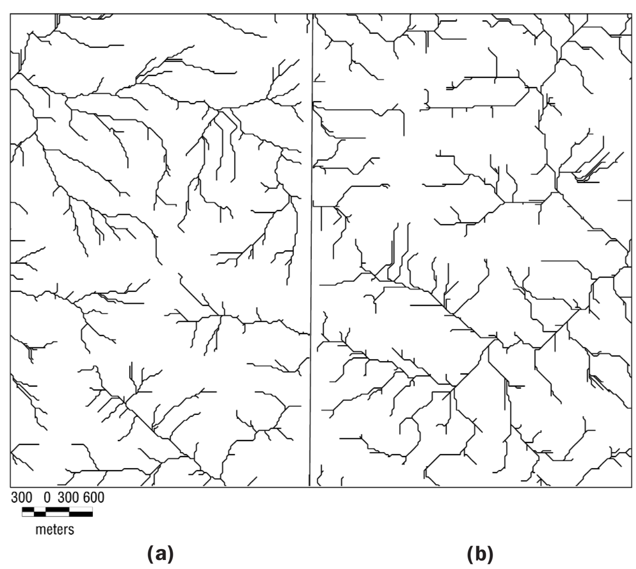

Figure 5. Stream generation comparison between Level 1 and Level 2 30-meter DEMs: (a) Elsie Quadrangle Level 2, 30-meter DEM; (b) Sunset Springs Quadrangle Level 1, 30-meter DEM.

TABLE 4. COMPARISON OF NUMBER OF CORRECT HYDROLOGIC UNIT OUTLETS BETWEEN 10-METER DE-DEMS AND LEVEL 2 30-METER DEMS

Quadrangle Name	Total Number of Outlets	10-Meter DE-DEM	30-Meter DEM
Tillamook	10	8	2
Olney	3	2	2
Toldeo North	5	5	2
Vinemaple	8	8	3
Pittsburgh	10	9	0
Jordan Creek	9	9	6
Warnicke Creek	8	8	4
Norton	4	4	2
Glenbrook	0	0	0
Elsie	6	6	5
Total	63	59 (94%)	26 (41%)

described by Garbrecht and Stark (1995). Additionally, they note that striping may block the drainage for drainage paths with a north-south flow component. We found striping also altered tributary junction angles.

Hydrologic Units

When compared with drainage features on 7.5-minute topographic quadrangles, HUs developed from the 10-meter DE-DEM matched HU outlet locations and ridgelines better than those derived from the 30-meter DEMs. However, both resolutions produced better HUs in steeper than flatter terrain. HU outlets matched the 1:24,000-scale stream confluences more often when produced with the 10-meter DE-DEMs than with the 30-meter DEMs (Table 4, Figure 6), reducing the amount of hand editing required to relocate HU pour-points to stream

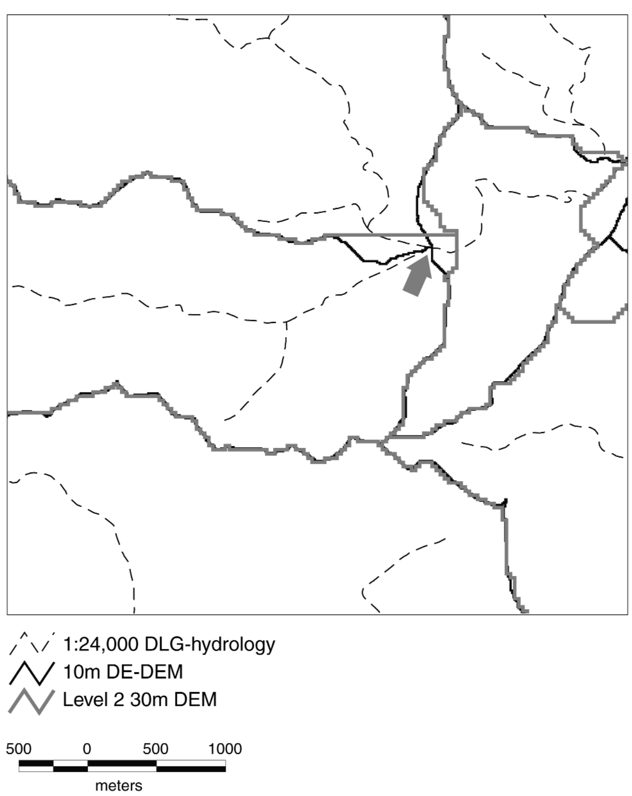

Figure 6. Hydrologic unit outlet delineation comparison for the Vinemaple Quadrangle, Willapa Hills ecoregion. Color version available on ASPRS Web site (www.asprs.org).

