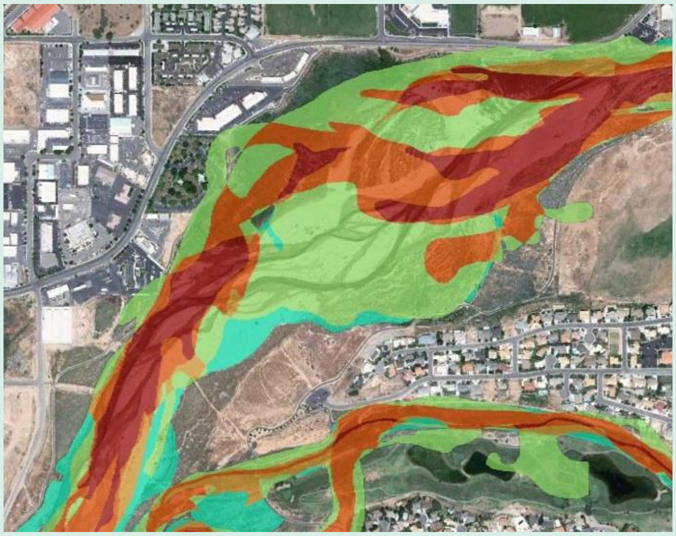
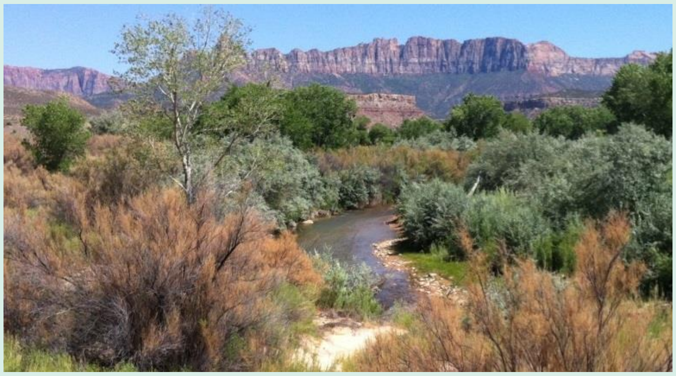
TECHNICAL REPORT ◦ MAY 2014

Virgin River Ecohydrological Assessment—Flood-Scour Analysis, Vegetation Mapping, and Restoration Suitability





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Cover graphics:

Upper left: Flood-scour mapping produced by Stillwater Sciences depicting frequency of disturbance from successive large flood events in St. George, Utah.

Top right: Photograph of lower Virgin River recently scoured during the December 2010 flood and partially bordered by defoliated tamarisk (at left); downstream of Littlefield, Arizona (photo by D. Orr)

Bottom left: Photograph of upper Virgin River recently flooded in December 2010 and bordered by defoliated tamarisk (in foreground), Russian olive (in middle ground), and cottonwood (in background); downstream of Rockville, Utah (photo by G. Leverich, Stillwater Sciences)

Bottom right: Vegetation-classification mapping produced by Utah State University's RS/GIS Laboratory depicting dominate riparian vegetation types near Mesquite, Nevada following the December 2010 flood event.

Acknowledgements:

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Project team:

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A Restoration Science Team collaborated on certain elements of this work; the members included: Dr. Tom Dudley of the Marine Science Institute at U.C. Santa Barbara; Dr. Kevin Hultine of the Desert Botanical Garden, and Dr. Matthew Johnson of the Colorado Plateau Research Station at Northern Arizona University (http://rivrlab.msi.ucsb.edu/colorado-basin/virgin-river).

Remote sensing data collection and processing conducted for this study were led by Drs. Christopher Neale and Robert Pack at Utah State University's Remote Sensing/Geographical Information Systems Laboratory (http://www.gis.usu.edu/).

