Report of the West Valley Erosion Working Group

Study 2: Recent Erosion and Deposition Processes

Task 2.1(b) Digital Mapping of Potential Analogue Sites

WEST VALLEY DEMONSTRATION PROJECT AND WESTERN NEW YORK NUCLEAR SERVICE CENTER

Submitted to:

United States Department of Energy, and
New York State Energy Research and Development Authority

Prepared By:

Dr. Sean J. Bennett
Member, WV Phase 1 Studies EROSION WORKING GROUP

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ECS

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West Valley Demonstration Project (WVDP) and
Western New York Nuclear Service Center (WNYNSC)

Phase 1 Studies EROSION WORKING GROUP:

Sean Bennett, Ph.D. *Dept. of Geography, State University of New York at Buffalo*

Sandra Doty, M.S., P.E. *Consulting Geological Engineer*

Robert Fakundiny, Ph.D. *New York State Geologist, Emeritus*

Greg Tucker, Ph.D. *Dept. of Geological Sciences, University of Colorado*

Michael Wilson, Ph.D. *Dept. of Geosciences, State University of New York at Fredonia*

Richard Young, Ph.D. *Dept. of Geological Sciences, State University of New York at Geneseo*

ECS Study Area Manager:

Michael Wolff, P.G., C.E.G.

This report has been peer-reviewed and accepted by the West Valley Erosion Working Group, and is formally submitted to:

United States Department of Energy, and
New York State Energy Research and Development Authority

EXECUTIVE SUMMARY

Enviro Compliance Solutions, Inc. and the West Valley Erosion Working Group (EWG) recommended erosion assessment to be performed as part of the Phase 1 Studies at the West Valley Demonstration Project (WVDP) and Western New York Nuclear Service Center (WNYNSC). These studies seek to improve forecasts of future erosion at this facility and to reduce the uncertainty of such predictions, and these studies include a focus on recent erosion and deposition processes. Gully erosion remains an important geomorphic process of concern for the current and future integrity of the site, and the use of analogue sites for gully erosion investigation is being explored. The current study examines the morphologic and geologic characteristics of gullies at the WVDP and at selected locations off-site using readily available data. On the basis of this analysis, potential analogue gullies can be identified in nearby environs within and near the Western New York Service Center.

The primary database used in the analysis of gullies is the 2010 aerial LiDAR[1] survey jointly funded by the New York State Energy Research and Development Authority (NYSERDA) and the Department of Energy (DOE). These digital data were manipulated in Geographic Information System (GIS) software to process, analyze, and extract information for the gullies at the WVDP and at selected off-site areas nearby.

A total of 13 gullies were identified using the LiDAR on and near the WVDP, and nearly all of the gullies exhibit a two-stage morphology, where the gully can be divided into inner and outer portions. The inner gully is incised into the relatively flat plateau region of the landscape, and gully width and depth increase in the downstream direction. The outer gully occurs at the point where the gully emerges from this incised portion of the landscape. The gullies tend to display no concavity or convexity, their average slope is about 0.70±0.35 m/m, and they have V-shaped profile in cross-section. Total inner gully lengths are about 47±30 m, and all of the gullies are found on landscapes mantled by the Lavery Till, as per the published surficial geology map of LaFleur (1979). The inner gully tends to be relatively small in size near its most upstream reaches, and width and depth increase in the downstream direction.

Investigation of current erosion processes within the WVDP and the WNYNSC presents many safety, regulatory, and logistical challenges owing to potential study locations falling within WVDP radiological control areas and WNYNSC designated Access Prohibited Areas (APAs) that may not be resolved in a timely fashion. As such, an alternative approach consisting of the use of analogue sites for gully erosion assessment located outside of the WVDP and WNYNSC has been adopted.

Five areas containing potential analogue gullies were investigated near the WVDP for gully erosion features, and these areas lie within and adjacent to the WNYNSC but are outside the designated

[1]LiDAR is a remote-sensing surveying technology that uses light in the form of a pulsed laser to measure distance from a source (e.g., an airplane) to the Earth. These data then can be transformed into a map of surface topography.

APAs. The morphologic signatures of the potential analogue gullies were compared with the gullies on and near the WVDP using a simple qualitative assessment. In general, the attribute comparisons show very good agreement between the gullies. Five (5) gullies in particular are deemed to be very similar morphologically and geologically to the gullies on and near the WVDP. These features are just east of the WVDP near Heinz Road and just north of the WVDP near Route 240. Given such strong morphologic similarity, these five (5) gullies can be considered potential analogue gullies for the WVDP. Analogue gullies can be used for a variety of purposes, including site visits by agencies, researchers, and concerned citizens, the analysis of landform and landscape evolution using remotely sensed data, and field-based monitoring programs to assess hydrology, sediment transport, and hillslope processes. Field investigations should also include reconnaissance, analysis and verification of surface geological materials, and an assessment of access to sites and their suitability for the installation of monitoring equipment. On-going efforts are now focused on a newly acquired LiDAR survey in 2015 of this same region, which allows direct determination of the time- and space-variation of the gullies. This analysis can provide important information on the rates, styles, and characteristics of gully erosion and landscape evolution and can be used to inform conceptual and numerical models of gully erosion at the WVDP and within the WNYNSC.

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List of Acronyms

APA	Access Prohibited Area
ECS	Enviro Compliance Solutions, Inc.
EWG	Erosion Working Group
GIS	Geographic Information System
Hfp	Holocene Floodplain surficial geology mapping unit (LaFleur, 1979)
Htl	Holocene Landslides and Slumps surficial geology mapping unit (LaFleur, 1979)
LiDAR	Light detection and ranging; portmanteau of "light" and "radar"
NYSERDA	New York State Energy Research and Development Authority
Wfg	Defiance fluvial gravel surficial geology mapping unit (LaFleur, 1979)
Wtc	Lavery Till surficial geology mapping unit (LaFleur, 1979)
WVDP	West Valley Demonstration Project
WVEWG	West Valley Erosion Working Group (same as EWG)
WNYNSC	Western New York Nuclear Service Center

1. Introduction

Enviro Compliance Solutions, Inc. (ECS) and the West Valley Erosion Working Group (EWG) prepared a document that recommended erosion studies to be performed as part of the Phase 1 Studies at the West Valley Demonstration Project (WVDP) and Western New York Nuclear Service Center (WNYNSC; WVEWG and ECS, 2015). These recommended erosion studies seek to improve forecasts of erosion at the WVDP and WNYNSC, to reduce the associated uncertainty, and to assist the agencies in reaching consensus on the likely effects of future erosion. These studies were divided into three focus areas: Study 1: Terrain Analysis, Age Dating, and Paleoclimate; Study 2: Recent Erosion and Deposition Processes; and Study 3: Model Refinement, Validation, and Improved Erosion Projections. The collective activities of these studies are designed so that each will contribute substantively to reducing the uncertainty in quantifying the erosion processes and to facilitate consensus amongst the agencies. This report focuses on preliminary results for Study 2.

The overall objective of Study 2 is to quantify and characterize recent rates of surface and near-surface erosion and temporary sediment storage occurring on hillslopes, in regions of concentrated flow, and in stream channels at and near the facility (WVDPEWG and ECS, 2015). A priority listing of specific studies and components has been identified on the basis of further consideration of uncertainty in erosion-prediction technology, and these can be grouped into three categories: (1) hydrologic parameters, which include storm depth, duration, and frequency parameters, and soil infiltration capacities; (2) erodibility parameters, which include stream-bed sediment entrainment thresholds, soil and till entrainment thresholds and erodibility coefficients, and soil and till particle sizes and bulk densities; and (3) gully geomorphic parameters, which include the morphometric characteristics of all gullies and the morphodynamics of any headcuts or knickpoints.

Gully erosion processes at the WNYNSC and WVDP remain an important geomorphic process of concern for the future integrity of the facility. Monitoring gully erosion processes over time and space will assist in the evaluation of these geomorphic processes. Development and application of gully erosion prediction technology would greatly assist the evaluation and mitigation of erosion in the near-term (10s to 100s of years).

An important step in this gully erosion assessment and prediction technology development is to characterize those gullies currently present at the WVDP (herein referred to as "on-site"). Yet on-site investigation of current erosion processes presents many safety, regulatory, and logistical challenges that may not be resolved in a timely fashion. As such, an alternative approach consisting of the use of analogue sites for gully erosion assessment located outside of the WVDP and Access Prohibited Areas (APAs) and within the WNYNSC has been adopted (herein referred to as "off-site"). This concept is predicated on the scientifically-based conviction that, if morphologically-, hydrologically-, and geologically-similar gullies can be identified on the landscape nearby, then the results of studying these gullies can be applied with confidence to the gullies at the WVDP. These results would include rates and styles of erosion processes, and the development and application of gully erosion prediction technology.

The overall objectives of this study are (1) to define the morphologic and geologic characteristics of gullies at the WVDP (on-site) using readily available data, and (2) to identify gullies off-site in areas near the WVDP (within the WNYNSC but outside the APAs) and to define their morphologic and geologic characteristics using the same data and methodologies. By using a simple qualitative analysis, several gullies are recommended for investigation as potential analogue sites. The current effort constitutes Task 2.1(b) Digital Mapping of Potential Analogue Sites.

2. Methods

The primary database used in the analysis of gullies is the 2010 aerial LiDAR survey funded by NYSERDA and DOE. The topographic survey has a horizontal resolution of about 0.95 m and a vertical resolution of about 0.35 m for the WNYNSC.

The following methods were employed using these LiDAR data in ArcGIS[2] to process, analyze, and extract digital information for the gullies at the WVDP. These pre-processing steps included creating hillshade maps, slope (gradient) value maps, and slope (overland flow) direction maps. The flow direction maps were particularly helpful in unambiguously identifying gullies on the landscape simply by mapping the presence of converging flow paths from opposing slopes.

Algorithms were written within ArcGIS to automate the process of extracting topographic information from the gullies. These processing steps included identifying gullies and thalwegs[3] on the basis of slope value and flow direction maps and by drawing gully margins by hand using the flow direction maps. From these identified gullies, the following information was obtained: gully length, Euclidian distance, average orientation, width perpendicular to the thalweg extending from one gully margin to the other, depth from the projected gully width at the elevation of the margins drawn normal to the thalweg, and thalweg concavity. Selected topographic data along the gully widths were extracted so that representative cross-sections could be constructed near the head (termed upstream) and mouth (termed downstream) of each inner gully and at its mid-point location (termed mid-stream). Note that the cross-sections are oriented perpendicular to the average orientation of the gully rather than perpendicular to the gully reach.

3. Results

A total of 15 gullies were identified on- and off-site, and the locations of these are shown in Figure 1. The gullies were identified primarily by the flow direction maps created in GIS, which could easily demarcate swales on the landscape. The number and location of gullies in the region could vary depending on the specific criteria employed, but the focus here will be restricted to those

[2]ArcGIS is a commercial GIS software package developed by Environmental Systems Research Institute for creating maps and working with geographic information.

[3]Thalweg as used here refers to a line along a creek or gully joining the lowest points (maximum depth).

identified and their proximity to site features of concern. From this initial survey, two gullies were eliminated from further analysis (Gully 8 and Gully 15) because they displayed characteristics inconsistent with the other gullies present and they were judged to be less critical to the site features of concern. The focus of the subsequent analysis is on 13 gullies.

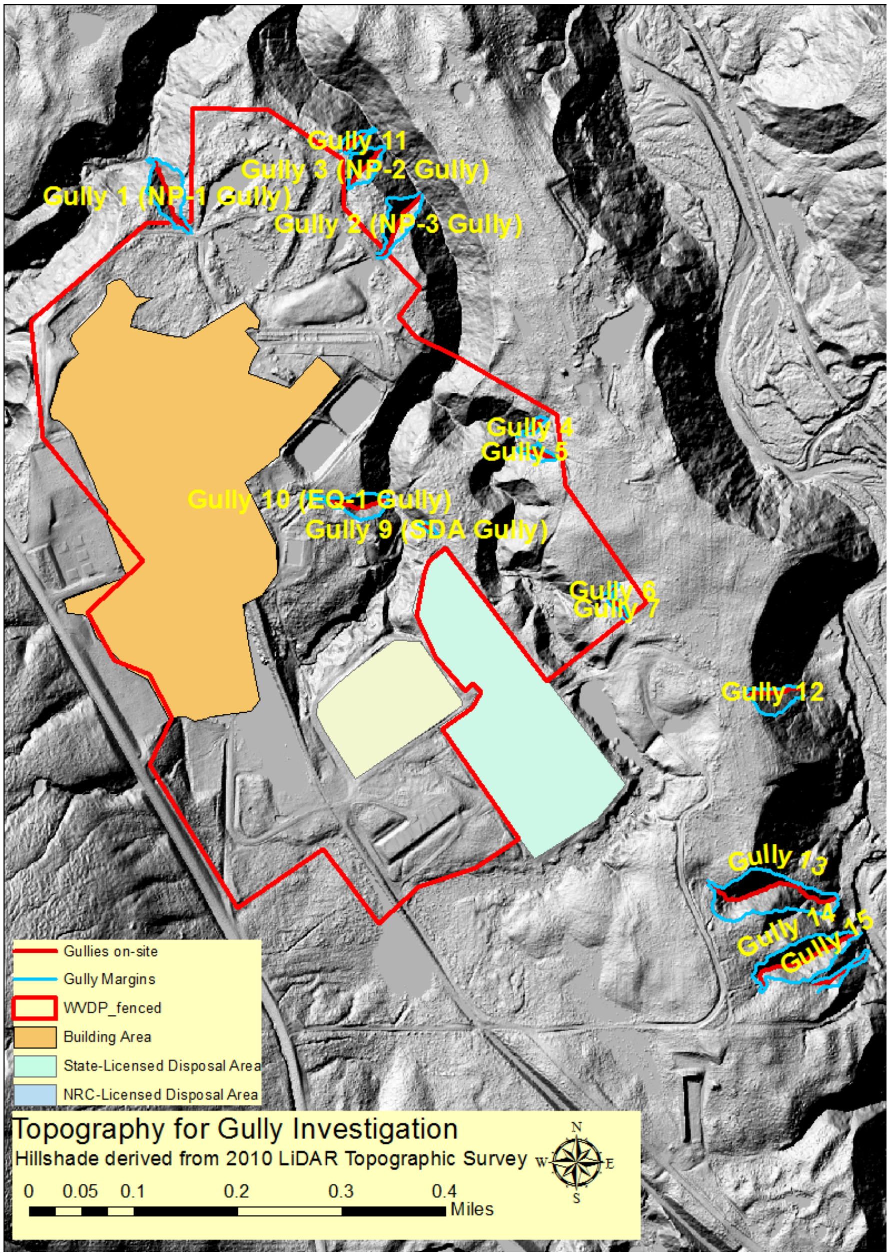


Figure 1. *Hillshade map of surface topography of the West Valley Demonstration Project using the 2010 LiDAR survey, showing the location of the 14 gullies identified on or adjacent to the premises (Gully 8 is not included here).*

3.1. Schematic Morphology of Gullies on and near the WVDP

An important morphologic observation should be made before presenting the data obtained for the gullies on-site, and this observation is schematically illustrated in Figure 2. Nearly all of the gullies at or near the WVDP (and within the WNYNSC) exhibit a two-stage morphology, where the gully can be divided into inner and outer portions. The inner gully is incised into the relatively flat plateau region of the landscape, with its arcuate head extending into this flatted surface, and gully width and depth increase in the downstream direction. Inner gully width is defined as the orthogonal distance spanning the inner gully drainage divide, and inner gully depth is defined as the perpendicular distance from the projected inner gully width (extending from one gully margin to the other) to the bottom of the gully channel (the thalweg).

At the location where the inner gully's width and depth tend toward their maximum values, termed the inner gully mouth, the gully emerges from its incised valley and traverses the plateau scarp toward the stream (Figure 2). No longitudinal discontinuity occurs at the transition from the inner to the outer gully, but the drainage divide moves toward the outer gully channel, greatly reducing gully width and depth with distance downstream, effectively pinching the gully as it enters the stream.

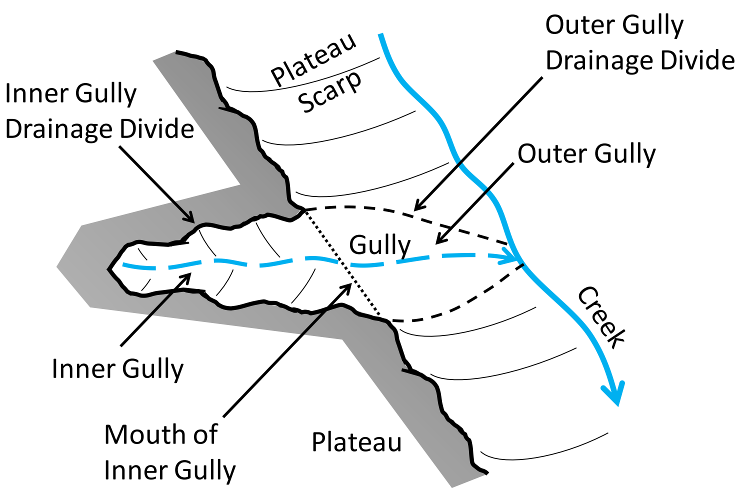


Figure 2. *Schematic drawing of a typical gully on-site at the WVDP defining the key components of the two-stage morphology.*

3.2. Example Gully on the WVDP

Figure 3 displays the morphologic characteristics of Gully 1 (also referred to as NP-1) located on the WVDP. This gully is typical of the geomorphic features found on and near the WVDP (and within the WNYNSC), and its characteristics are exemplified in Figure 2. As noted above, gully cross-sections were selected near the inner gully head (noted as upstream in Figure 3d), near the inner gully mouth (noted as downstream in Figure 3d), and near the inner gully mid-point (noted as midstream in Figure 3d), and these were selected to illustrate the gully morphology.

On the basis of this figure, the following gully attributes can be noted: (1) the gully displays the two-stage morphology in planform, with an inner gully incised into the landscape and an outer gully flowing across the plateau scarp; (2) the gully has a clearly identifiable swale where overland flow within the gully is directed toward the thalweg; (3) the longitudinal profile of the gully is relatively linear with distance, and no discernible change is noted in gully bed topography where the inner gully ends and where the outer gully begins; (4) width and depth of the inner gully increase with distance downstream; and (5) the gully exhibits a V-shaped profile in cross-section. Lastly, this gully is found on the Lavery Till (Wtc) and the Holocene Floodplain (Hfp) surficial deposits, as defined by LaFleur (1979).

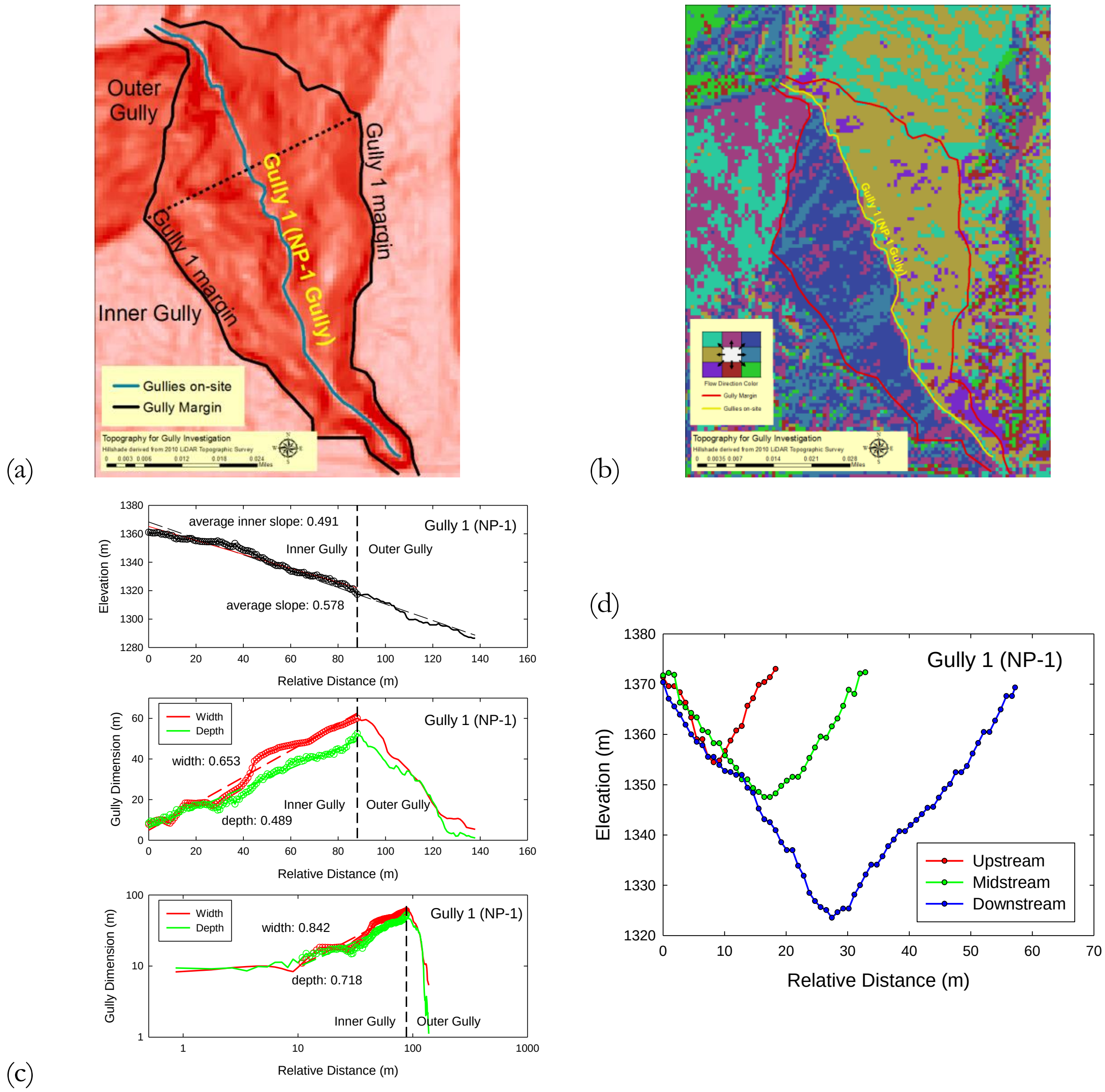


Figure 3. *Summary plots for Gully 1 (NP-1) on the WVDP showing (a) slope value map, (b) flow direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections of the inner gully (looking downstream along the gully thalweg).*

3.3. Morphologic Signatures of Gullies on and Near the WVDP and Within the WNYNSC

Table 1 summarizes the morphologic features for 13 gullies on and near the WVDP and within the WNYNSC, as well as simple statistics (average, standard deviation, and median). For the total gully, which includes the inner and outer portions of the gully, these attributes include the total length (from head to mouth), average slope, sinuosity, average geographic orientation, concavity of the longitudinal profile, and the surficial material (as per LaFleur, 1979). For the inner gully, where the gully is deeply incised into the landscape, these attributes include the total length (from head to mouth), average slope, width and depth near the gully head, near the gully mid-point (mid-width and mid-depth), and near the gully mouth, the rates of change of width and depth (exponents) with longitudinal distance downstream using arithmetic (arith.) and logarithmic (log.) axes, and ratios of the length and slope of the inner gully to the total gully. Appendix 1 contains all maps and plots created for these gullies, similar to those presented in Figure 3. On the basis of these results, the following observations can be made (refer to Figures 1, 3, and 4, and Appendix 1). Simple statistics are reported here, including the mean (numerical value) and standard deviation (± the mean value) of the observations. The rather large standard deviations relative to the means, such as 11±10 m for the upstream inner gully width, reflect the large variance observed for the small sample size (13).