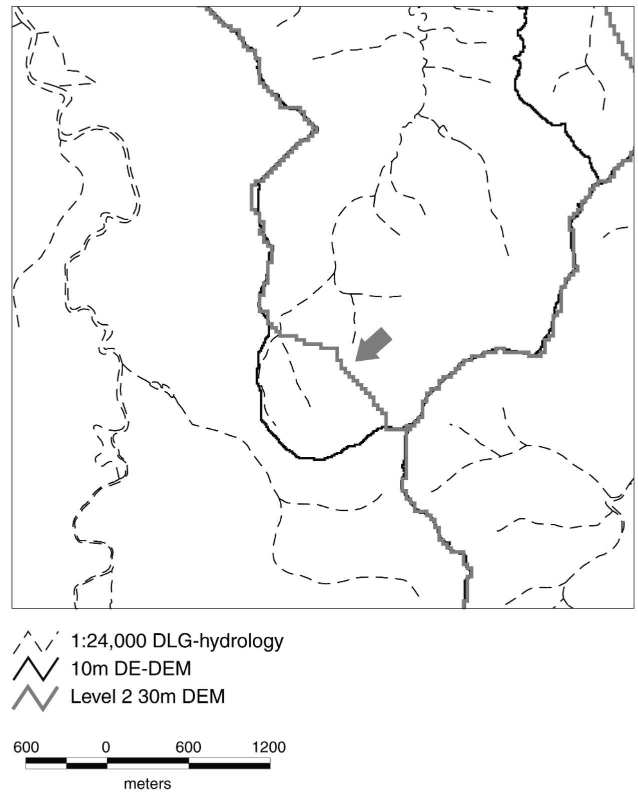

Figure 7. Hydrologic unit ridgeline delineation comparison for the Olney Quadrangle, Coastal Uplands ecoregion. Color version available on ASPRS Web site (www.asprs.org).

confluences. HU boundaries differed from the ridgeline shown on the topographic map more often when produced from the 30-meter DEMs than from the 10-meter DE-DEMs (Figure 7). On five quadrangles, the 30-meter DEM-derived HUs incorrectly cut off streams depicted on the 1:24,000-scale USGS hydrography DLG. The length of stream cut off ranged from 400 to 1300 meters for Level 2 30-meter DEMs and was 3500 meters for the Level 1 30-meter DEM. No streams were cut off by HUs derived from 10-meter DE-DEMs. Problems of boundaries matching stream confluences and ridgelines potentially alter the ability to accurately characterize landscapes by HU. The comparison of Level 1 and 2 30-meter DEMs with 10-meter DE-DEMs revealed that HU boundaries missed some tributary junctions and ridgelines at both levels. However, the Level 1 30-meter DEM was more likely to produce this type of error because of striations. The Level 2 30-meter DEM correctly identified seven out of eight HU outlets compared to eight correct HU outlets on the corresponding 10-meter DE-DEM. The Level 1 30-meter DEM incorrectly identified both HU outlets on the chosen quadrangle, but both were correctly identified using the 10-meter DE-DEM.

Slopes

As indicated in the coincidence matrix, Level 1 and Level 2 30-meter DEMs generally underrepresented steep slopes and low gradient areas when compared to 10-meter DE-DEMs (Table 5). The amount of underrepresentation varied by ecoregion. Overall, the average percent coincidence was least in the highest slope class (31 percent) (Table 5); slope classes that represented the most area had the greatest percent coincidence (72 percent and 77 percent). The coincidence for the 3 to 6 percent slope class was only slightly greater than for the

TABLE 5. PERCENT AGREEMENT BETWEEN 10-METER DE-DEMS AND 30-METER DEMS FOR EACH 7.5-MINUTE QUADRANGLE (ALL 30-METER DEMS ARE LEVEL 2 UNLESS NOTED OTHERWISE)

		Slope Class (in percent)					
Quadrangle Name	Level IV Ecoregion	0–3	3–6	6–20	20–40	40–65	>65
Tillamook	Coastal Lowlands	87(h)	35	68	58	32	21(l)
Olney	Coastal Uplands	64	48	84(h)	76	47	31(l)
Toledo North	Coastal Uplands	66	33	75	74(h)	46	11(l)
Vinemaple	Willapa Hills	68	52	87(h)	81	47	26(l)
Pittsburgh	Willapa Hills	61	52	85(h)	74	50	21(l)
Jordan Creek	Volcanics	38(l)	35	65	72	71	65(h)
Warnicke Creek	Volcanics	21(l)	22	73	55(h)	69	51
Norton	Mid-Coastal Sedimentary	31(l)	33	72	80(h)	64	25
Glenbrook	Mid-Coastal Sedimentary	50	45	83	82(h)	60	29(l)
	Mean	54	39	77	72	54	31
Elsie	Volcanics	58(l)	44	84	80(h)	72	66
Sunset Springs (Level 1)	Volcanics	11(l)	16	61	64(h)	40	16

Note: (h) represents the most area for the quad and (l) represents the least area for the quad on the 10-meter DE-DEM.

greater than 65 percent class. This possibly is due to the narrow range of slopes in this class and also to the proximity of areas in this class to stream channels, where abrupt changes in slope are more common.

Most of the Tillamook Quadrangle (Coastal Lowlands ecoregion) consists of flat agricultural and estuarine areas, surrounded by hills (Pater *et al.*, 1998). An 87 percent coincidence was observed between the two resolutions in the lowest slope class, mainly because this class occurs as large contiguous areas. Coincidence was poorer for the 3 to 6 percent slope class (35 percent). Along major stream channels, the 30-meter DEM had more area in this class than on the 10-meter DE-DEM where the same area was in the 0 to 3 percent slope class. Coincidence was also poor in the two highest slope classes, which contained less than 10 percent of the area at both resolutions.

The Coastal Uplands and Mid-Coastal Sedimentary ecoregions are underlain by sandstone deposits and are topographically similar, but the Mid-Coastal Sedimentary ecoregion has slightly higher relief (Pater *et al.*, 1998). Results were fairly similar for the four quadrangles, two in each ecoregion (Table 5). The best coincidence was in the slope class (6 to 20 percent or 20 to 40 percent) that had the greatest percentage area at both resolutions. The greater than 65 percent slope class had the poorest coincidence for all four quads. At both resolutions, this class usually appears as a linear feature rather than a large contiguous block. For the more spatially contiguous 3 to 6 percent slope class, coincidence was under 50 percent for all four quads. The two quadrangles in the Coastal Uplands ecoregion had better coincidence between resolutions for the 0 to 3 percent slope class than in Mid-Coastal Sedimentary ecoregion (64 percent and 66 percent versus 31 percent and 50 percent), given the greater area in this class (18 percent and 7 percent versus 2 percent and 4 percent, respectively).

The Willapa Hills ecoregion consists of low rolling hills and mountains (Pater *et al.*, 1998). Results for both quadrangles were similar (Table 5). Over 44 percent of the area for both resolutions is in the 6 to 20 percent slope class, where coincidence was best. Coincidence dropped off for both the lower and higher slope classes, reaching the least value for the greater than 65 percent slope class. This class represents less than 2 percent of the area for both resolutions. Between 4 percent and 8 percent of the area for both resolutions is in the 40 to 65 percent slope class, where coincidence was around 50 percent.