Morphologic signatures of the gullies on and near the WVDP and within the WNYNSC:

- The longitudinal slopes of the gullies show no concavity or convexity[4] of significance, and the average slope is about 0.70±0.35 m/m (or about 33±13°; these values represent the mean and standard deviation of the observations). The longitudinal slopes of the inner gullies are nearly identical to the slopes of the total gullies, where the ratio of the inner slope-to-total slope is about 0.94±0.18. No discernible change is noted in the elevation of the gully thalweg when the inner gully transitions to the outer gully.
- The gullies tend to be rather straight in planform, exhibiting a relatively low sinuosity (defined as the sum total distance along the meandering thalweg divided by the straight line distance) of about 1.08±0.07. Their orientations, from upstream to downstream, tend to be directed toward the north, with 46% of the gullies are oriented toward the northeast and 31% of the gullies are oriented toward the northwest. The gullies also have V-shaped profile in cross-section.
- The total gully lengths tend to be about 94±60 m, and the inner gully lengths tend to be about 47±30 m. The ratio of the inner gully length-to-total gully length is about 0.54±0.23.
- All gullies are found on landscapes mantled by the Lavery Till (Wtc as per LaFleur, 1979). Two gullies are also found in association with the Holocene Floodplain (Hfp).
- The inner gully has incised into the landscape, and it is bounded by the gully sidewalls. The outer gully emerges from this incised region and extends across the plateau scarp toward the local stream.
- The inner gully tends to be relatively narrow near its most upstream reaches, where its width is about 11±10 m, its depth is about 4±4 m, and its width-to-depth ratio is about 3.9±2.9. At the mouth of the inner gully, gully width increases to about 36±21 m, its depth increases to about 22.2±15.7, and its width-to-depth ratio decreases to about 1.9±0.91.
- The width and depth of the inner gully increase with distance downstream. Using logarithmic axes, the rate of change of width with distance downstream is about 0.54±0.35

[4]Longitudinal profiles of rivers tend to be concave-upward (typical of tributary water and sediment transport networks). Longitudinal profiles along hillslopes without channels, river deltas, alluvial fans, and submarine fans tend to be convex-upward (more typical of distributary water and sediment transport networks).

> and the rate of change of depth is about 0.70±0.30. As the inner gully increases in size downstream, it tends to deepen at a rate faster than it widens. The rates of change of these dimensions in the downstream direction can be used to define, discriminate, and model the hydraulic geometry of gullies.

It is noted here that there is little information presented above on the characteristics of the outer gully. The working hypothesis is that the inner and outer portions of the gully would conform to different governing equations and different erosion prediction technology. That is, the inner gullies, given their morphologic characteristics, should conform to readily-available gully erosion theory for edge-of-field or classic gullies. The outer gullies, in contrast, might require a different analytical framework more akin to slope stability. The selection of potential analogue gullies will be based on this two-stage morphology, but the current emphasis was placed on the morphologic indices of the inner gully to facilitate the selection process. It is anticipated that the outer gullies will feature more prominently in future research investigations.

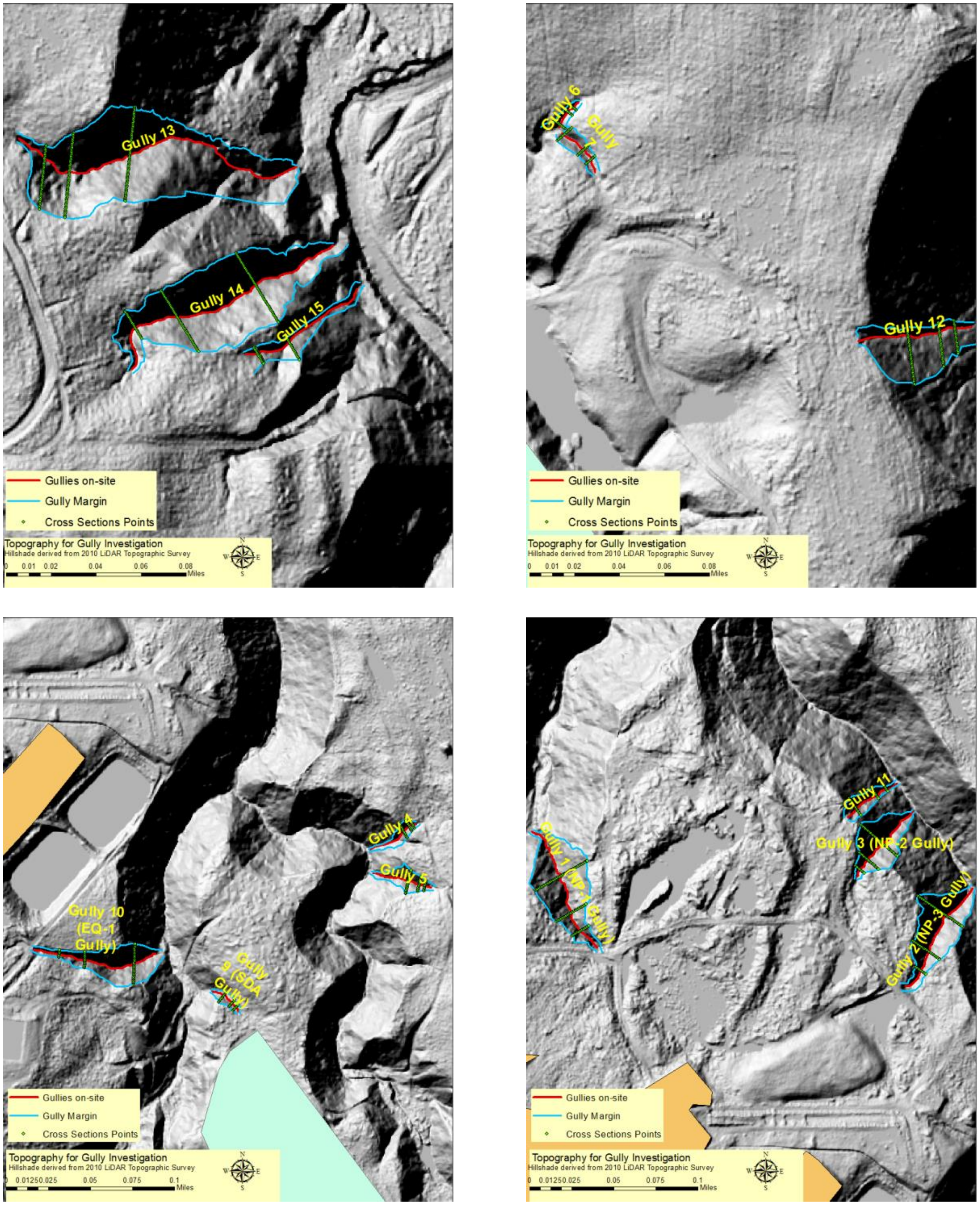


Figure 4. *Hillshade maps of surface topography of the WNYNSC on and near the WVDP using the 2010 LiDAR survey, showing the locations of the gullies and the cross-sections plotted. Refer to Figure 1 for additional information.*

Table 1: *Summary of morphologic parameters determined for selected gullies within the WNYNSC on and near the WVDP and their statistics (average, standard deviation, and median).*

Gully	1	2	3	4	5	6	7	9	10	11	12	13	14	Ave.	St. Dev.	Median
Parameter									***Total Gully***							
Total length (m)	137.89	119.2	86.37	52.99	58.20	23.59	38.84	34.57	125.42	59.06	84.01	213.7	193.94	94.44	60.37	84.01
Drainage area (m^2)	4760	4240	4091	1199	1800	987	478	1330	2257	952	603	2962	1658	2101	1458	1658
Average slope (m/m)	0.578	0.712	0.958	0.901	0.825	0.238	0.232	0.553	0.454	1.434	1.144	0.482	0.586	0.70	0.35	0.59
Average slope (deg)	30.0	35.5	43.8	42.0	39.5	13.4	13.1	28.9	24.4	55.1	48.8	25.7	30.4	33.1	12.7	30.4
Sinuosity	1.10	1.05	1.05	1.04	1.02	1.06	1.07	1.27	1.08	1.03	1.03	1.15	1.15	1.08	0.07	1.06
Orientation (deg)	330.4	34.4	40.6	241.4	283.8	38.0	318.8	309.2	92.2	55.4	82.8	95.9	58.5	152.4	122.0	92.2
Concavity	0.31	-0.06	0.17	0.32	0.001	0.69	0.35	0.59	0.06	-0.11	-0.03	-0.07	-0.03	0.17	0.26	0.06
Surficial material	Wtc/Hfp	Wtc	Wtc	Wtc/Hfp	Wtc/Hfp	Wtc	Wtc	Wtc	Wtc	Wtc	Wtc	Wtc	Wtc			
									Inner Gully							
Length (m)	88.12	82.66	43.67	13.68	22.66	23.59	34.27	18.20	86.49	15.31	37.46	59.79	91.17	47.47	30.25	37.46
Slope (m/m)	0.491	0.612	0.953	0.794	0.763	0.238	0.232	0.431	0.370	2.103	1.197	0.429	0.421	0.69	0.51	0.49
Slope (deg)	26.2	31.5	43.6	38.4	37.3	13.4	13.1	23.3	20.3	64.6	50.1	23.2	22.8	31.4	15.0	26.2
Width at head (m)	8.35	9.80	5.59	4.92	6.04	4.44	6.30	0.69	5.94	10.36	13.31	40.96	20.08	10.52	10.32	6.30
Mid-width (m)	38.85	30.67	28.62	11.33	14.15	7.25	10.41	0.775	15.41	18.08	36.08	60.08	30.92	23.28	16.19	18.08
Width at mouth (m)	60.06	51.47	46.49	14.94	22.98	10.72	14.92	12.29	39.89	20.43	41.77	70.45	61.65	36.00	21.06	39.89
Depth at head (m)	12.51	8.15	3.52	3.66	0.71	1.94	1.13	0.904	2.06	1.64	2.17	9.18	2.37	3.84	3.71	2.17
Mid-depth (m)	26.99	25.65	21.63	8.36	11.18	3.96	4.63	0.285	13.54	15.61	11.86	29.3	21.54	14.96	9.42	13.54
Depth at mouth (m)	52.6	33.70	26.25	12.51	16.20	3.75	7.47	4.95	28.01	13.74	9.34	39.12	40.93	22.20	15.72	16.20
Width exponent (arith.)	0.653	0.550	1.122	0.773	0.760	0.187	0.229	0.294	0.395	0.519	0.854	0.557	0.450	0.56	0.27	0.55
Depth exponent (arith.)	0.489	0.434	0.904	0.915	0.623	0.110	0.202	0.243	0.298	0.598	0.183	0.526	0.423	0.46	0.26	0.43
Width exponent (log.)	0.842	1.021	0.863	0.493	0.502	0.197	0.206	0.200	1.260	0.150	0.495	0.406	0.353	0.54	0.35	0.49
Depth exponent (log.)	0.718	0.944	0.953	1.025	0.528	0.305	0.489	0.639	1.061	0.407	0.200	0.937	0.958	0.70	0.30	0.72
Inner length/total length	0.64	0.69	0.51	0.26	0.39	1.00	0.88	0.53	0.69	0.26	0.45	0.28	0.47	0.54	0.23	0.51
Inner slope/total slope	0.85	0.86	0.99	0.88	0.92	1.00	1.00	0.78	0.81	1.47	1.05	0.89	0.72	0.94	0.18	0.89

3.4. Morphologic Characteristics of Analogue Gullies

The identification of potential analogue sites for gully erosion was discussed with NYSERDA and DOE personnel (L. Gordon and Z. Zadins, pers. comm.). The tenor of this discussion focused on the following issues: (1) the many safety, regulatory, and logistical challenges of conducting erosion research in WVDP radiological controlled areas and within APAs in the WNYNSC, which may not be adequately addressed or resolved in a timely fashion; and (2) the need to move forward with the erosion studies, which are designed to reduce the associated uncertainty of predicting current and future erosion on-site. On the basis of this discussion, five areas were identified for further investigation, as these regions lie within the WNYNSC but outside the APAs.

Areas investigated:

1. Area 2, just south of the WVDP near Thornwood Drive;
2. Area 3, just south of the WVDP near the intersection of Thornwood Drive and Fox Road;
3. Area 4, just east of the WVDP near Buttermilk Road;
4. Area 5, just east of the WVDP near Heinz Road; and
5. Area 6, just north of the WVDP near Route 240.

Figures 5 and 6 show the locations of these areas and the gullies examined in relation to the WVDP and the WNYNSC. Given their proximity, it is assumed that these areas and the WVDP would share similar climate and hydrology, bedrock and surficial material, geologic history, landform ages, and landscape evolution.

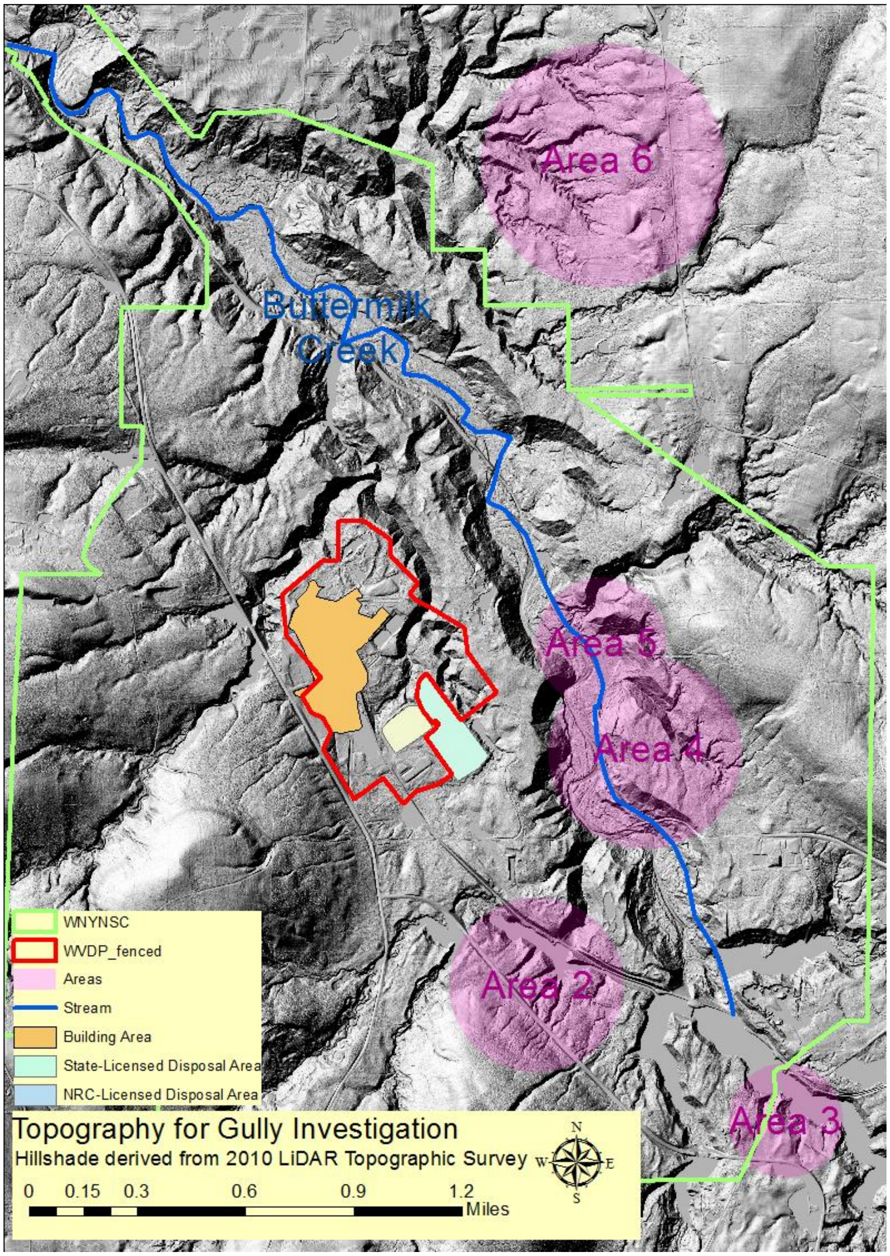


Figure 5. *Hillshade map of surface topography of the WNYNSC and adjacent areas using the 2010 LiDAR survey, showing the five areas (labelled Areas 2 through 6) investigated for potential analogue gullies.*

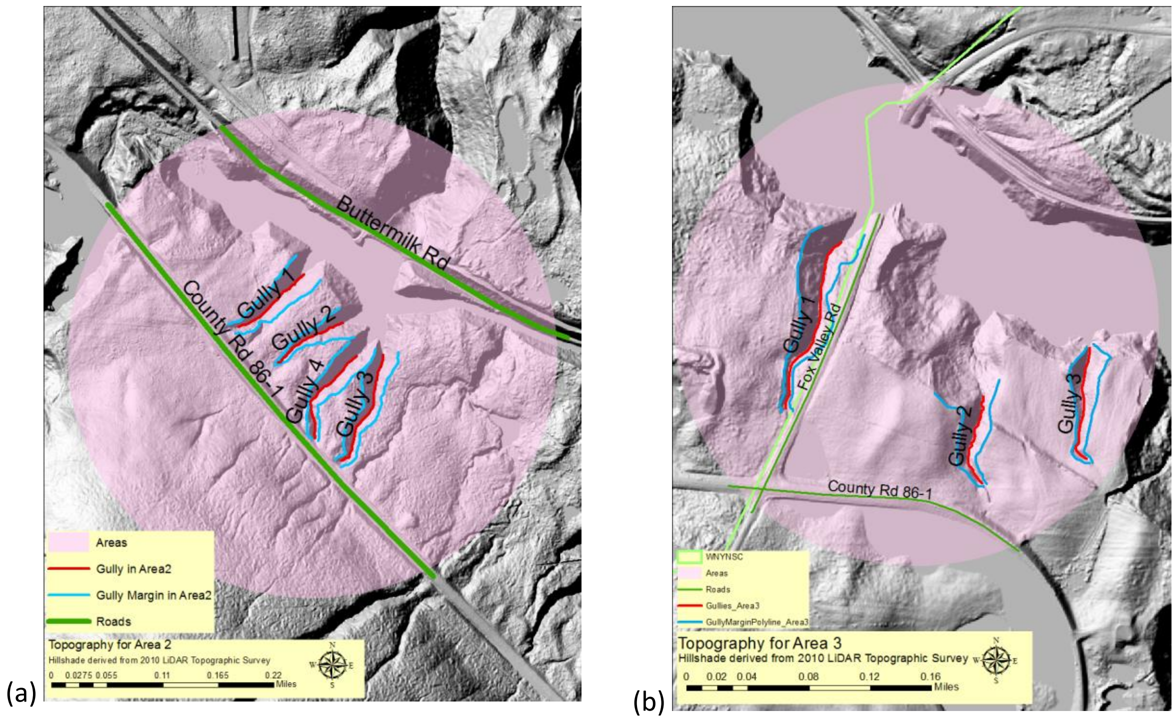


Figure 6. *Hillshade maps of surface topography of the WNYNSC and adjacent areas using the 2010 LiDAR survey, showing the location of potential analogue gullies in (a) Area 2, (b) Area 3, (c) Area 4, (d) Area 5, and (e) Area 6. Refer to Figure 5 for additional information..*

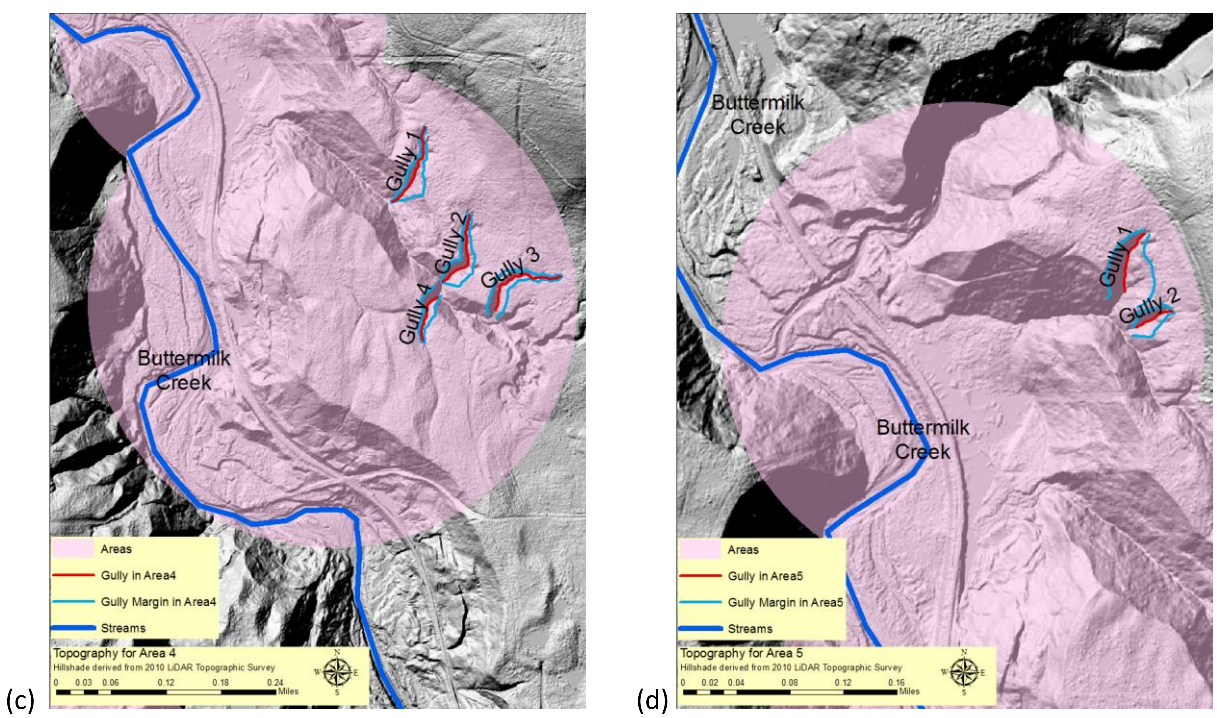


Figure 6. Continued.

(e)

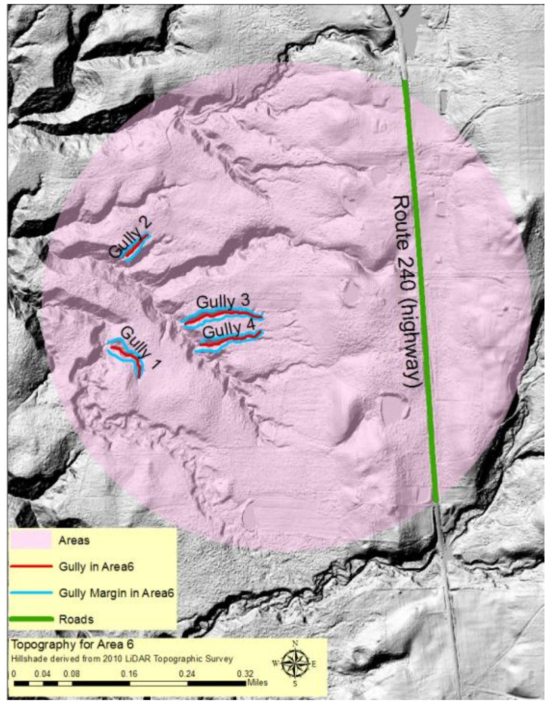


Figure 6. Continued.

Area 5 is selected to illustrate the characteristics of the off-site gullies. Two gullies in Area 5 have been identified, and Gully 2 is shown in Figure 7. This gully displays the two-stage morphology like those at the WVDP. Gully width and depth increase with distance until a point on the landscape where gully width and depth decrease markedly, which defines the transition from the inner gully to the outer gully. The total gully is 78.4 m long and it has a longitudinal slope of 0.647 m/m, a sinuosity of 1.07, and an orientation of 199°. This gully occurs on a part of the landscape mantled by the Lavery Till (Wtc) and Holocene Landslides and Slumps (Htl), as per LaFleur (1979).

The inner gully of Gully 2 in Area 5 has an upstream width of about 13.7 m and an upstream depth of about 2.3 m, and these values increase to about 59.8 m and 37.8 m, respectively, at the mouth of the inner gully. The slope of the inner gully is 0.654 m/m, which is similar to the total gully. The rates of change of inner gully width and depth with distance using logarithmic axes are 0.545 and 0.629, respectively. As the gully increases in size in the downstream direction, its depth increases at a greater rate as compared with its width. Gully cross-sections were selected near the inner gully head (noted as upstream in Figure 7d), near the inner gully mouth (noted as downstream in Figure 7d), and near the inner gully mid-point (noted as midstream in Figure 7d), which illustrated a V-shaped profile.