The steepest terrain is in the Volcanics ecoregion. Because of the larger, more contiguous area in the greater than 65 percent slope class, the best coincidence for this class was in this ecoregion (51 to 65 percent) (Table 5). Despite both quadrangles being in the Volcanics ecoregion, the Jordan Creek quadrangle has more area with volcanic rock, yielding more area in the highest slope class. For this quadrangle, both resolutions show the same pattern of steep slopes, but 10 percent more area was in the highest slope class at 10-meter resolution than at 30-meter resolution. In the middle slope classes (6 to 20 percent and 20 to 40 percent) coincidence was moderate (55 to 73 percent) and usually slightly lower than for the other ecoregions. The two lowest slope classes, with limited spatial distributions, had low coincidences (21 to 38 percent).

Adjacent Level 1 and 2 30-meter DEMs yielded very different results when compared to 10-meter DE-DEMs (Table 5). For the Level 2 DEM, percent coincidences with the 10-meter DE-DEM were similar to the other two quadrangles located in the Volcanics ecoregion (Table 5). For the Level 1 DEM, percent coincidence with the 10-meter DE-DEM for each slope class was less than all other Level 2 quadrangles located in the Volcanics ecoregion, except for the 20 to 40 percent slope class on the Warnicke quadrangle. Guth (1999) acknowledged that Level 2 DEMs were a major improvement over Level 1 DEMs despite his concerns about the influence of DEMs generated with biased contour-to-grid algorithms on derived characteristics such as slope and aspect.

Results of our slope comparisons between 10-meter DE-DEMs and 30-meter DEMs are similar to those of other authors. Higher resolution DEMs better represent slope (Chang and Tsai, 1991; Zhang *et al.*, 1999). Additionally, lower resolution DEMs were shown to underrepresent both low (Gao 1997) and high (Elsheikh and Guercio, 1997; Zhang *et al.*, 1999) slope classes. This is suggested by sampling theory that states a feature must be greater than or equal to twice the size of the grid cell to be adequately described. A feature must exceed 60 meters on a 30-meter DEM or 20 meters on a 10-meter DE-DEM to be resolved (Weih and Smith, 1990). Additionally, increased vertical resolution may also contribute to a better representation of slope especially in areas of low relief (Hutchinson and Gallant 2000). Chang and Tsai (1991) conclude that relative relief significantly and predictably affects slope differences, which is consistent with variation we observed among ecoregions in slope class differences.

Summary and Conclusions

Overall quality of streams, HUs, and slope characterizations were generally best when derived with 10-meter DE-DEMs, intermediate with Level 2 30-meter DEMs, and worst with the Level 1 30-meter DEM. Stream layers were more realistic and positionally accurate and HUs more commonly matched drainage confluences and ridgelines on 1:24,000-scale topographic maps when generated from 10-meter DE-DEMs than from 30-meter DEMs. Both lower and higher slope classes were better represented by 10-meter DE-DEMs than by 30-meter DEMs. Classifications with 10-meter DE-DEMs and Level 2 30-meter DEMs were similar for large contiguous blocks of the same slope. However, many small features, and especially linear features, are below the detectable resolution of 30-meter DEMs. Increased horizontal and vertical resolution of 10-meter DE-DEMs contributed most to better resolving higher and lower slope classes. Although the higher resolution of 10-meter DE-DEMs enhanced stream and HU delineation, drainage enforcement likely had a greater impact. Inferior products that were created with the Level 1 30-meter DEM resulted largely from systematic errors in the DEM.

The 10-meter DE-DEMs are a valuable advancement over the 30-meter DEMs for many aquatic applications. A better stream layer increases accuracy when characterizing stream buffers, calculating channel gradients, and representing tributary junction angles; the latter two are important for modeling the routing of debris flows. Improved HU boundaries can render landscape characterizations more reliable. Enhanced capability to distinguish slope classes can aid when describing or modeling aquatic systems. For example, accurate maps of low and high slopes are essential when attempting to locate potential salmonid habitat or model debris flow transport. Such improved descriptions of aquatic-related resources are relevant for research, management, and conservation applications. As a result of this study, the CLAMS project, with financial and other support from state and federal agencies, coordinated production of 10-meter DE-DEMs for the entire Coast Range Province of Oregon using a consistent method and a single contractor (Averstar Geospatial Services, now Titan Corp.).

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