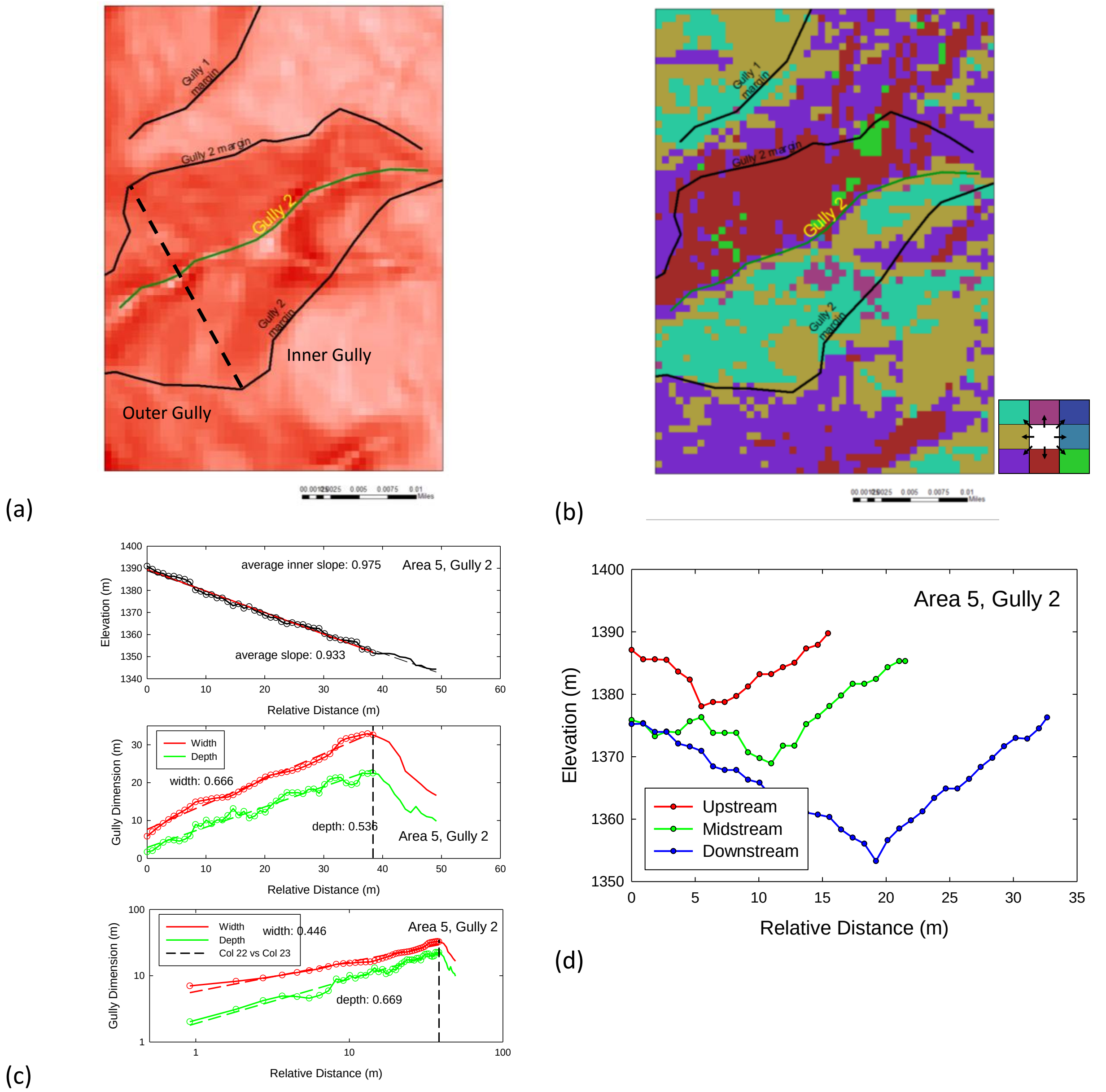


Figure 7. *Summary plots for Gully 2 in Area 5 showing (a) slope value map, (b) flow direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).*

Within each of these off-site areas, two to four gullies were identified using the same data and methodologies employed for the gullies at the WVDP. Figure 6 shows the locations of the gullies in each area investigated, and Tables 2 through 6 summarize all morphologic parameters defined. All maps and plots in support of these tabulated results are provided in Appendix 2.

Table 2: *Summary of morphologic parameters determined for gullies in Area 2 and their summary statistics (average, standard deviation, and median).*

Gully	1	2	3	4	Ave.	St. Dev.	Median
Parameter				***Total Gully***			
Total length (m)	141.2	126.9	191.8	165.9	156.5	28.6	153.6
Drainage area (m^2)	1305	1364	1149	1212	1257	95	1258
Average slope (m/m)	0.333	0.437	0.328	0.360	0.360	0.050	0.347
Average slope (deg)	18.4	23.6	18.2	19.8	20.0	2.5	19.1
Sinuosity	1.05	1.06	1.05	1.12	1.07	0.03	1.06
Orientation (deg)	231	239	202	207	220	18	219
Concavity	-0.18	0.08	0.002	0.13	0.01	0.14	0.04
Surficial material		Wfg, Wtc					
				Inner Gully			
Length (m)	141.2	126.9	191.8	165.9	156.45	28.55	153.55
Slope (m/m)	0.333	0.437	0.328	0.360	0.36	0.05	0.3465
Slope (deg)	18.4	23.6	18.2	19.8	20.00	2.51	19.1083 2
Width at head (m)	23.8	6.6	22.8	20.9	18.53	8.04	21.85
Mid-width (m)	38.6	24.3	27.6	31.6	30.53	6.16	29.6
Width at mouth (m)	57.1	50.0	40.1	47.9	48.78	7.00	48.95
Depth at head (m)	16.4	3.1	14.5	10.3	11.08	5.90	12.4
Mid-depth (m)	32.4	20.6	21.4	26.1	25.13	5.42	23.75
Depth at mouth (m)	40.1	39.6	26.1	34.6	35.10	6.49	37.1
Width exponent (arithmetic)	0.251	0.318	0.112	0.217	0.22	0.09	0.234
Depth exponent (arithmetic)	0.188	0.279	0.087	0.205	0.19	0.08	0.1965
Width exponent (logarithmic)	0.361	0.560	0.234	0.407	0.39	0.13	0.384
Depth exponent (logarithmic)	0.350	0.715	0.238	0.593	0.47	0.22	0.4715
Inner length/total length	1.00	1.00	1.00	1.00	1.00	0.00	1
Inner slope/total slope	1.00	1.00	1.00	1.00	1.00	0.00	1

Wfg – Defiance fluvial gravel; Wtc – Lavery Till

Table 3: *Summary of morphologic parameters determined for gullies in Area 3 and their summary statistics (average, standard deviation, and median).*

Gully	1	2	3	Ave.	St. Dev.	Median
Parameter				***Total Gully***		
Total length (m)	195.0	104.0	125.6	141.5	47.6	125.6
Drainage area (m^2)	2399	2037	915	1784	773	2037
Average slope (m/m)	0.295	0.214	0.278	0.260	0.04	0.278
Average slope (deg)	16.4	12.1	15.5	14.7	2.3	15.5
Sinuosity	1.06	1.15	1.07	1.09	0.05	1.07
Orientation (deg)	198	180	181	186	10	181
Concavity	0.03	-0.07	-0.03	-0.02	0.05	-0.03
Surficial material		Wfg, Wtc				
				Inner Gully		
Length (m)	195.0	86.6	103.7	128.4	58.3	103.7
Slope (m/m)	0.295	0.212	0.244	0.250	0.040	0.244
Slope (deg)	16.4	12.0	13.7	14.0	2.3	13.7
Width at head (m)	14.4	12.0	14.8	13.7	1.5	14.4
Mid-width (m)	32.8	27.4	15.5	25.2	8.9	27.4
Width at mouth (m)	54.7	28.0	35.4	39.4	13.8	35.4
Depth at head (m)	4.1	2.0	1.9	2.7	1.2	2.0
Mid-depth (m)	18.2	12.6	6.0	12.3	6.1	12.6
Depth at mouth (m)	23.2	10.7	22.0	18.6	6.9	22.0
Width exponent (arithmetic)	0.252	0.221	0.319	0.260	0.050	0.252
Depth exponent (arithmetic)	0.110	0.131	0.202	0.150	0.050	0.131
Width exponent (logarithmic)	0.868	0.340	0.888	0.700	0.310	0.868
Depth exponent (logarithmic)	0.845	0.551	1.241	0.880	0.350	0.845
Inner length/total length	1.00	0.83	0.83	0.89	0.10	0.83
Inner slope/total slope	1.00	0.99	0.88	0.96	0.07	0.99

Wfg – Defiance fluvial gravel; Wtc – Lavery Till

***Table 4**: Summary of morphologic parameters determined for gullies in Area 4 and their summary statistics (average, standard deviation, and median).*

Gully	1	2	3	4	Ave.	St. Dev.	Median
Parameter				***Total Gully***			
Total length (m)	161.3	148.0	162.2	89.3	140.2	34.6	154.7
Drainage area (m^2)	2621	5692	2664	3808	3696	1440	3236
Average slope (m/m)	0.451	0.270	0.232	0.331	0.320	0.100	0.300
Average slope (deg)	24.3	15.1	13.1	18.3	17.7	4.9	16.7
Sinuosity	1.14	1.16	1.25	1.10	1.16	0.06	1.15
Orientation (deg)	204	202	242	198	211	20	203
Concavity	0.56	-0.50	-1.31	0.18	-0.27	0.82	-0.16
Surficial material		Wtc, Htl					
				Inner Gully			
Length (m)	104.3	119.4	145.9	74.7	111.1	29.7	111.9
Slope (m/m)	0.300	0.228	0.239	0.267	0.260	0.030	0.253
Slope (deg)	16.7	12.8	13.4	14.9	14.5	1.7	14.2
Width at head (m)	5.0	8.8	5.1	6.5	6.4	1.8	5.8
Mid-width (m)	11.5	20.7	17.4	15.9	16.4	3.8	16.7
Width at mouth (m)	34.8	41.8	41.7	26.5	36.2	7.3	38.3
Depth at head (m)	2.5	3.6	3.6	1.9	2.9	0.8	3.1
Mid-depth (m)	9.3	15.4	9.8	11.4	11.5	2.8	10.6
Depth at mouth (m)	27.5	24.8	19.1	19.3	22.7	4.2	22.1
Width exponent (arithmetic)	0.269	0.311	0.278	0.290	0.290	0.020	0.284
Depth exponent (arithmetic)	0.259	0.161	0.121	0.260	0.200	0.070	0.210
Width exponent (logarithmic)	0.794	0.606	0.817	0.537	0.690	0.140	0.700
Depth exponent (logarithmic)	0.890	0.569	0.833	0.954	0.810	0.170	0.862
Inner length/total length	0.65	0.81	0.90	0.84	0.80	0.11	0.82
Inner slope/total slope	0.67	0.84	1.03	0.81	0.84	0.15	0.83

Wtc – Lavery Till; Htl – Holocene landslides and slumps

Table 5: *Summary of morphometric parameters determined for gullies in Area 5 and their summary statistics (average, standard deviation, and median).*

Gully	1	2	Ave.	St. Dev.	Median
Parameter			***Total Gully***		
Total length (m)	78.4	49.1	63.8	20.7	63.8
Drainage area (m^2)	1266	1390	1328	88	1328
Average slope (m/m)	0.647	0.933	0.790	0.200	0.790
Average slope (deg)	32.9	43.0	38.0	7.2	38.0
Sinuosity	1.07	1.04	1.06	0.02	1.06
Orientation (deg)	199	246	223	33	223
Concavity	0.56	-0.76	-0.10	0.93	-0.10
Surficial material	Wtc, Htl				
			Inner Gully		
Length (m)	67.5	38.4	53.0	20.6	53.0
Slope (m/m)	0.654	0.975	0.810	0.230	0.815
Slope (deg)	33.2	44.3	38.7	7.8	38.7
Width at head (m)	13.7	5.8	9.8	5.6	9.8
Mid-width (m)	38.6	18.3	28.5	14.5	28.5
Width at mouth (m)	59.8	32.7	46.3	19.2	46.3
Depth at head (m)	2.3	1.7	2.0	0.4	2.0
Mid-depth (m)	22.8	12.4	17.6	7.4	17.6
Depth at mouth (m)	37.8	22.4	30.1	10.9	30.1
Width exponent (arithmetic)	0.776	0.666	0.720	0.080	0.721
Depth exponent (arithmetic)	0.518	0.536	0.530	0.010	0.527
Width exponent (logarithmic)	0.545	0.446	0.500	0.070	0.500
Depth exponent (logarithmic)	0.629	0.669	0.650	0.030	0.649
Inner length/total length	0.86	0.78	0.82	0.06	0.82
Inner slope/total slope	1.01	1.05	1.03	0.02	1.03

Wtc – Lavery Till; Htl – Holocene landslides and slumps

Table 6: *Summary of morphologic parameters determined for gullies in Area 6 and their summary statistics (average, standard deviation, and median).*

Gully	1	2	3	4	Ave.	St. Dev.	Median
Parameter				***Total Gully***			
Total length (m)	146	67.6	181.1	146.0	135.2	48.0	146.0
Drainage area (m²)	2287	2166	2377	2072	2226	134	2227
Average slope (m/m)	0.267	0.316	0.260	0.267	0.280	0.030	0.267
Average slope (deg)	14.9	17.5	14.6	14.9	15.5	1.8	14.9
Sinuosity	1.21	1.01	1.06	1.06	1.09	0.09	1.06
Orientation (deg)	318	224	265	257	266	39	261
Concavity	-0.65	1.25	-0.13	-0.14	0.08	0.82	-0.14
Surficial material		Wtc, Hfp, Htl					
				Inner Gully			
Length (m)	118.7	55.7	166.0	122.4	115.7	45.4	120.6
Slope (m/m)	0.246	0.284	0.260	0.250	0.260	0.020	0.255
Slope (deg)	13.8	15.9	14.6	14.0	14.6	0.9	14.3
Width at head (m)	5.8	6.7	8.2	8.2	7.2	1.2	7.5
Mid-width (m)	18.3	19.1	17.3	13.9	17.2	2.3	17.8
Width at mouth (m)	38.9	23.1	32.0	29.7	30.9	6.5	30.9
Depth at head (m)	1.5	6.0	2.4	1.7	2.9	2.1	2.1
Mid-depth (m)	9.6	10.7	11.8	11.8	11.0	1.1	11.3
Depth at mouth (m)	10.9	12.9	20.6	19.1	15.9	4.7	16.0
Width exponent (arithmetic)	0.150	0.312	0.115	0.158	0.180	0.090	0.154
Depth exponent (arithmetic)	0.120	0.190	0.117	0.123	0.140	0.040	0.122
Width exponent (logarithmic)	0.338	0.582	0.357	0.353	0.410	0.120	0.355
Depth exponent (logarithmic)	0.532	0.549	0.634	0.839	0.640	0.140	0.592
Inner length/total length	0.81	0.82	0.92	0.84	0.85	0.05	0.83
Inner slope/total slope	0.92	0.90	1.00	0.94	0.94	0.04	0.93

Wtc – Lavery Till; Hfp – Holocene floodplain; Htl – Holocene landslides and slumps

3.5. Qualitative Morphologic Comparisons of Gullies on and Near the WVDP and the Analogue Gullies Within and Adjacent to the WNYNSC

A simple qualitative method was employed to compare the morphologic signatures of the off-site with on-site gullies. The primary attributes of gully morphologies were tabulated, and the mean and standard deviation of each were noted, if applicable (derived from Table 1). These mean attributes for the on-site gullies were compared with each gully off-site, and a simple binary test was employed as follows. If the gully attribute was the same, or nearly so, in both localities, then a "Yes" response was recorded. For those gully attributes having a numerical value, a positive comparison was achieved if the values were within one-half of the standard deviation of the mean. For example, the mean and standard deviation of gully sinuosity on-site was determined to be 1.08±0.07 (Table 1). A positive comparison to this gully attribute would be noted if an off-site gully had a sinuosity ranging from 1.045 to 1.115. If the sinuosity of the off-site gully was greater than or less than this value, then a "No" response was recorded. On the basis of this binary qualitative assessment, percentages of positive values for each attribute and for each gully were determined. All results are summarized in Table 7.

In general, the attribute comparisons show very good agreement between the on-site and off-site gullies. Those morphologic gully attributes displaying the highest degree of concurrence include surficial geology (all (100%) of the off-site gullies are underlain by the Lavery Till), inner gully width upstream (76%) and downstream (82%), two-stage morphology (71%), and thalweg sinuosity (71%). In contrast, virtually no agreement is observed in gully orientation (6%), as gullies on-site drain toward the north and gullies off-site drain toward the south. In addition, little agreement is noted in the length (18%) and longitudinal slope (18%) of the inner gully, as the gullies off-site tend to be longer and have shallower longitudinal slopes. Those gully attributes not discussed here display reasonable agreement between the localities (ca. 50%).

3.6. Identification of Potential Analogue Gullies

The data summarized in Table 7 can be used to identify potential analogue gullies worthy of additional investigation, which is the primary goal of this analysis. A comparative score for each gully can be derived simply by determining the percentage of positive comparisons to on-site gullies. A gully score of 100% means that all morphologic attributes for that gully agree with those attributes on-site.

Using these results, many of the gullies off-site are similar to the gullies on-site using the morphological and geological attributes examined. Of the 17 gullies investigated off-site, eight (8) gullies (or nearly half) have comparison percentage scores of 67% or higher (Table 7). Five (5) gullies, in particular, have very high comparison percentage scores (75%). These are Gullies 1 and 2 in Area 5, which are just east of the WVDP near Heinz Road (Figures 5 and 6d, and Table 5), and Gullies 2, 3, and 4 in Area 6, just north of the WVDP near Route 240 (Figures 5 and 6e, and Table 6). Given such strong morphologic similarity, it is recommended that these five (5) gullies be further investigated as potential analogue gullies for the WVDP. It is noted here that these comparison results could vary if other morphologic, hydrologic, and/or geologic criteria are used, and if other numerical thresholds or statistical tests are employed to assess gully similarity.

Further investigation of potential analogue gullies is required to determine if such sites are geomorphically-, hydrologically-, and geologically-similar to on-site gullies. These additional investigations could include the following activities.

Recommended investigations for selecting analogue gullies:

- General reconnaissance and visual inspection;

- Near surface examination and sample retrieval of environmental media samples for grain size and mineralogical analysis, pebble counts, etc., to verify the geological materials present and their regional stratigraphy;
- Mapping of geomorphic and geological features of importance; and
- Assessing adequate access to the site and its suitability for the installation of planned field-based monitoring equipment such as meteorological stations, in-gully measurement flumes, water and sediment samplers, surveying equipment, etc.

3.7. Use of Potential Analogue Gullies in the Erosion Assessment

This work on analogue gullies provides important baseline information that can be used to facilitate and inform erosion assessment at the WVDP. The geomorphic characteristics of all gullies examined herein using the 2010 LiDAR survey can now be repeated using the recent availability of a subsequent LiDAR survey conducted in 2015. This new dataset allows direct determination of the time- and space-variation of the gullies and can provide important information on the rates, styles, and characteristics of gully erosion and landscape evolution, conditioned by the resolution of these geospatial data. On-going efforts are quantifying these changes, and the results will be used to inform conceptual and numerical models of gully erosion at the WVDP and within the WNYNSC.

Table 7: *Qualitative results of comparing selected gully attributes in nearby areas (off-site) with the mean values reported at the WVDP (on-site) as summarized in Table 1. A positive comparison (a "Yes" answer) is noted when the gully value within an area is near the mean value for the WVDP (the mean ± one-half of the reported range).*

Parameter	**Area 2**				**Area 3**			**Area 4**				**Area 5**		**Area 6**				**Percentage of Positive Comparisons**
Gully	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**1**	**2**	**3**	**4**	**1**	**2**	**1**	**2**	**3**	**4**	
Two-stage gully morphology	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	71
Inner gully length (47±30 m)	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	Y	N	Y	18
Inner gully slope (0.69±0.51)	N	Y	N	N	N	N	N	Y	N	N	N	Y	N	N	N	N	N	18
Sinuosity (1.08±0.07)	Y	Y	Y	Y	Y	N	Y	N	N	N	Y	Y	Y	N	Y	Y	Y	71
Orientation (northerly)	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	6
Width at head (11±10 m)	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	76
Depth at head (4±4 m)	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	N	65
Width at mouth (36±21 m)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y	82
Depth at mouth (22±16 m)	N	N	Y	N	Y	N	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	65
Width exponent (log.; 0.54±0.35)	Y	Y	N	Y	N	N	N	N	Y	N	Y	Y	Y	N	Y	Y	Y	53
Depth exponent (log.; 0.70±0.30)	Y	Y	N	Y	Y	Y	N	N	Y	Y	N	Y	Y	N	Y	Y	Y	65
Surficial material	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100
Percentage of Positive Comparisons (%)	42	67	33	42	50	50	58	58	67	58	67	75	75	42	75	75	75	

Y, N – Yes, No

4. Conclusions

Enviro Compliance Solutions, Inc. and the West Valley Erosion Working Group recommended erosion assessment to be performed as part of the Phase 1 Studies at the West Valley Demonstration Project and Western New York Nuclear Service Center. These studies seek to improve forecasts of future erosion at this facility, which includes a focus on recent erosion and deposition processes. Gully erosion remains an important geomorphic process of concern for the current and future integrity of the site. Yet investigation of gully erosion processes within the WVDP and APAs of the WNYNSC presents many safety, regulatory, and logistical challenges that may not be resolved in a timely fashion. To address this issue, the use of analogue sites for gully erosion assessment is currently being explored. The objectives of the current study are to define the morphologic and geologic characteristics of gullies at the WVDP using readily available data, and to identify gullies off-site in areas near the WVDP and to define their morphologic and geologic characteristics using the same database and methodologies. On the basis of this analysis, potential analogue gullies may be identified for further study.

The primary database used in the analysis of gullies is the 2010 aerial LiDAR survey funded by NYSERDA and DOE. These digital data were manipulated in ArcGIS to process, analyze, and extract information for the gullies on the WVDP, WNYNSC, and areas outside of the WNYNSC. Various user-defined scripts were written to automate the process of extracting topographic information from the gullies. Several terrain attributes were identified to define the morphologic signatures of the gullies.

A total of 13 gullies were identified on the WVDP and near to the WVDP and within the WNYNSC using the LiDAR, and the following general characteristics were observed. Nearly all of the gullies exhibit a two-stage morphology, where the gully can be divided into inner and outer portions. The inner gully is incised into the relatively flat plateau region of the landscape, with its accurate head extending into this flatted surface, and gully width and depth increase in the downstream direction. At the location where the inner gully's width and depth tend toward their maximum values, termed the inner gully mouth, the gully emerges from its incised valley and traverses the plateau scarp toward the nearby stream. The lower portion of the gully is termed the outer gully. In general, the gullies display no concavity or convexity of significance, their average longitudinal slope is about 0.70±0.35 m/m, and they have a V-shaped profile in cross-section. Total inner gully lengths are about 47±30 m, and all of the gullies are found on landscapes mantled by the Lavery Till. The inner gully tends to be relatively small near its most upstream reaches, where width is about 11±10 m and depth is about 4±4 m. With increasing distance downstream, the inner gully width and depth increase, with depth increasing a faster rate than width.

Five areas were investigated near the WVDP for gully erosion features, and these areas lie within the Western New York Nuclear Service Center region but outside the Access Prohibited Areas. Using the same LiDAR data and terrain analysis methodologies, 17 gullies in these five (5) areas were identified and their morphologic signatures measured.

The morphologic signatures of the off-site gullies were compared with the on-site gullies using a simple qualitative assessment. In general, the attribute comparisons show very good agreement between the on-site and off-site gullies. Those morphologic gully attributes displaying the highest degree of concurrence include surficial geology, inner gully width, two-stage morphology, and sinuosity. Those attributes displaying less agreement include gully orientation, inner gully length, and longitudinal slope

Using these results, five (5) off-site gullies are deemed to be very similar morphologically and geologically to the gullies on-site. These features are just east of the WVDP near Heinz Road (Gullies 1 and 2 in Area 5), and just north of the WVDP near Route 240 (Gullies 2, 3, and 4 in Area 6). Given such strong morphologic similarity, it is recommended that these five (5) gullies can be considered analogue gullies. As such, these gullies could be used for a variety of purposes, including site visits and tours, further comparison of the gullies using remotely sensed data, and field-based monitoring programs of hydrology, sediment transport, and hillslope processes. It is suggested that any field-based monitoring program include general reconnaissance, an examination of the surface geological materials, mapping of geomorphic and geological features of importance, and assessing if such sites are suitable for the installation of monitoring equipment.

A newly acquired LiDAR survey in 2015 of this same region allows direct determination of the time- and space-variation of the gullies and can provide important information on the rates, styles, and characteristics of gully erosion and landscape evolution. On-going efforts are quantifying these changes, and the results will be used to inform conceptual and numerical models of gully erosion at the WVDP and within the WNYNSC.

5. References

LaFleur, R. G., 1979. Glacial Geology and Stratigraphy of Western New York Nuclear Service Center and

Vicinity, Cattaraugus and Erie Counties, New York, U.S. Geological Survey, Open File Report 79-989, Albany, New York.

West Valley Phase 1 Studies Erosion Working Group and Enviro Compliance Solutions, 2015, Phase 1 Erosion Study Plan, prepared for United States Department of Energy, and New York State Energy Research and Development Authority, June 19, 2015, 47 pp.

6. Acknowledgements

Lee Gordon, NYSERDA, provided the LIDAR data used here. Chengxi Zhu and Shengyu Zhang, University at Buffalo, conducted the GIS analysis.

Appendix 1. Maps and plots for all gullies on-site at the West Valley Demonstration Project.

Gully 1 (NP-1)

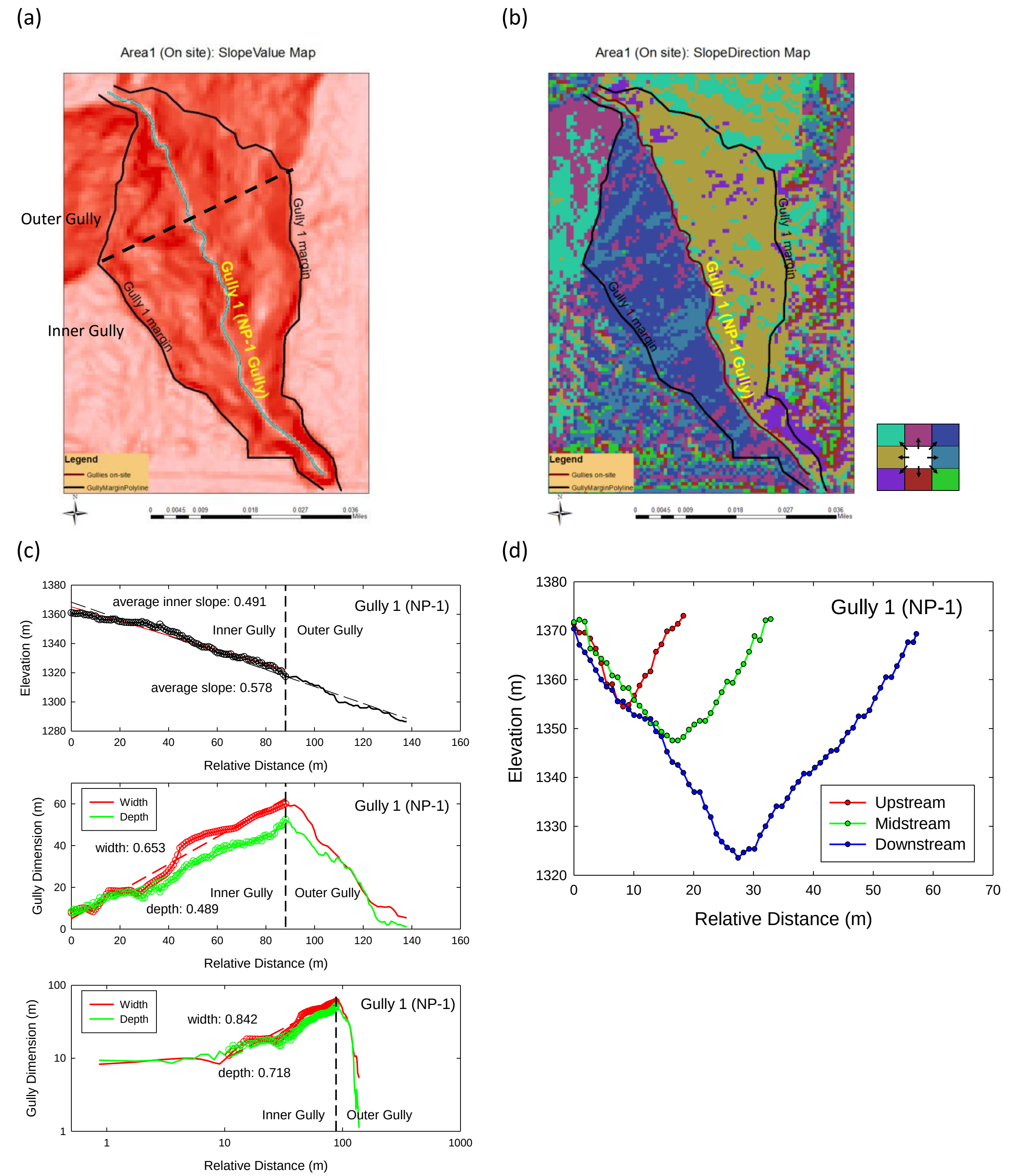


Figure A1-1. Summary plots for Gully 1 (NP-1) from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 2 (NP-3)

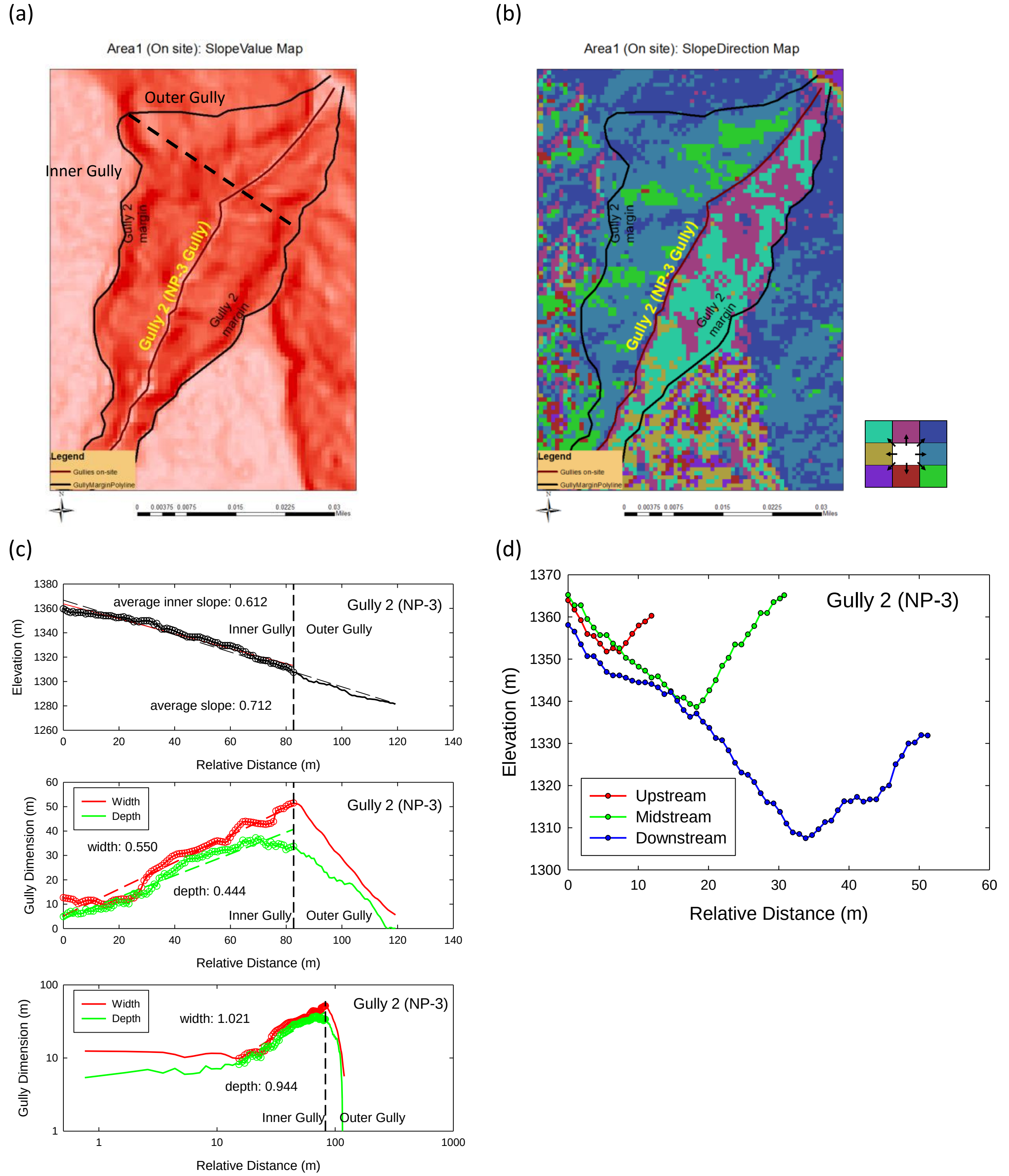


Figure A1-2. Summary plots for Gully 2 (NP-3) location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 3 (NP-2)

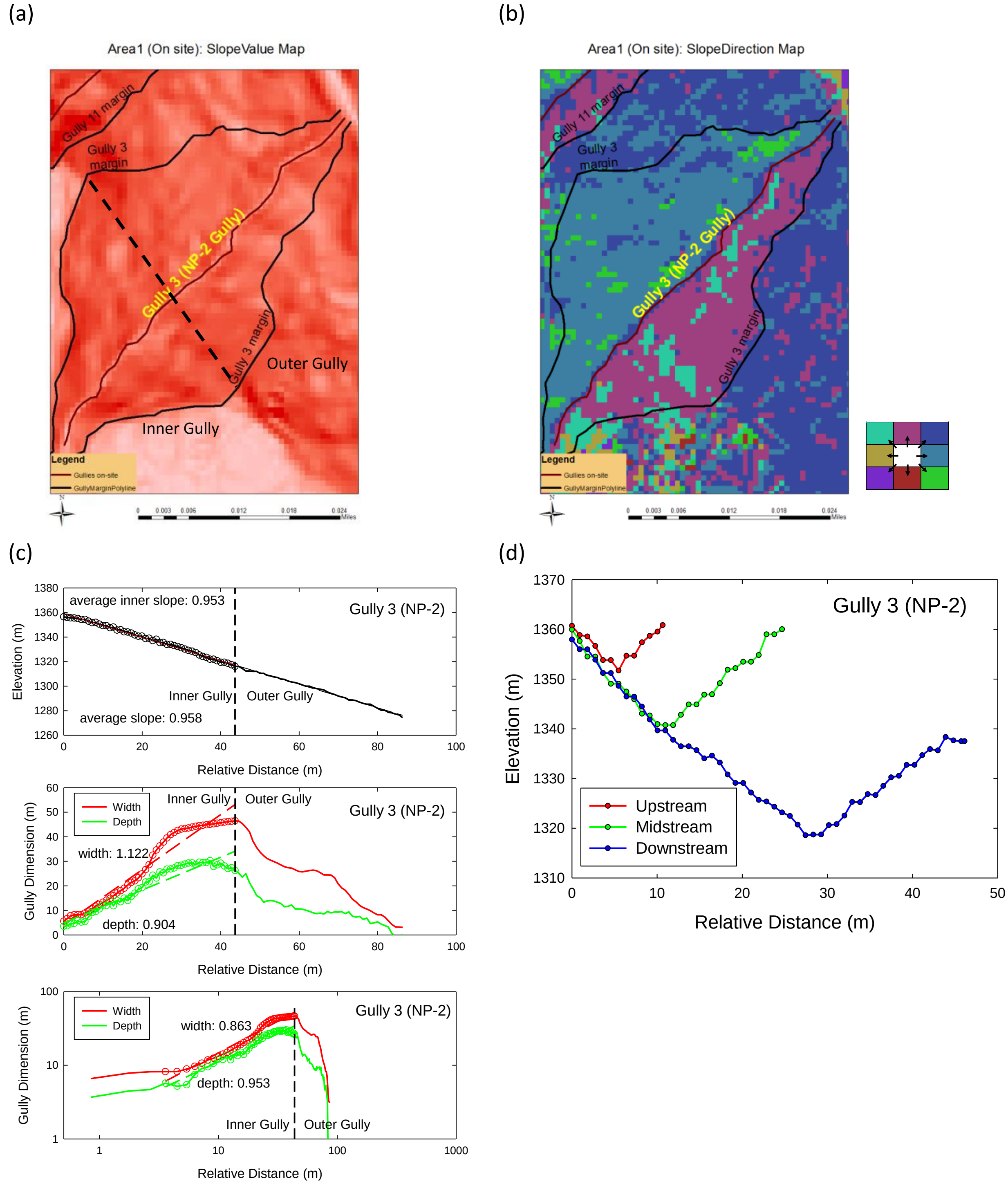


Figure A1-3. Summary plots for Gully 3 (NP-2) location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 4

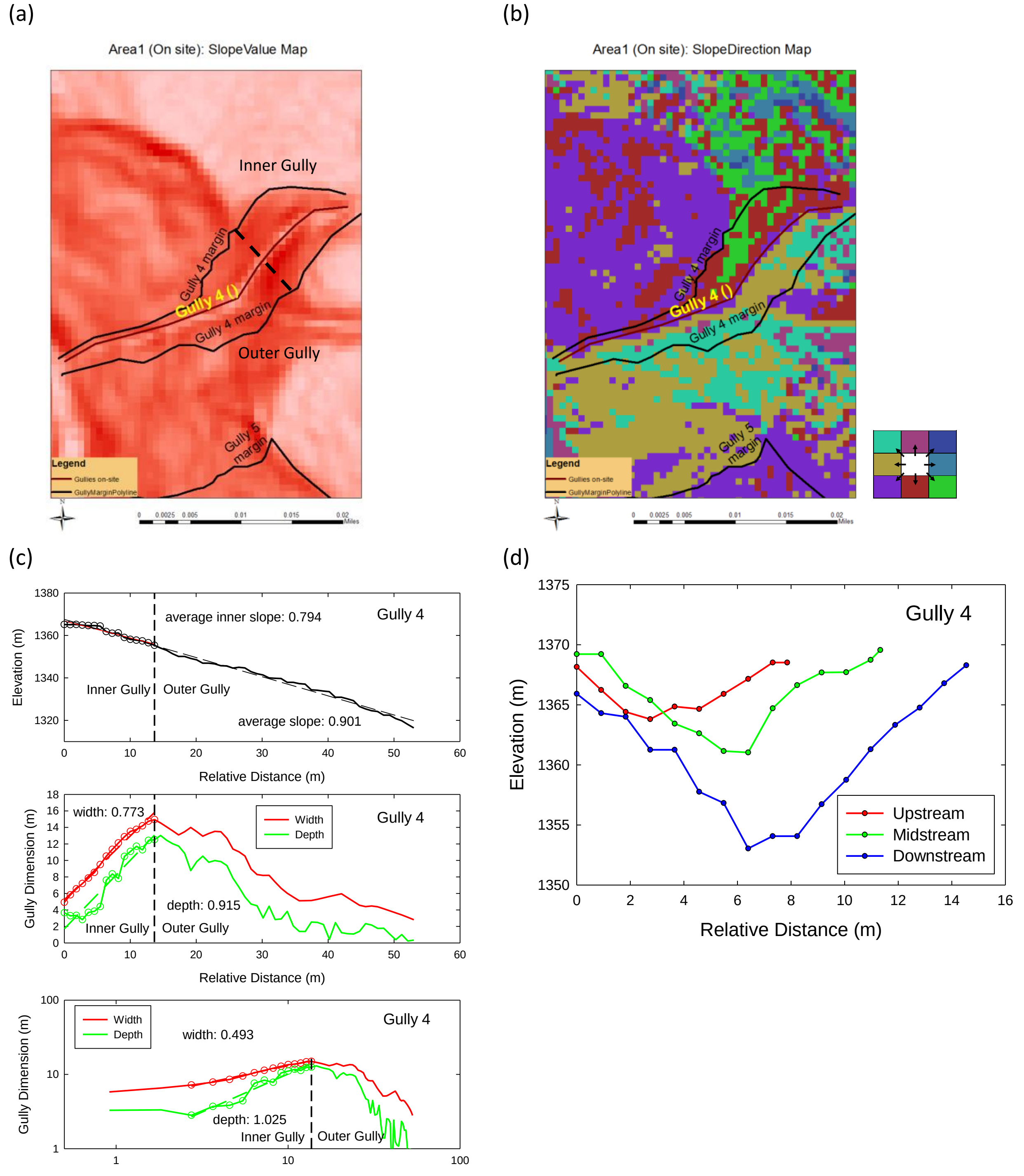


Figure A1-4. Summary plots for Gully 4 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 5

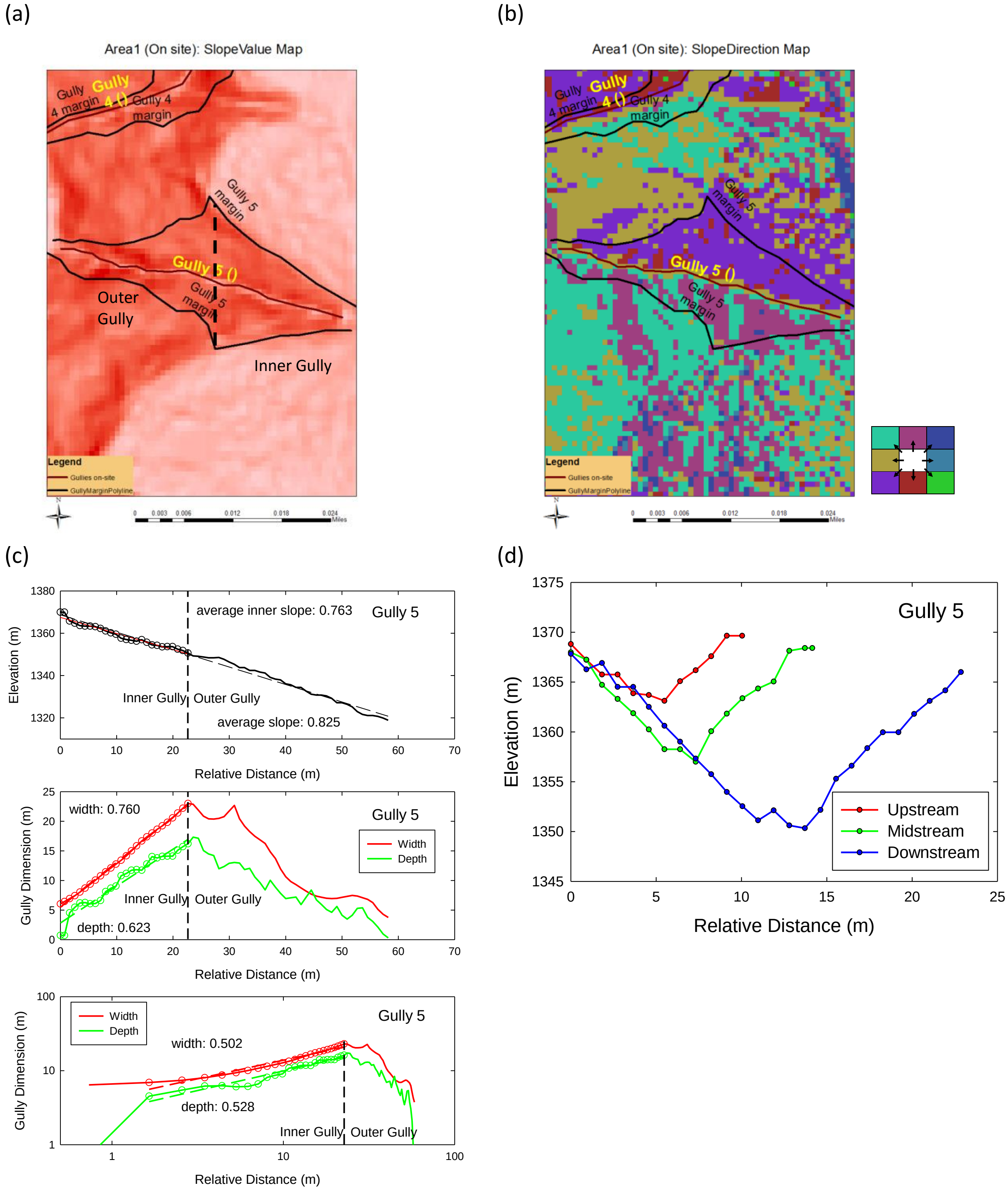


Figure A1-5. Summary plots for Gully 5 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 6

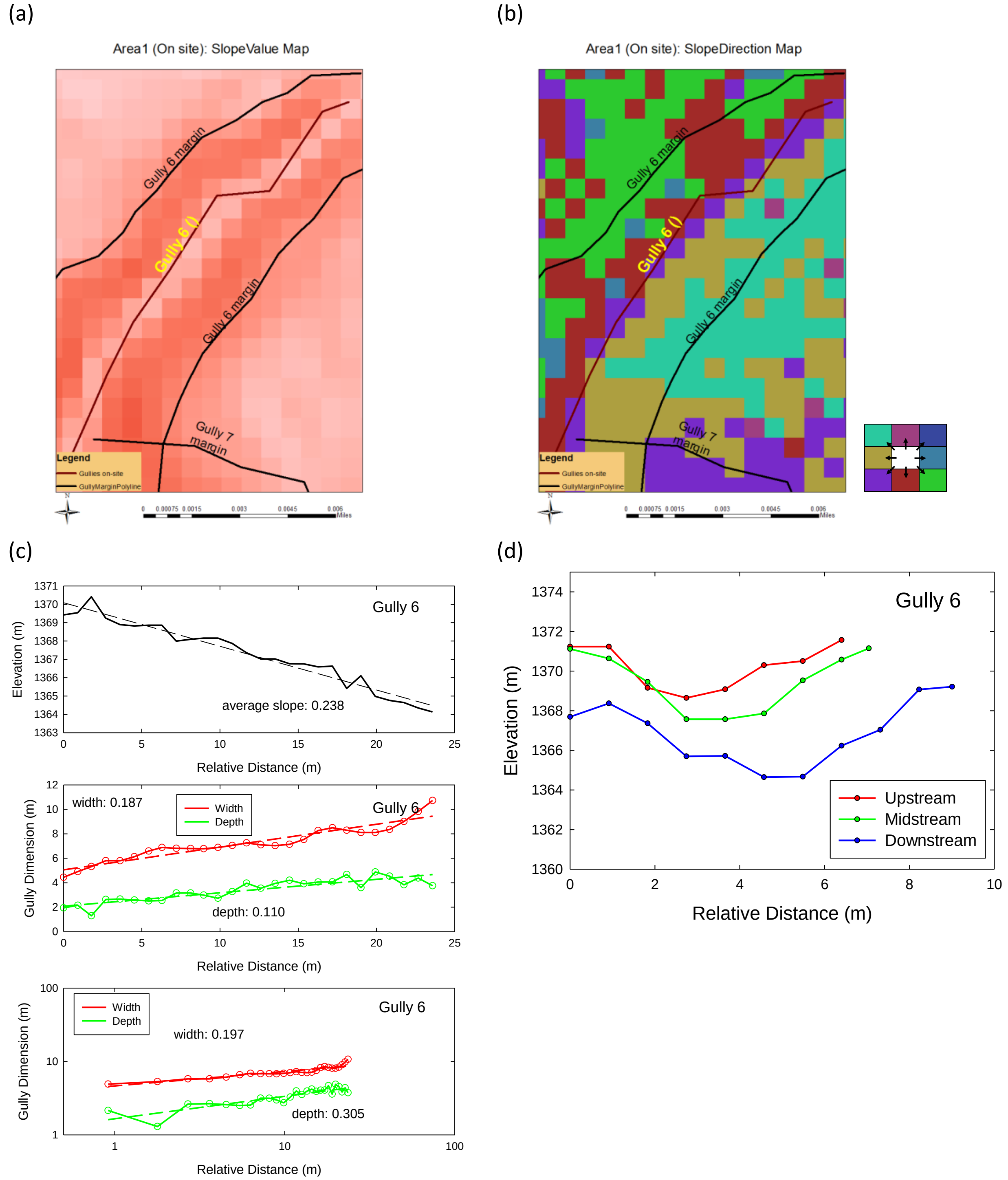


Figure A1-6. Summary plots for Gully 6 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 7

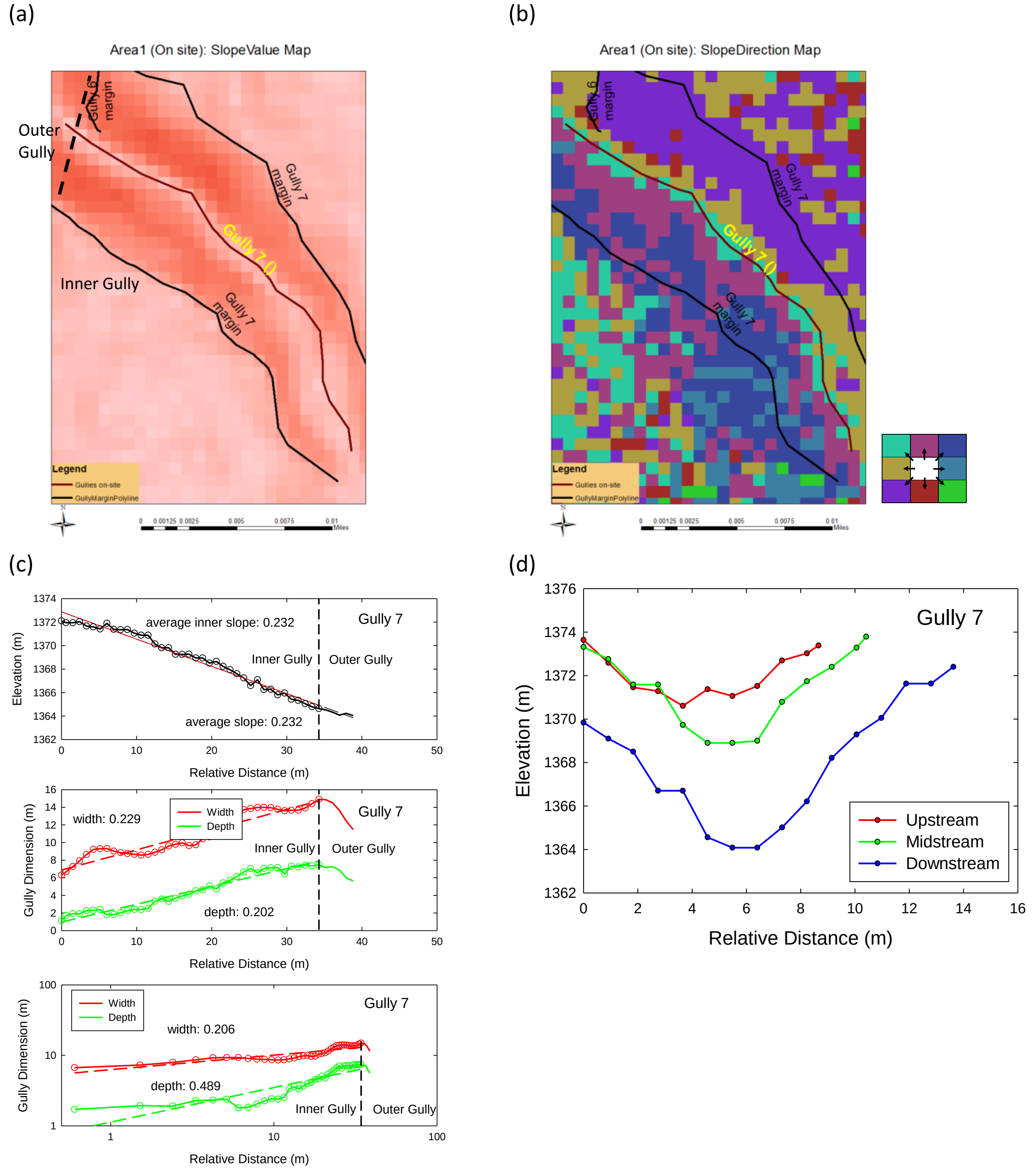


Figure A1-7. Summary plots for Gully 7 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 9 (EQ-1)

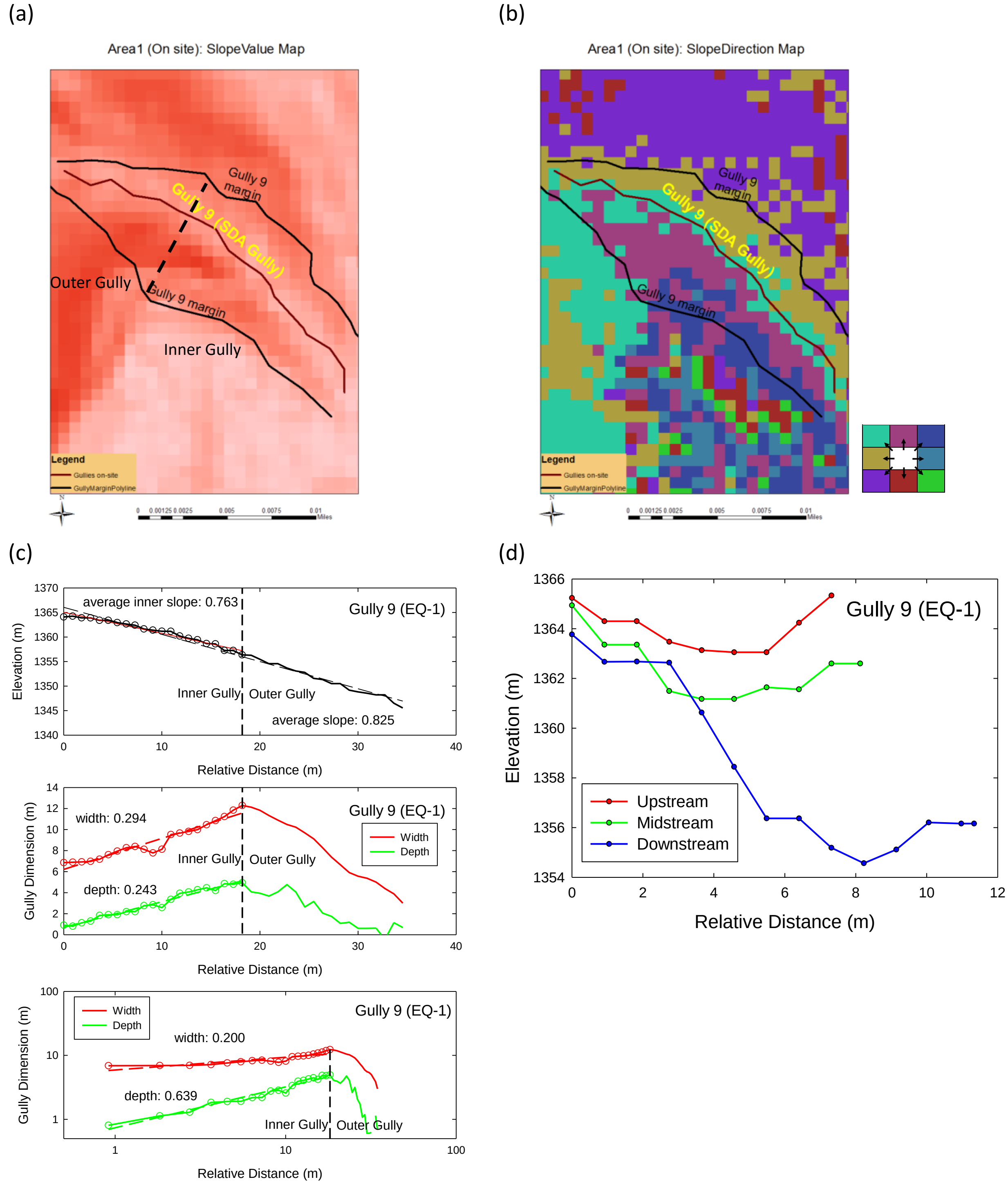


Figure A1-8. Summary plots for Gully 9 (EQ-1) location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 10

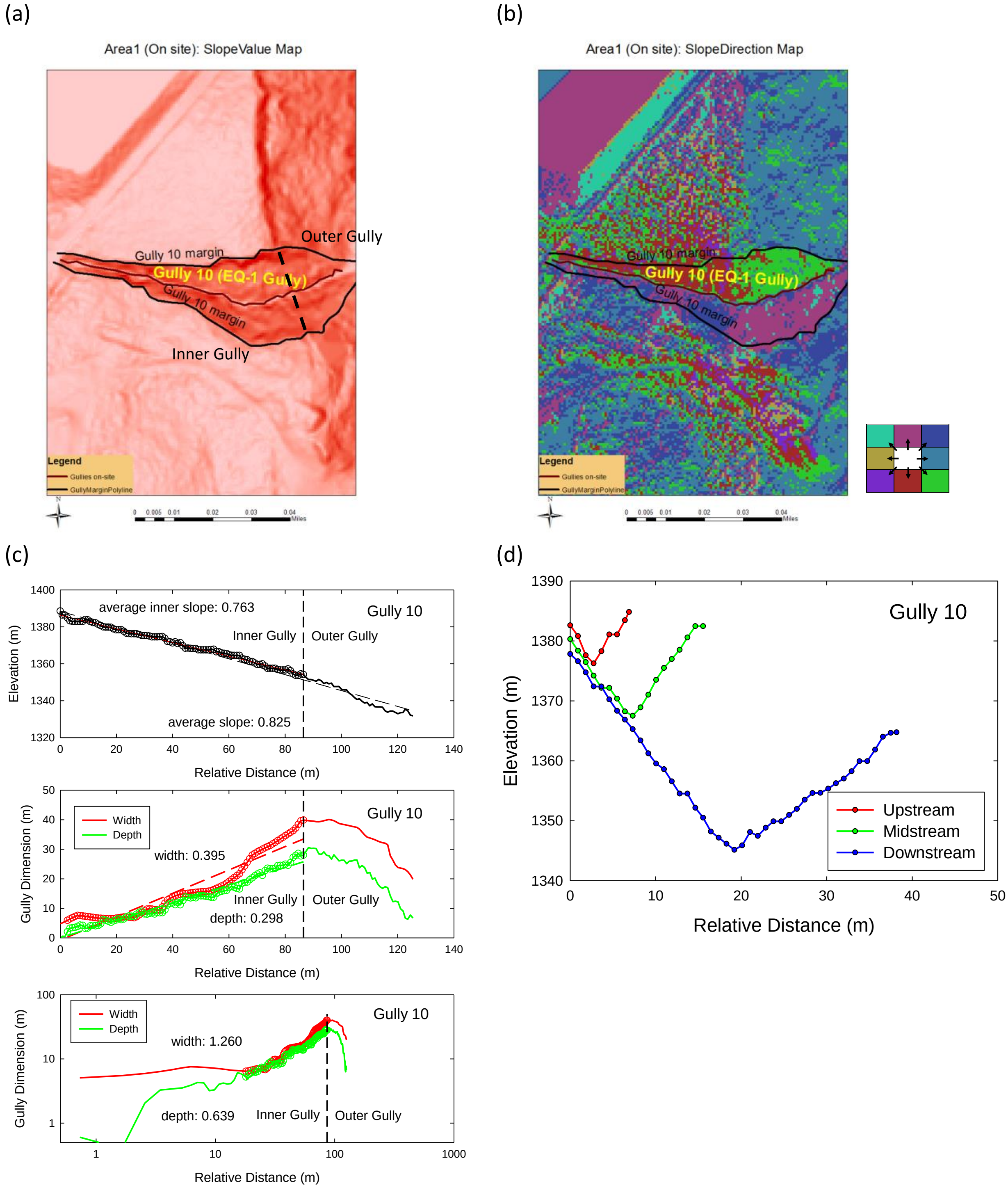


Figure A1-9. Summary plots for Gully 10 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 11

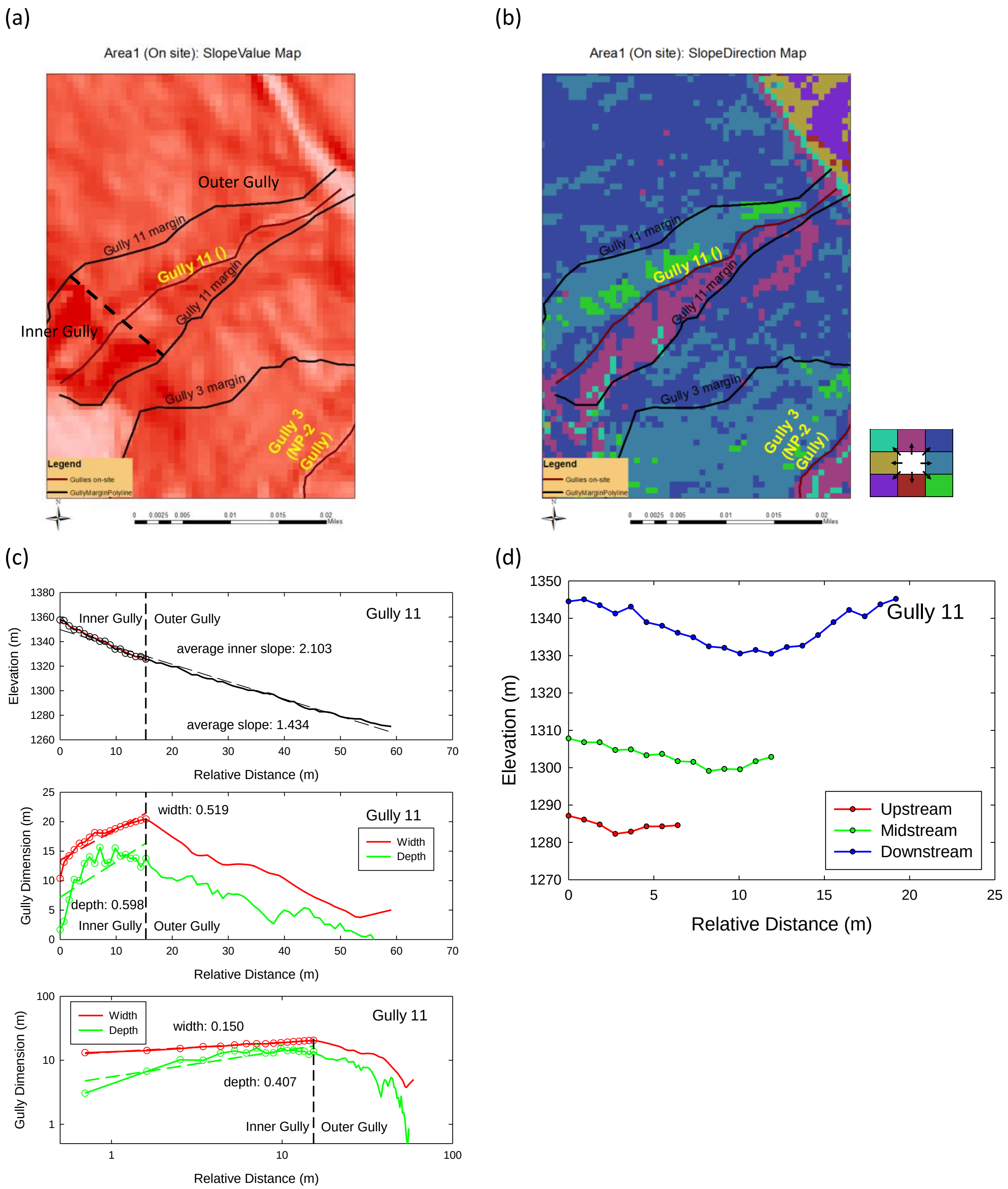


Figure A1-10. Summary plots for Gully 11 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 12

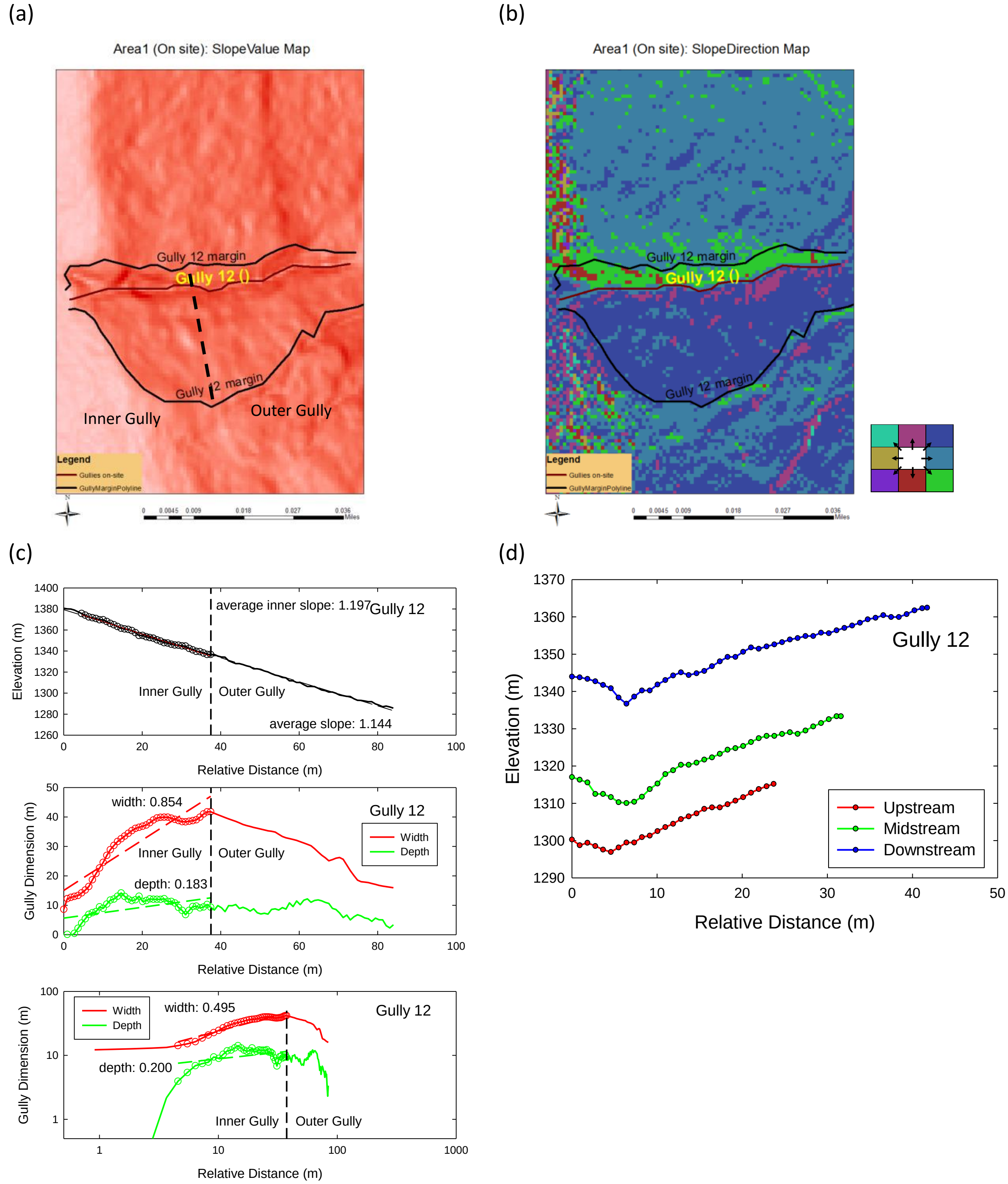


Figure A1-11. Summary plots for Gully 12 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 13

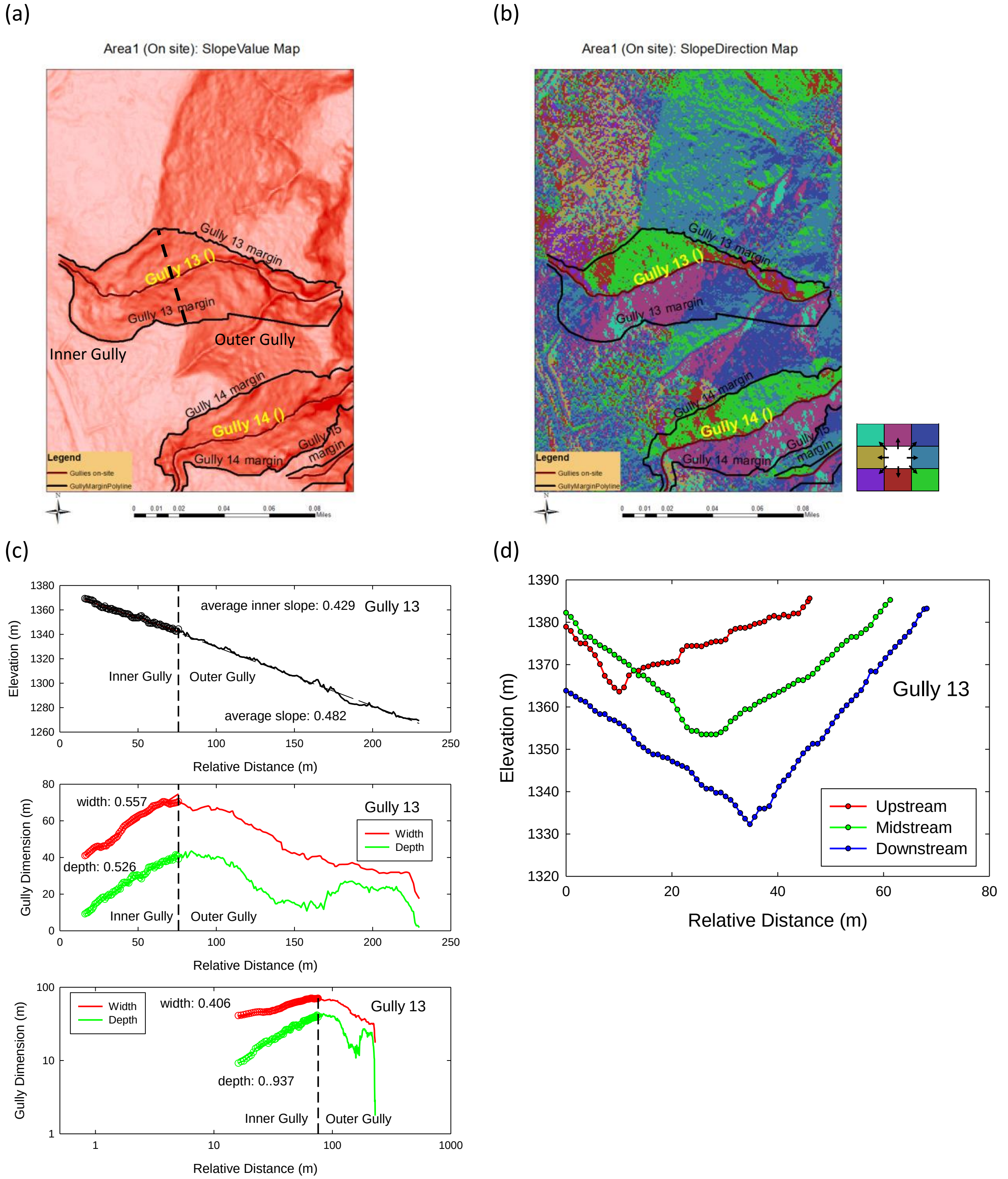
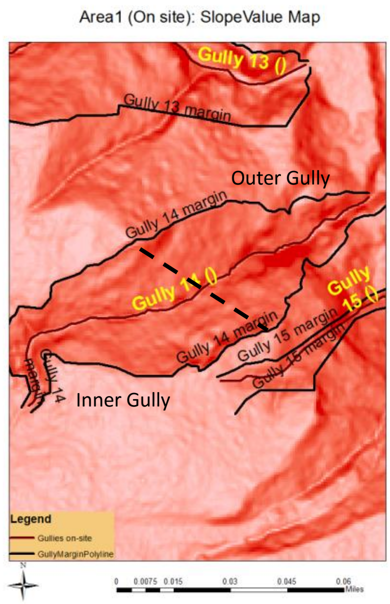


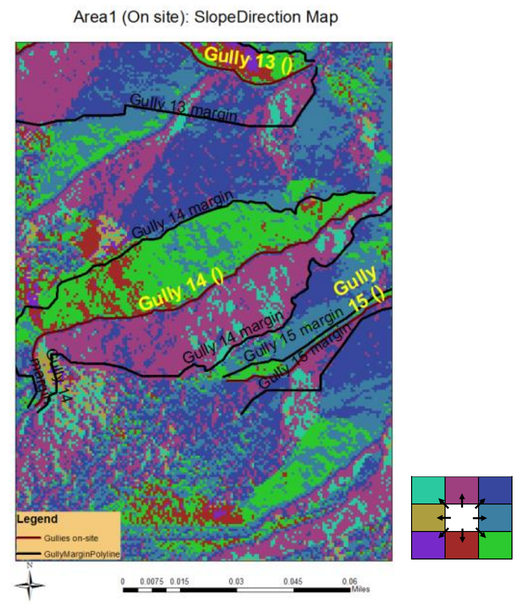
Figure A1-12. Summary plots for Gully 13 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 14

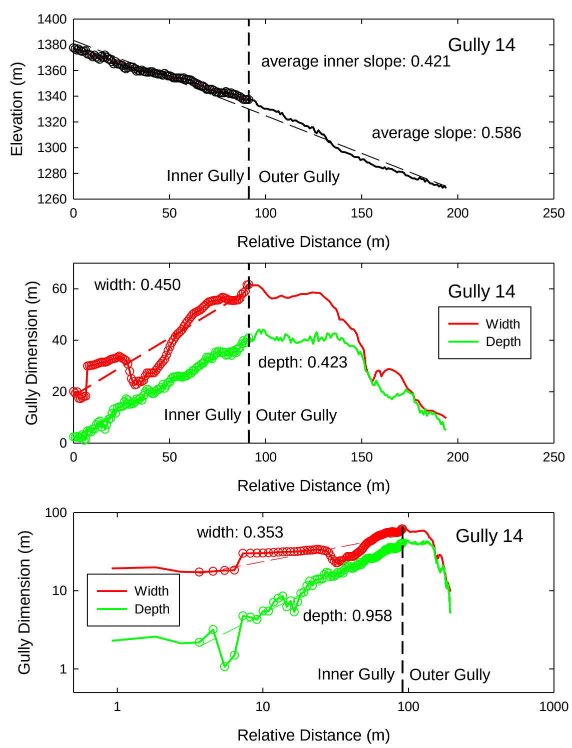
(a)



(b)



(c)



(d)

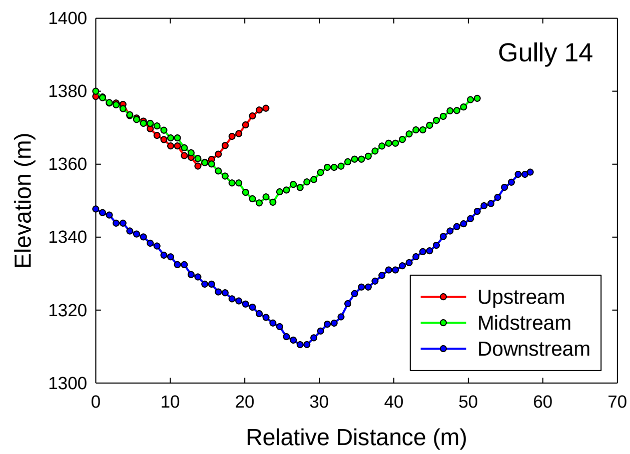


Figure A1-13. Summary plots for Gully 14 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 15

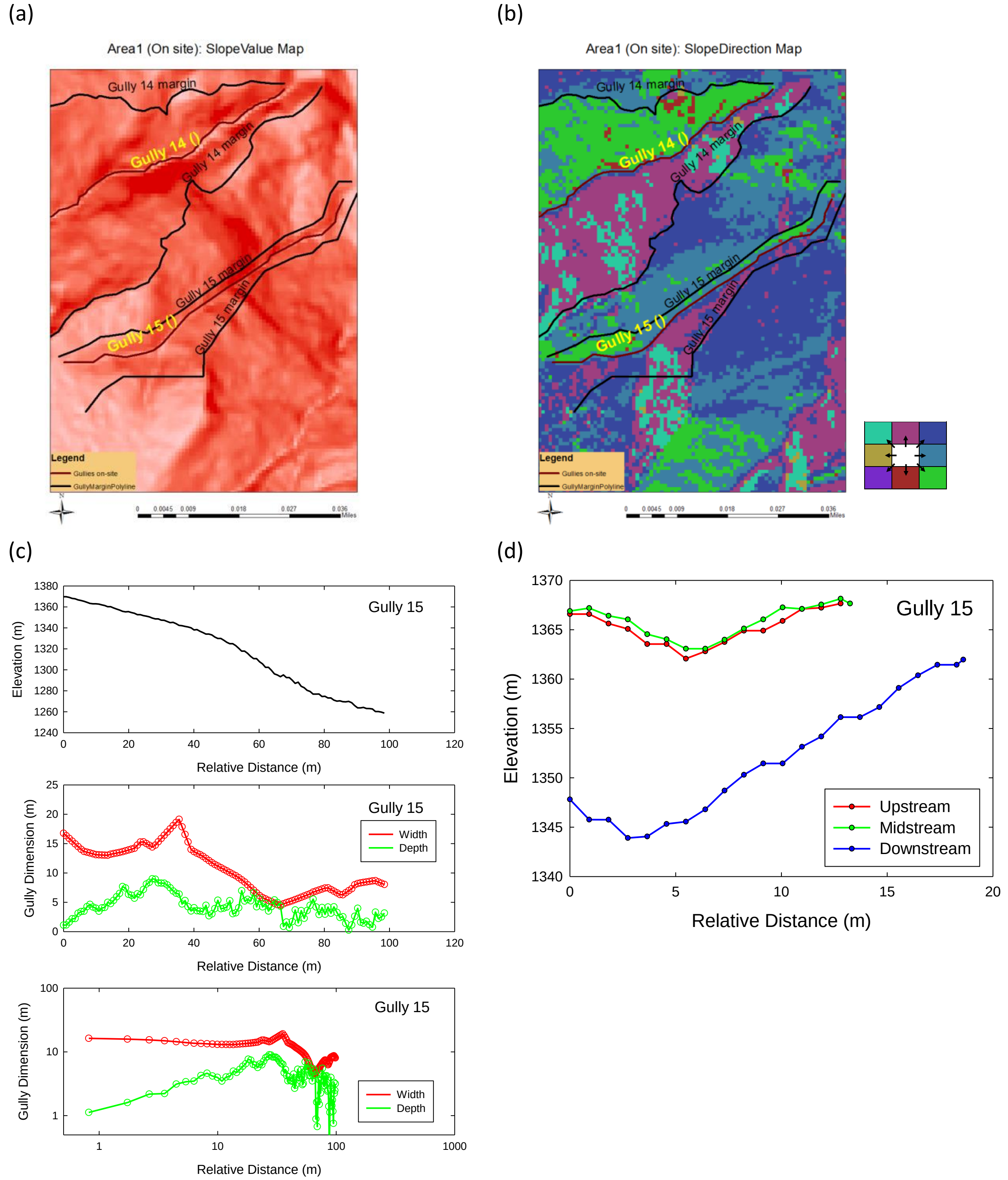


Figure A1-14. Summary plots for Gully 15 location from Figure 1 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance, and (d) selected cross-sections (looking downstream along the gully thalweg).

Appendix 2. Maps and plots for all off-site gullies.

Gully 1, Area 2

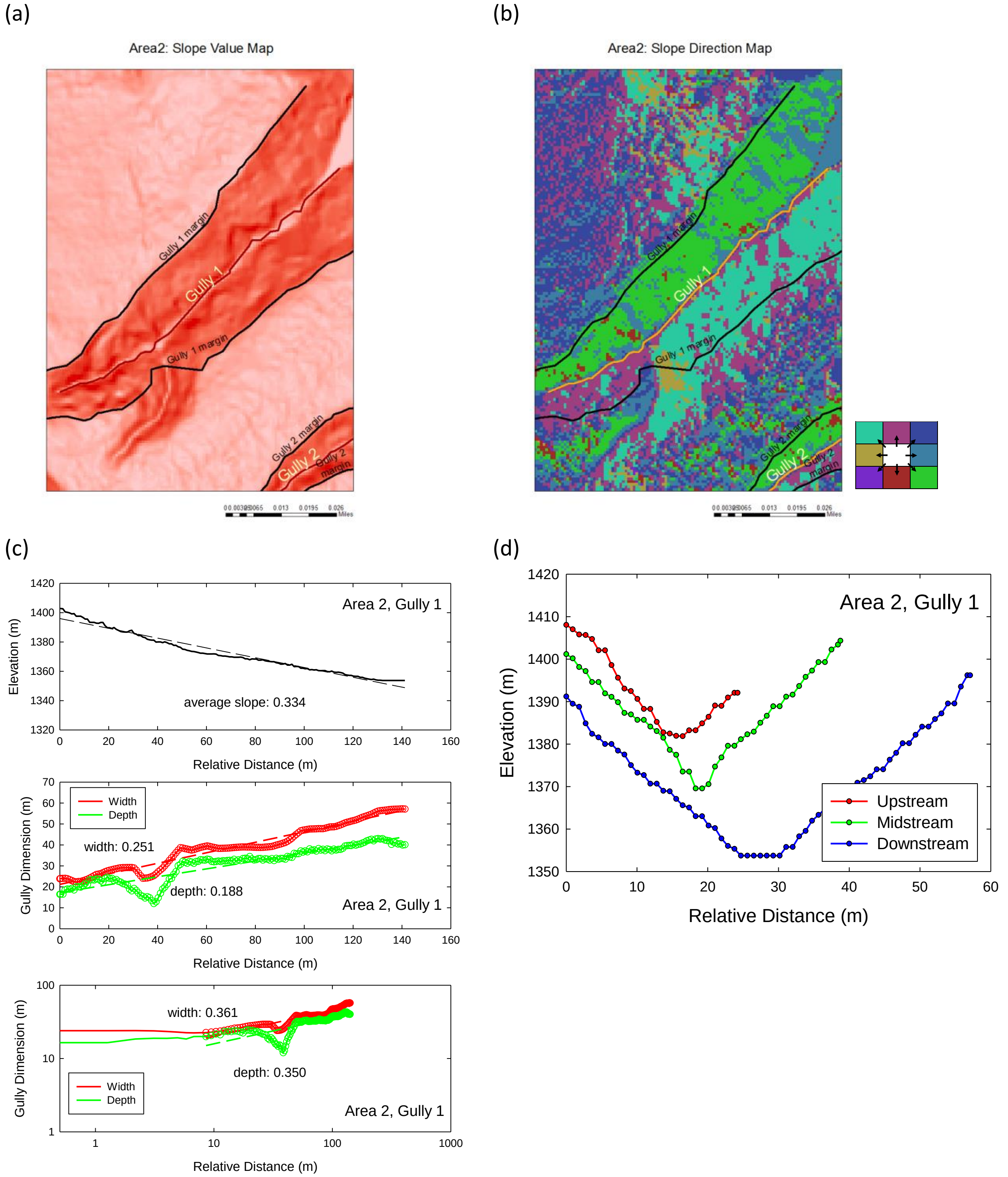


Figure A2-1. Summary plots for Gully 1 location in Area 2 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 2, Area 2

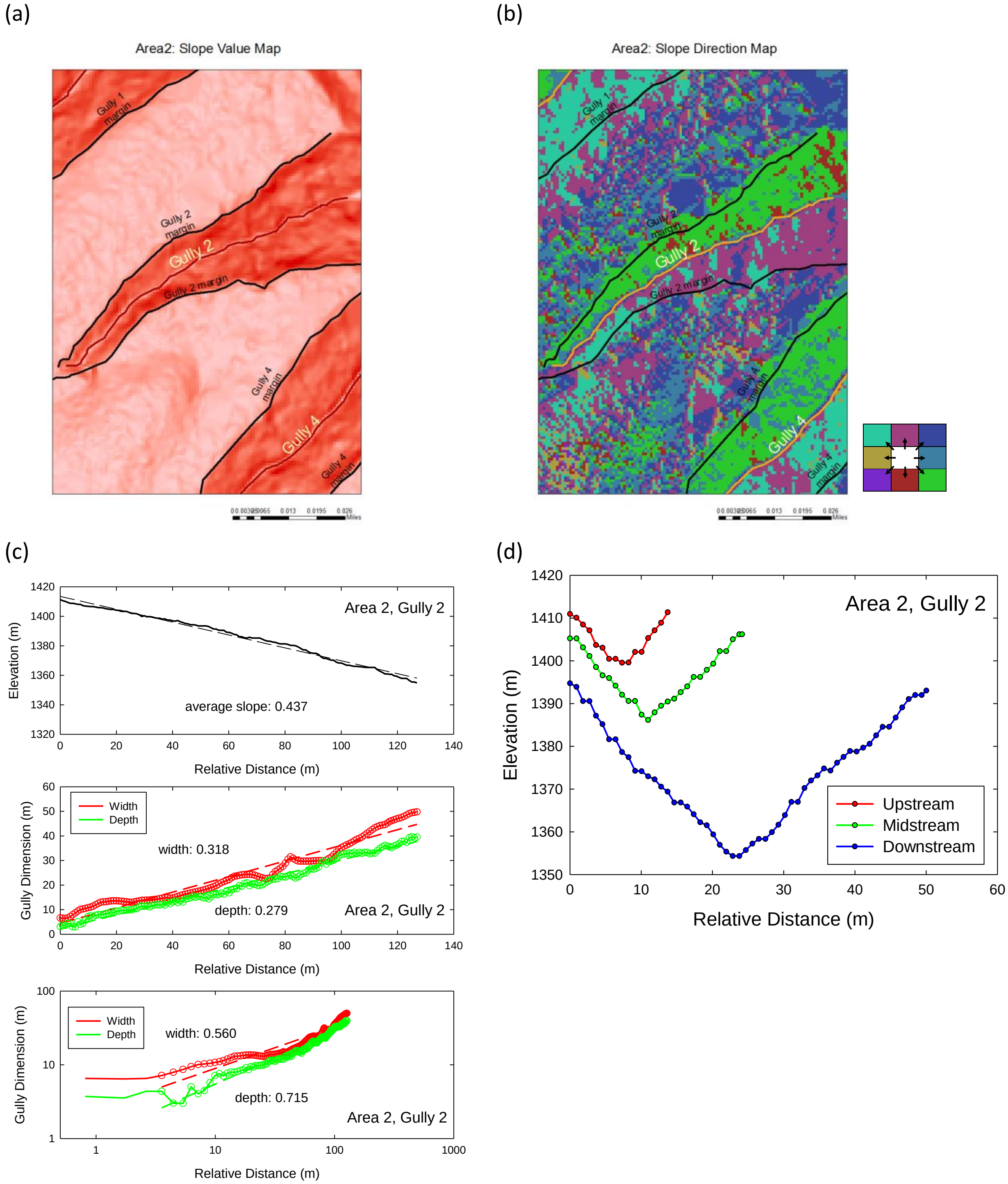


Figure A2-2. Summary plots for Gully 2 location in Area 2 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 3, Area 2

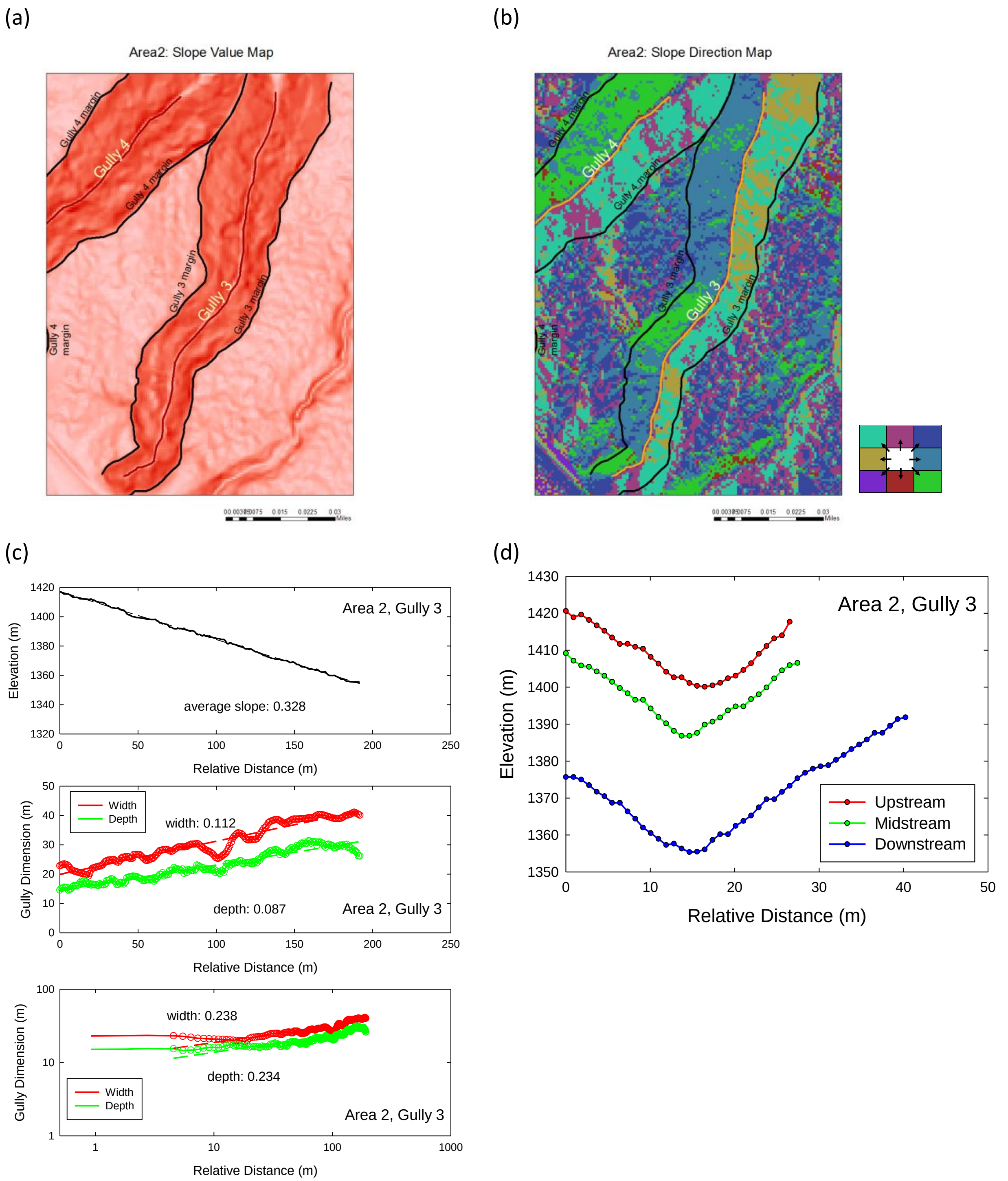


Figure A2-3. Summary plots for Gully 3 location in Area 2 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 4, Area 2

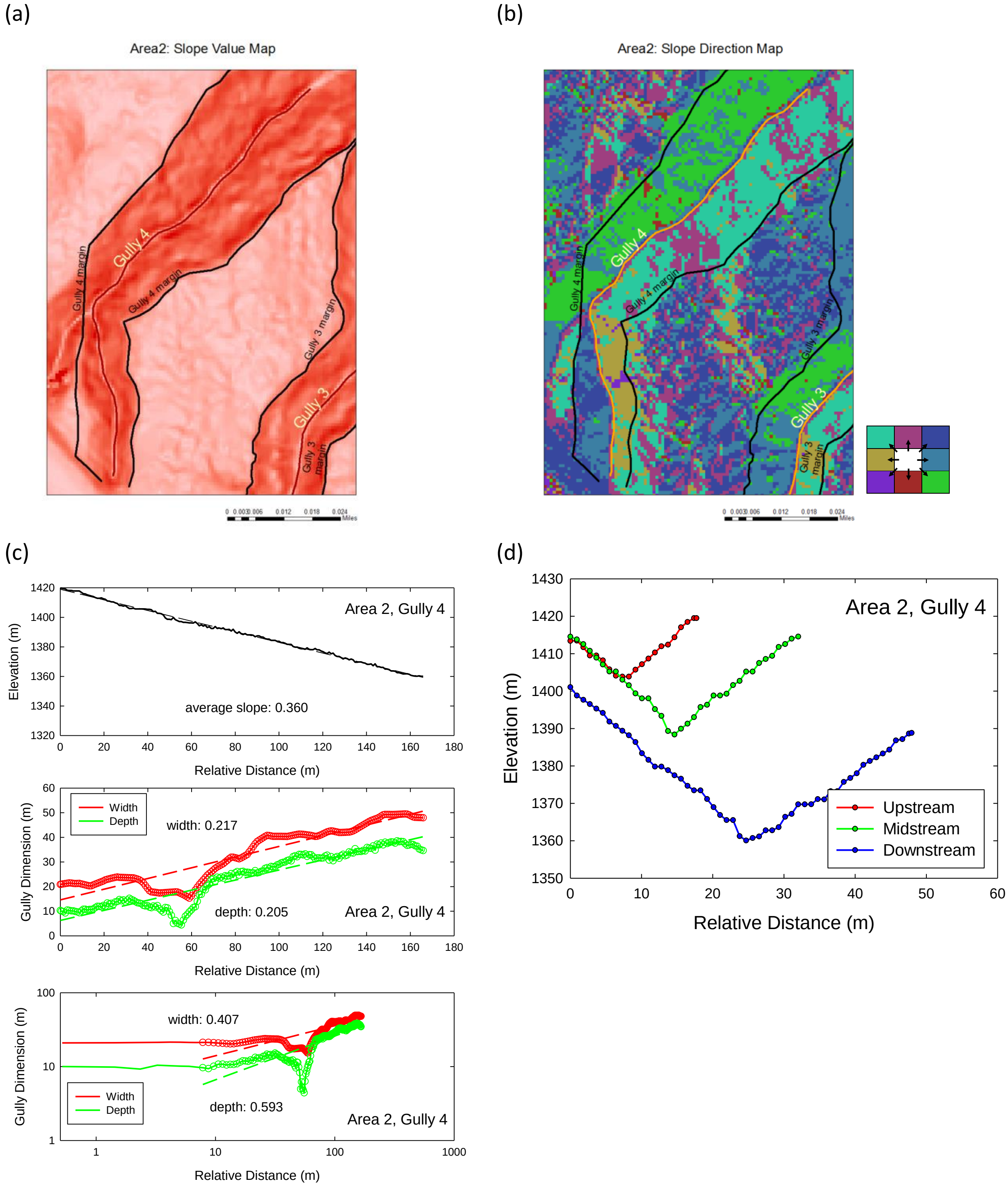


Figure A2-4. Summary plots for Gully 4 location in Area 2 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 1, Area 3

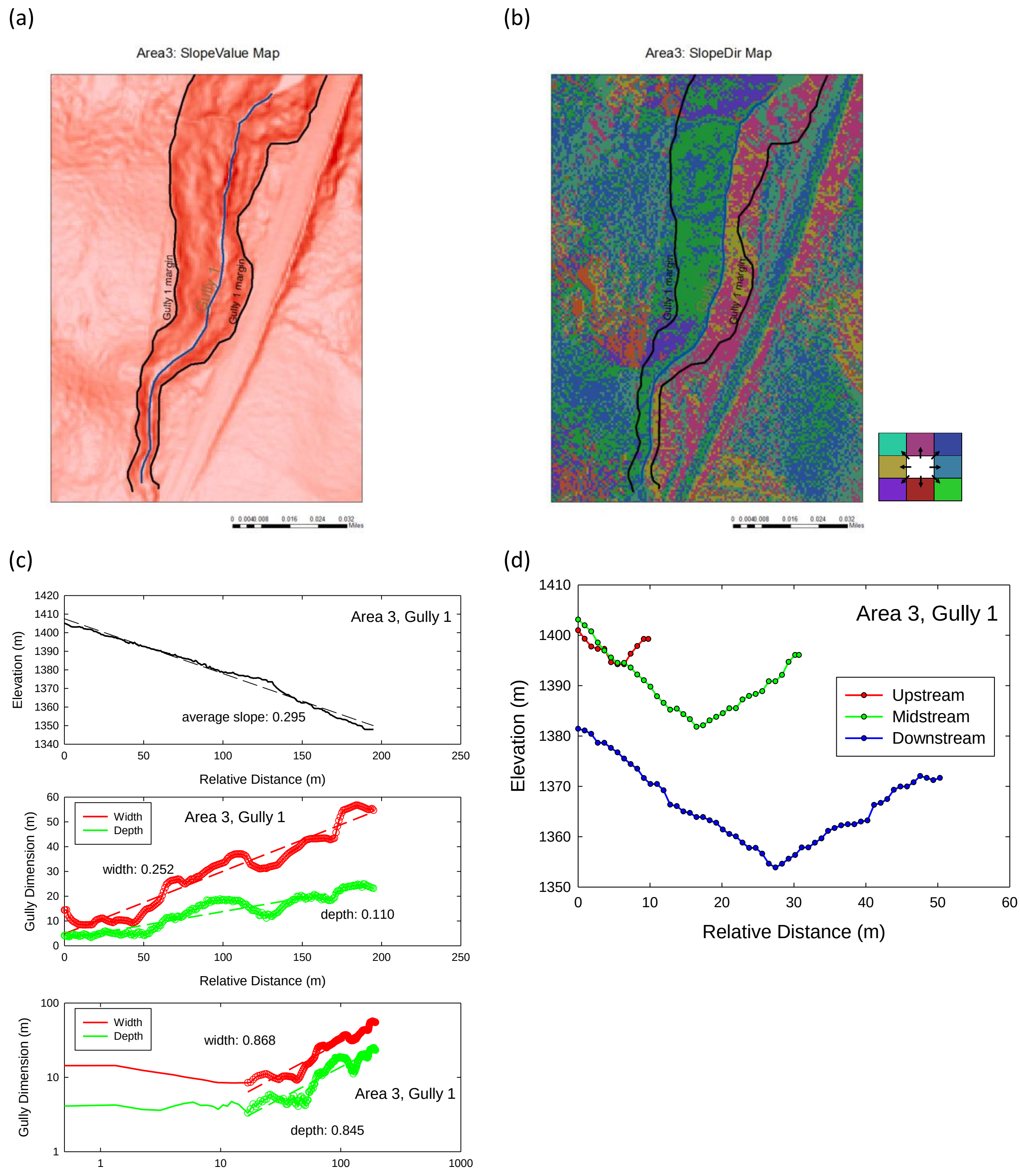


Figure A2-5. Summary plots for Gully 1 location in Area 3 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 2, Area 3

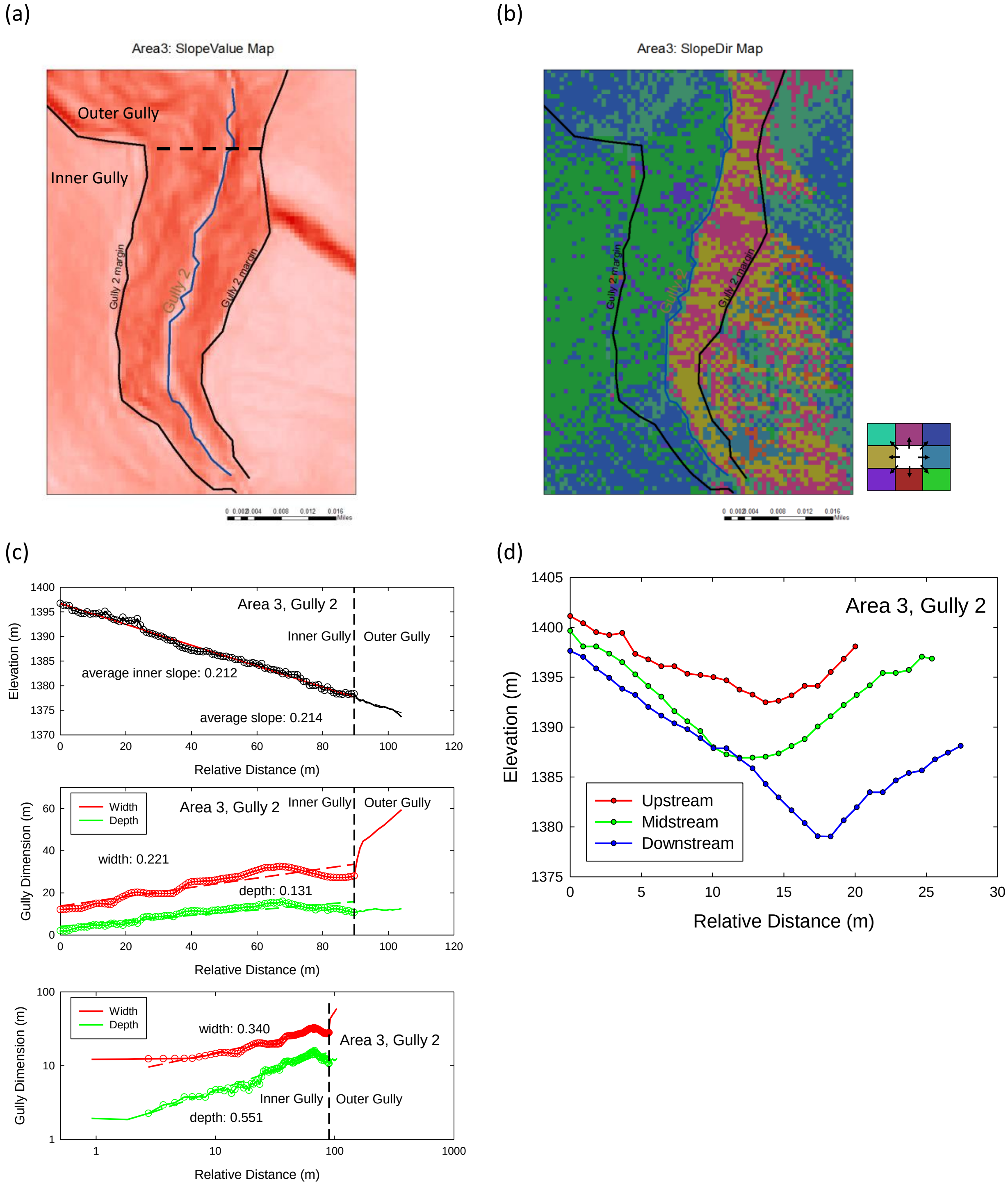


Figure A2-6. Summary plots for Gully 2 location in Area 3 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 3, Area 3

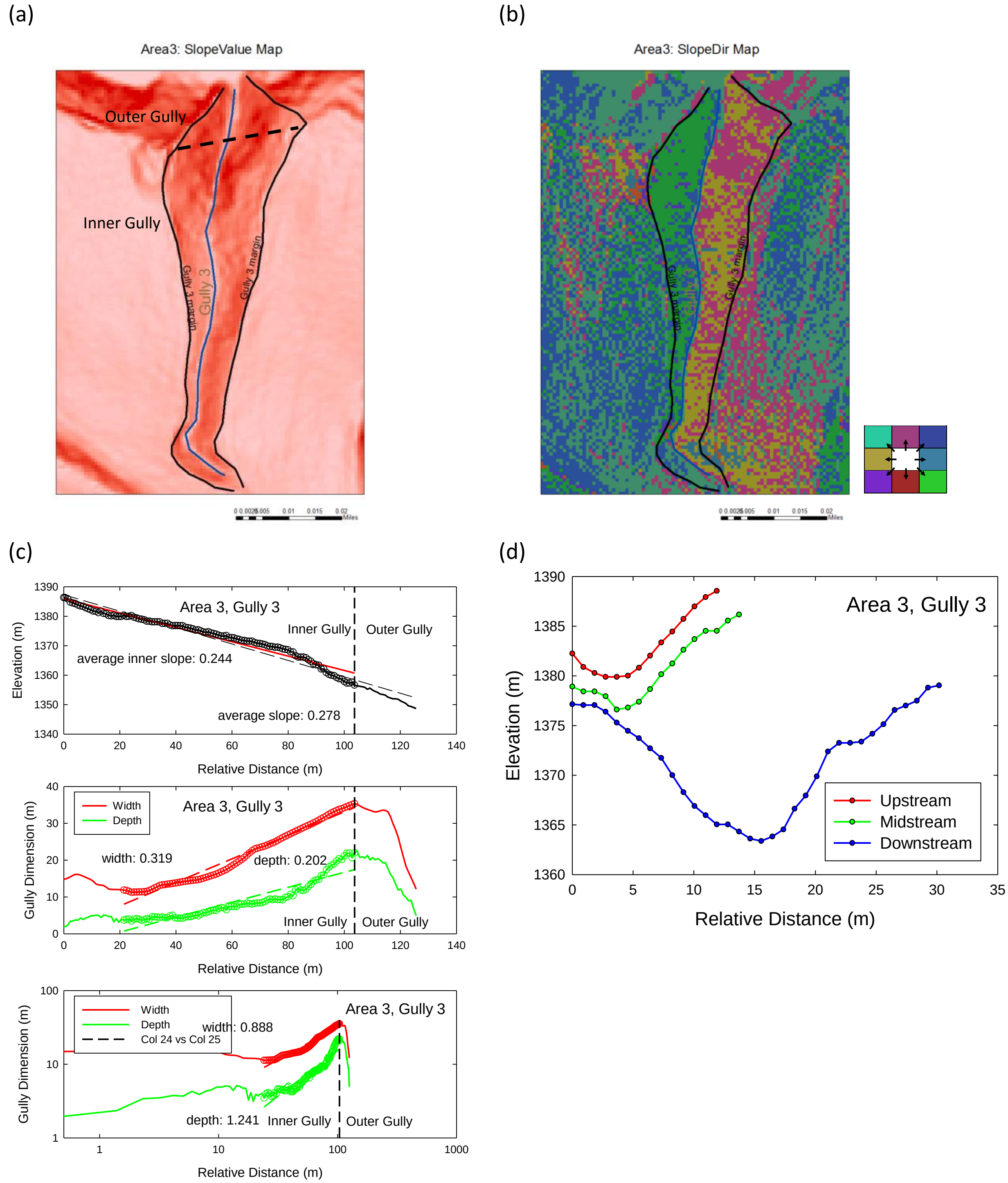


Figure A2-7. Summary plots for Gully 3 location in Area 3 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 1, Area 4

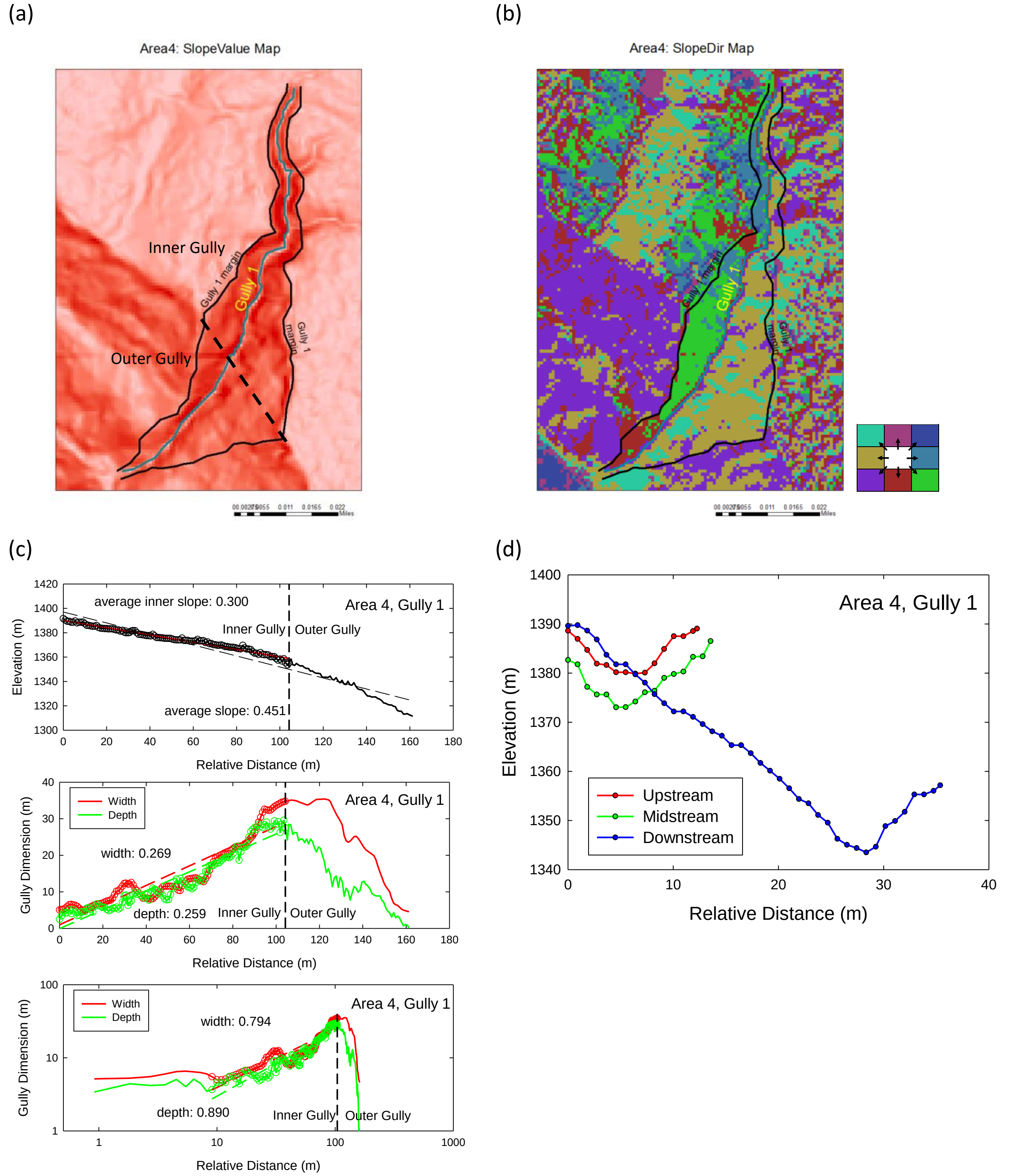


Figure A2-8. Summary plots for Gully 1 location in Area 4 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 2, Area 4

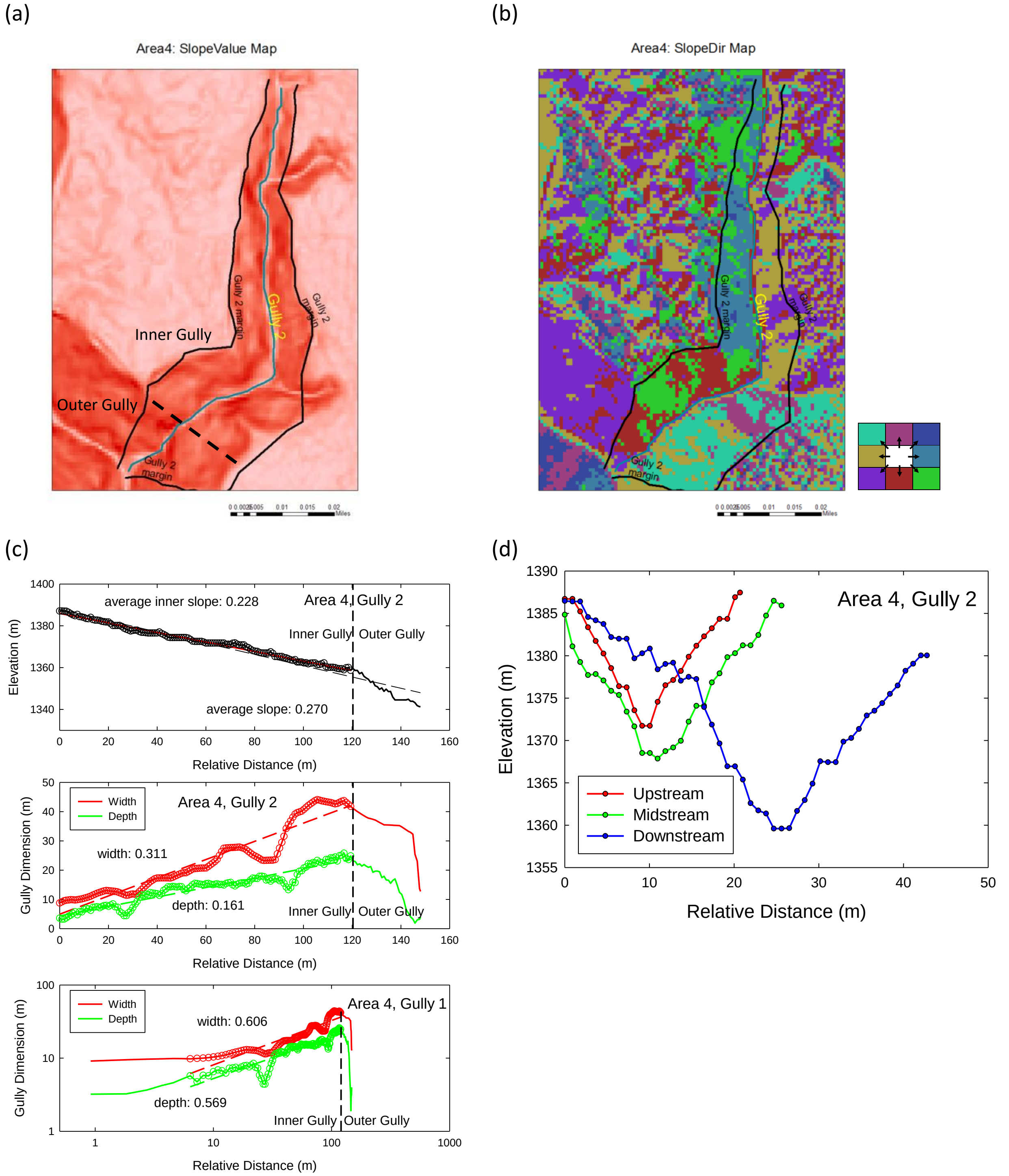


Figure A2-9. Summary plots for Gully 2 location in Area 4 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 3, Area 4

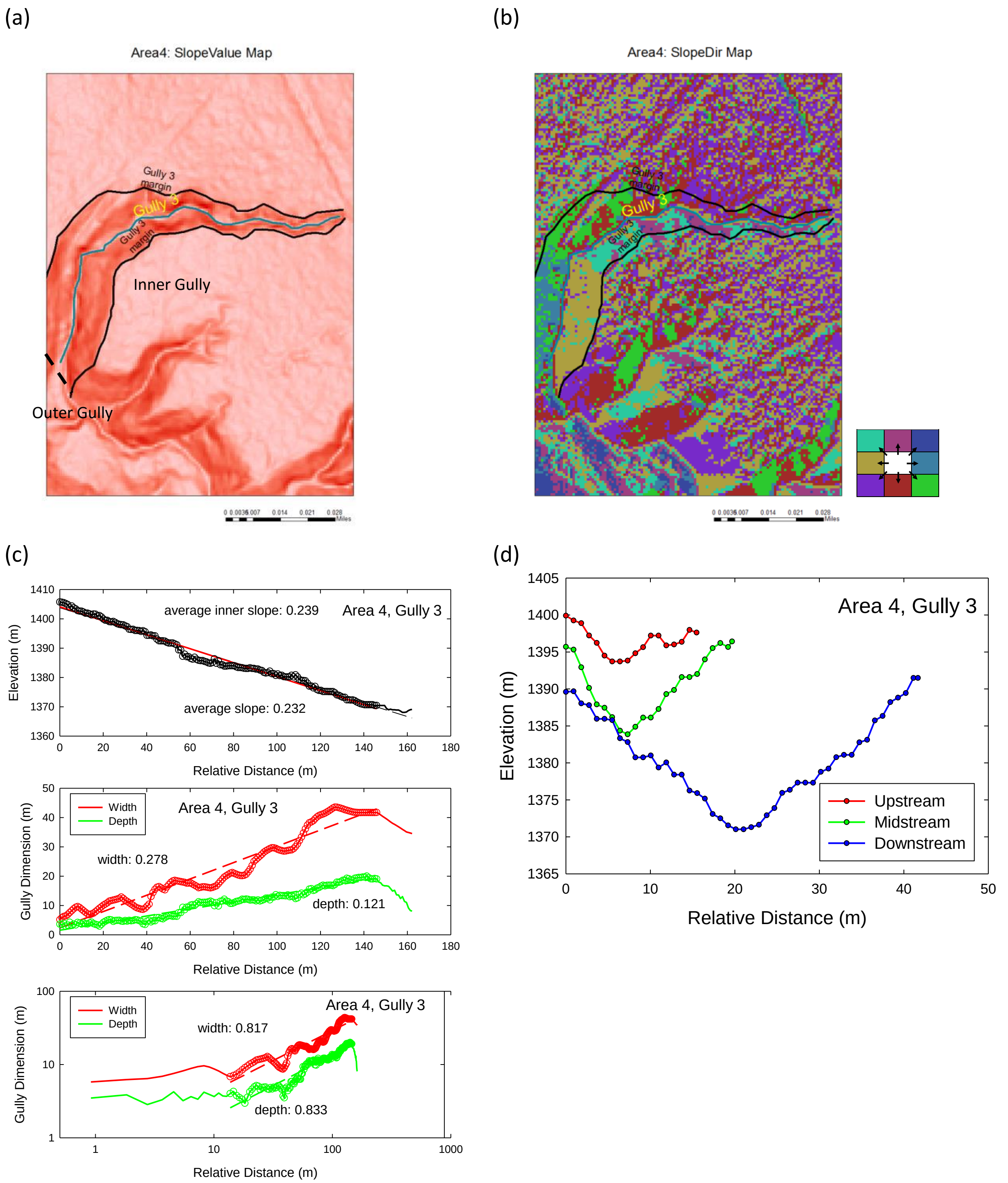


Figure A2-10. Summary plots for Gully 3 location in Area 4 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 4, Area 4

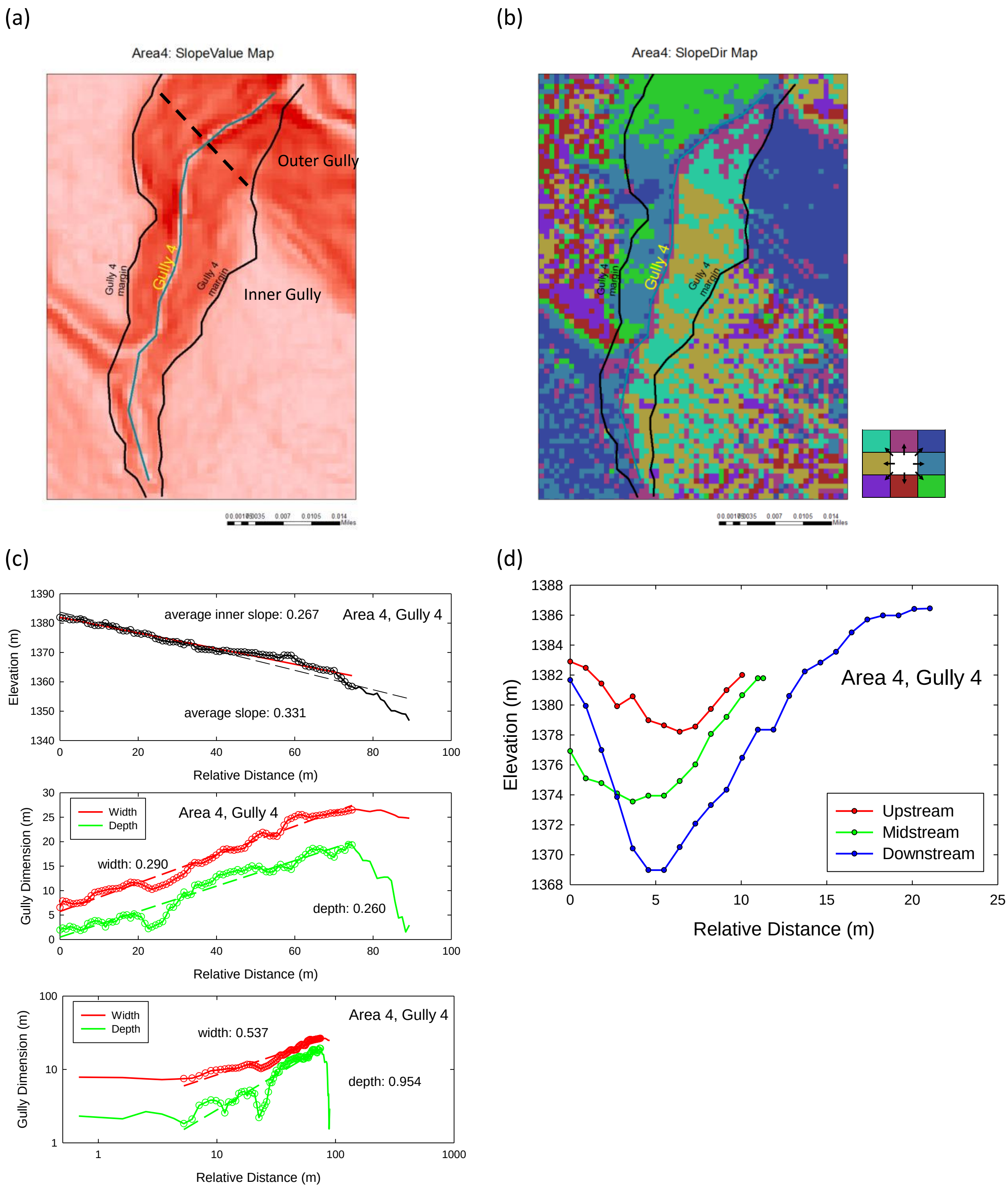


Figure A2-11. Summary plots for Gully 4 location in Area 4 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 1, Area 5

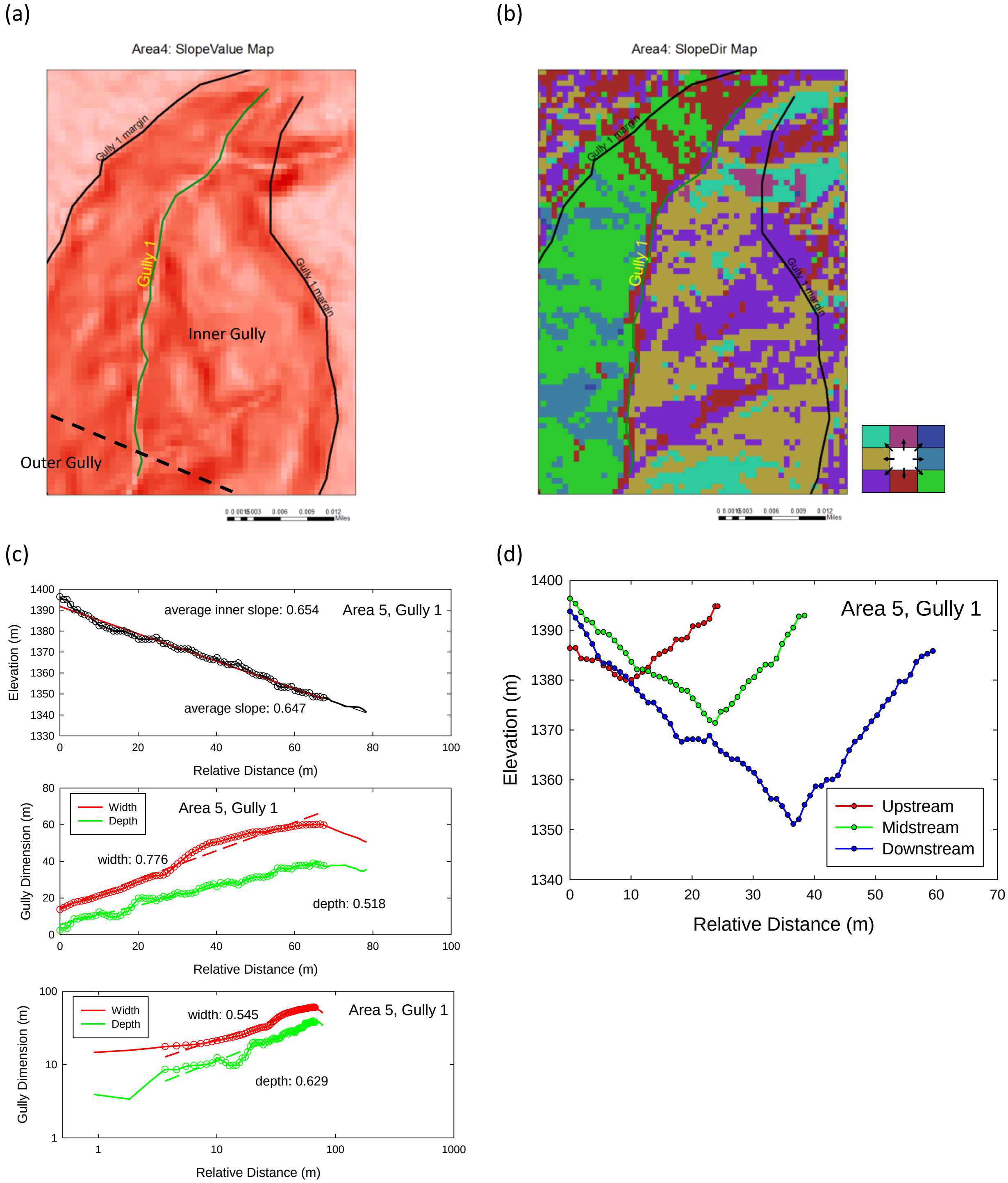


Figure A2-12. Summary plots for Gully 1 location in Area 5 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 2, Area 5

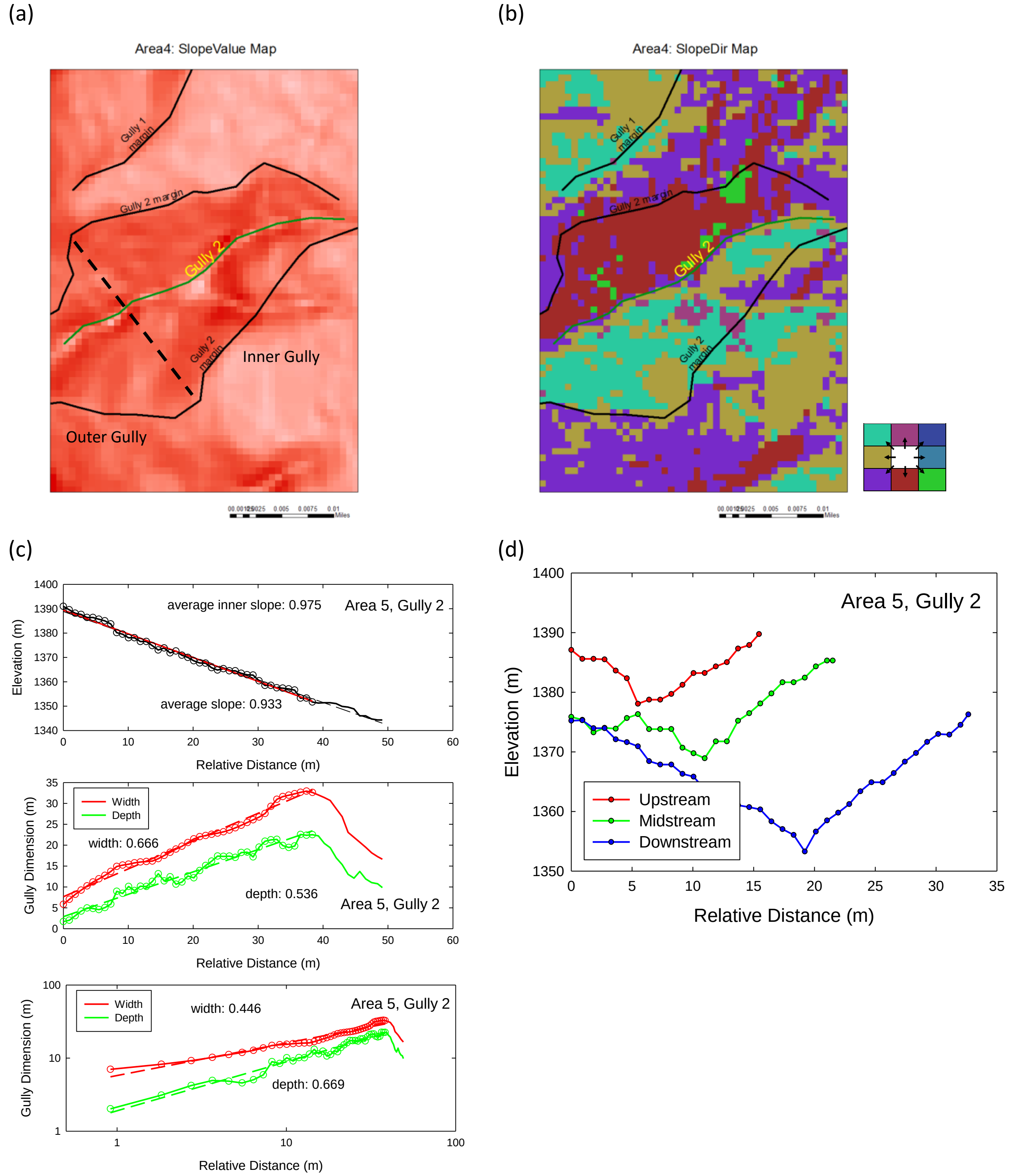


Figure A2-13. Summary plots for Gully 2 location in Area 5 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 1, Area 6

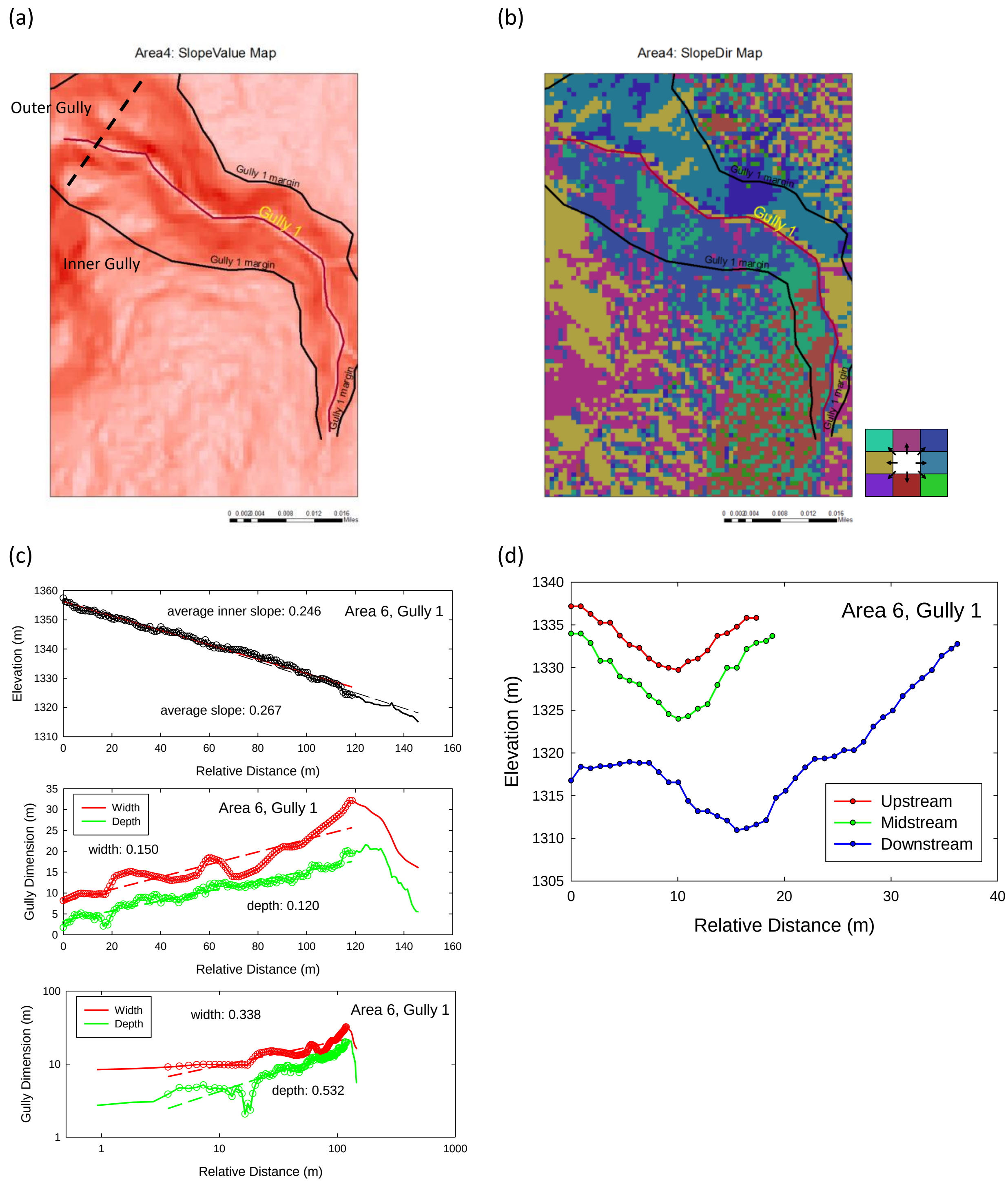


Figure A2-14. Summary plots for Gully 1 location in Area 6 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 2, Area 6

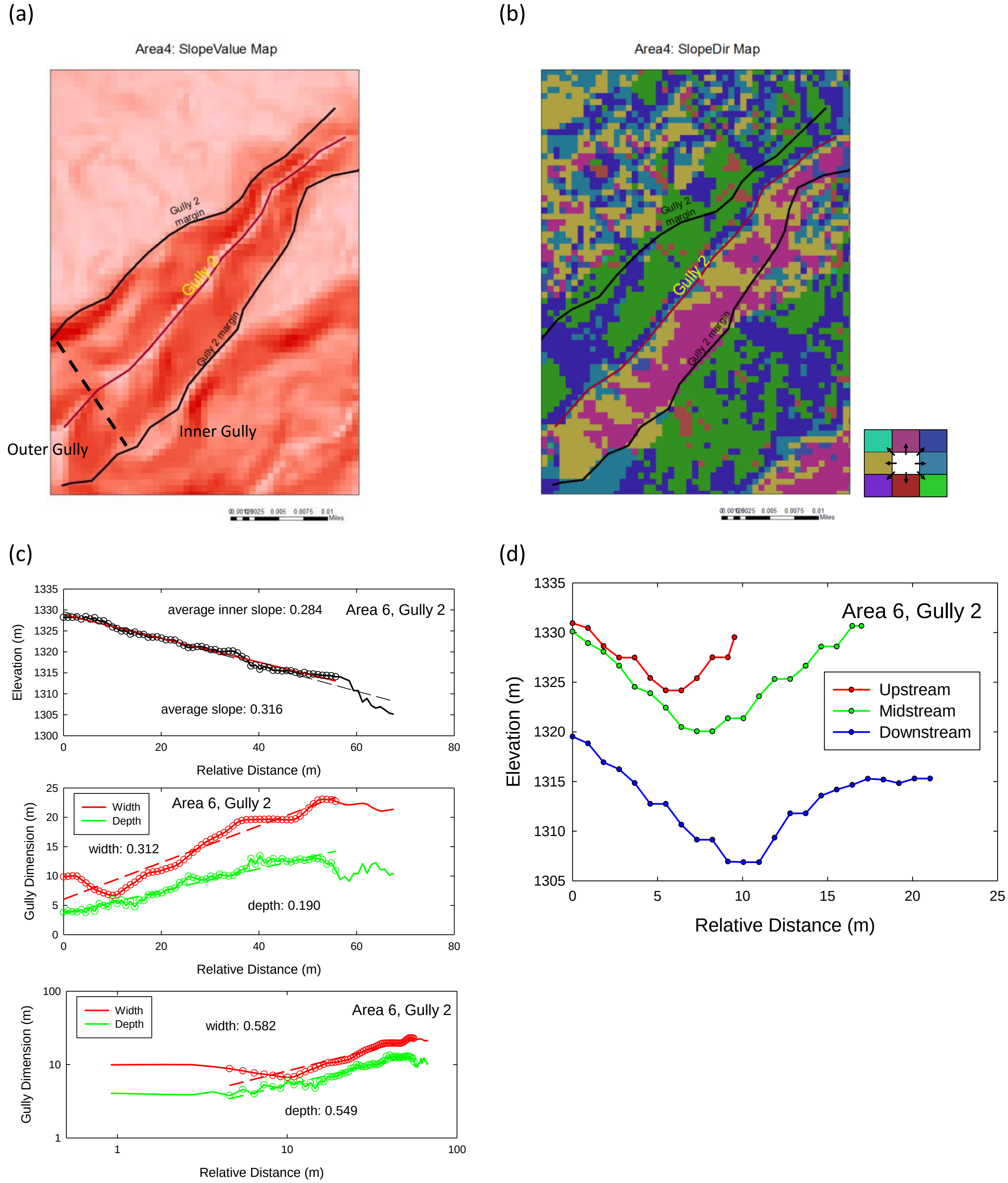


Figure A2-15. Summary plots for Gully 2 location in Area 6 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 3, Area 6

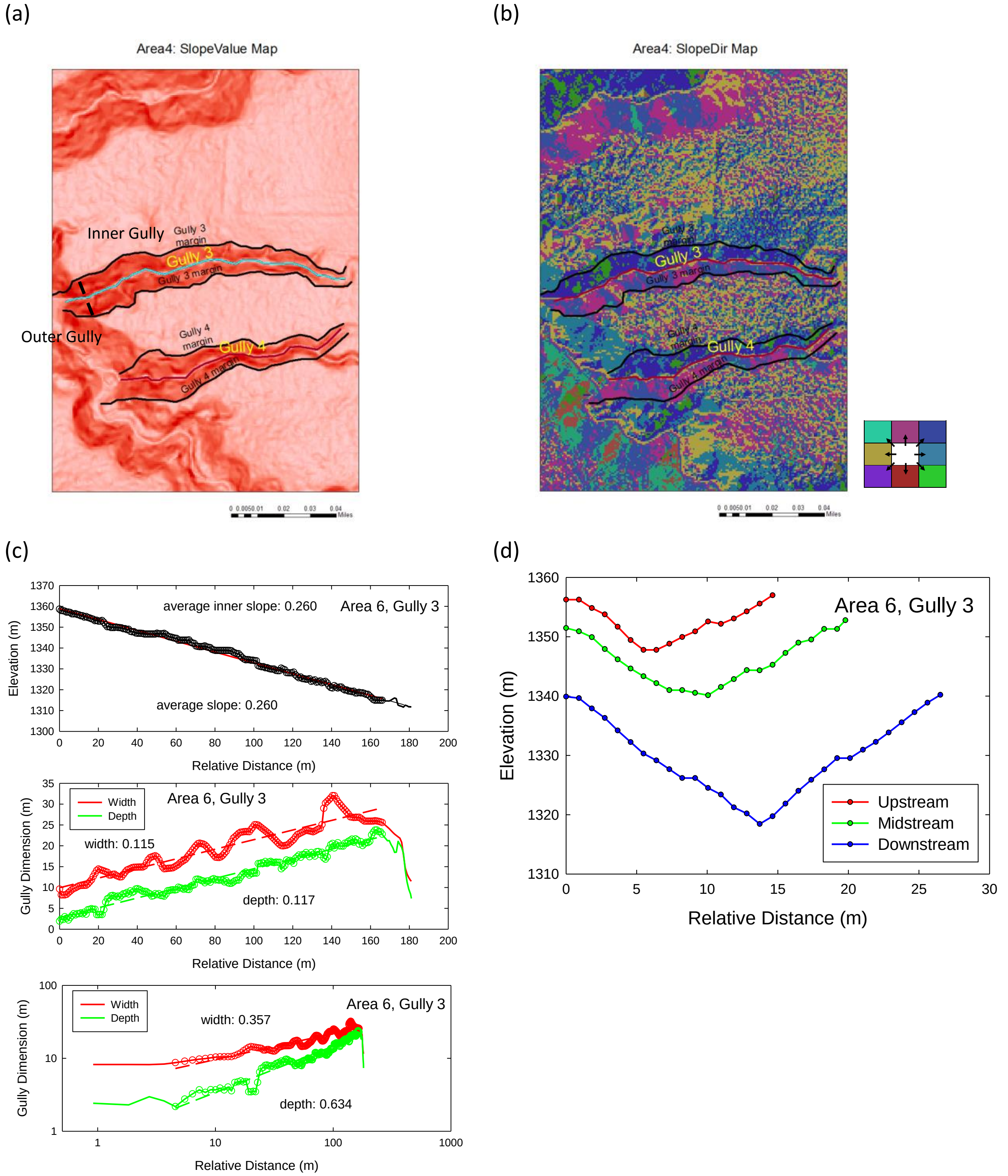


Figure A2-16. Summary plots for Gully 3 location in Area 6 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).

Gully 4, Area 6

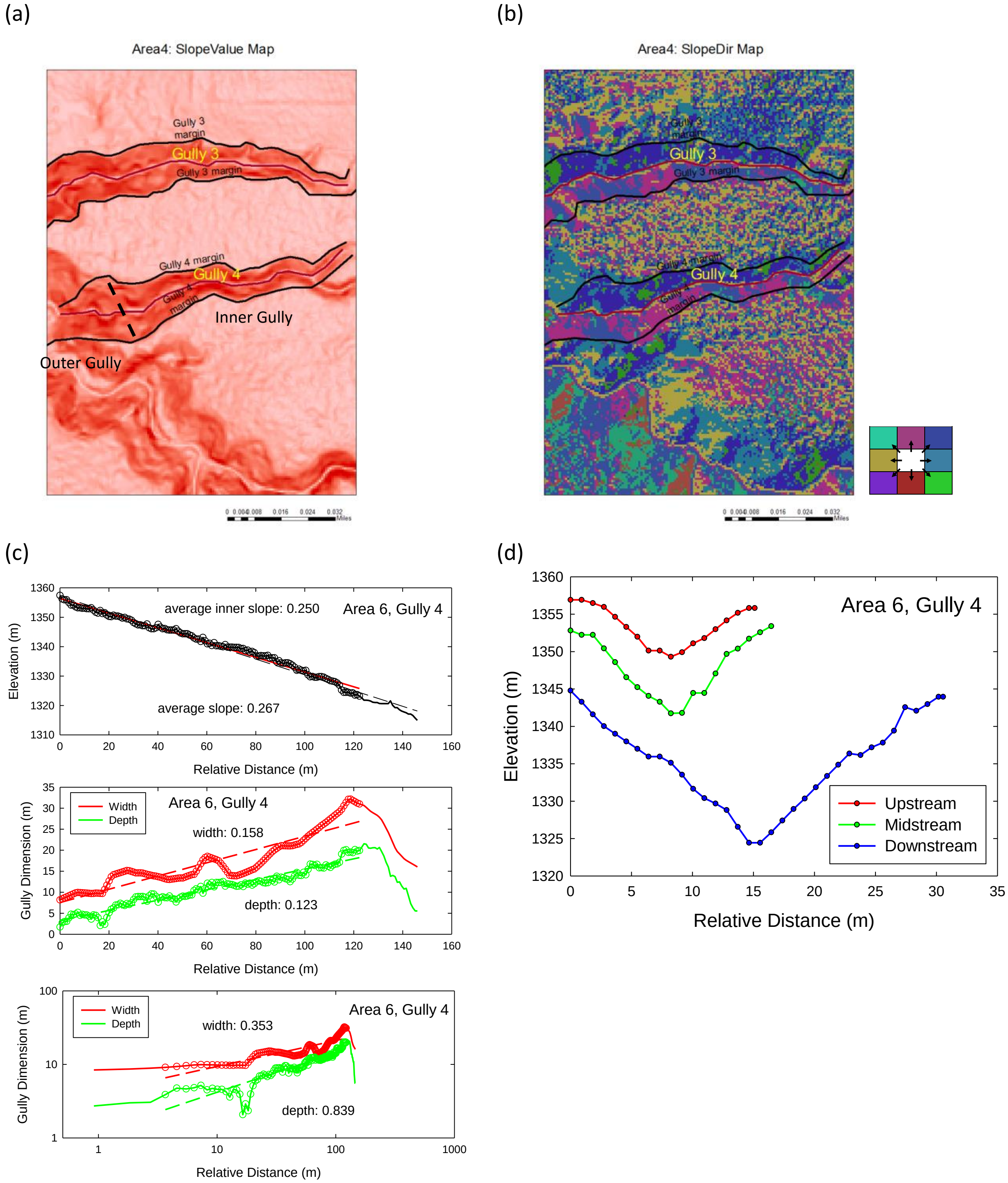


Figure A2-17. Summary plots for Gully 4 location in Area 6 showing (a) slope value map, (b) slope direction map, (c) longitudinal profile and the variation in gully width and depth with relative distance split into inner and outer gully portions (the values of the slopes of these curves are provided), and (d) selected cross-sections (looking downstream along the gully thalweg).