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EXECUTIVE SUMMARY

Virgin River Setting

This report presents the findings from an ecohydrological assessment performed along the Virgin River—a 154-mile (248-kilometer) water course originating in Zion National Park and terminating in Lake Mead. Similar to other large rivers in the Southwest region, the Virgin River is a hydrologically episodic and ecologically rich water course that simultaneously supports critical wildlife and fish habitat, dense tamarisk (saltcedar; *Tamarix ramosissima* and *T. parviflora*) infestation, agricultural land uses, and growing urban developments. The river is unique, however, in that it still has a mostly unregulated flow regime due to the lack of any storage reservoirs on the mainstem, though a few diversion facilities are present. Additionally, the recent establishment of the tamarisk leaf beetle (*Diorhabda carinulata*) within the critical habitat of the southwestern willow flycatcher (SWFL; *Empidonax traillii extimus*) made the Virgin River the first watershed in which the two are known to co-occur. Restoration managers have been further challenged by two successive floods in 2005 and 2010 that destroyed recent tamarisk removal and riparian restoration efforts.

Need for Informed Restoration Planning

While it is widely acknowledged that biological control of tamarisk will ultimately yield long-term benefits for wildlife and ecosystem services in the Southwest, such as through expanded wildlife habitat, water savings, and reduced flood and fire risks, there is elevated concern in the short term over the need for riparian restoration measures to mitigate possible negative impacts of biocontrol. In particular, this concern focuses on the loss of riparian canopy cover for nesting birds and elevated wildfire risk within the tamarisk-dominated riparian corridor along most of the river's length. Thus, there is a crucial need for immediate, yet strategic riparian restoration along the ecologically sensitive, flood-prone Virgin River.

Given the broad distribution of tamarisk along the river, implementation of potentially large-scale restoration efforts requires informed, coordinated planning amongst the multiple resource agencies, municipalities, and local citizens. This is especially true in highly dynamic systems, such as the large, flashy, and ecologically sensitive rivers in the arid Southwest, like the Virgin River, that do not fit the "classic" textbook river model and, thus, require consideration of regionally specific conditions.

Identification of Potentially Suitable Restoration Areas

This technical summary report describes a tool we developed for riparian restoration planning along the Virgin River and presents the findings intended to highlight potentially suitable locations for sustainable restoration. The tool integrates the key physical attributes of the river and its watershed—climate, hydrology, and geomorphology—with the ecological responses of vegetation and wildlife to those conditions. This integrative interdisciplinary approach provides an understanding of the watershed context, the dynamics of resource conditions, and the feasible types and locations of appropriate river-floodplain conservation and restoration projects.

The ecohydrological assessment of the Virgin River began with understanding the active hydrogeomorphic processes along the entire river corridor to predict likely future trends in channel evolution which will help to inform on suitable site selection. With large channel-resetting events occurring about once a decade, we analyzed a series of post-flood aerial photography to delineate the "hydrogeomorphically active channel"—that part of the river that carried a significant part of the flood and sediment discharge. While being a predominantly braided river, reach-level differences in channel morphology are still quite apparent and, accordingly, have strong influence on the types of management and restoration actions that may be suitably applied. Thus, we mapped flood-disturbance probability in each reach to highlight those channel areas most frequently disturbed by repeat flood events (i.e., the "flood reset zone").

Characterization of dominant vegetation types along the Virgin River is the second key component of our ecohydrological assessment, chiefly because it identifies those areas dominated by native versus non-native, invasive species, and because it identifies individual species and coverage classes (e.g., cottonwood, willow, tamarisk, Russian olive). Vegetation-classification was broadly produced via remote sensing activities conducted in support of this assessment, and provides a robust baseline of the riparian communities. Refinement of this map product was made in three focal reaches of the upper river in Utah using field-based mapping. Overall, the relative abundance of tamarisk is markedly greater downstream of the Virgin River Gorge, while native riparian species diversity and vegetation structural complexity are greatest in the upper Virgin Valley near Zion National Park.

Delineation of potentially suitable restoration areas at the reach-scale thus represented the synthesis of the flood-scour and vegetation mapping products. These areas were further screened through consideration of: minimum patch size for suitable SWFL-habitat ($\geq$10 acres); hydrologic connectivity with perennial surface water sources; avoidance of urban development or other active land uses; and proximity to known, recently-occupied SWFL habitat. A total of 3,480 acres (1,400 hectares) of potentially suitable restoration areas were identified along the lower river (between the mouth of the Virgin River Gorge in Arizona and Lake Mead in Nevada), which represents approximately 45% of the riparian corridor. Distribution of these areas is relatively isolated between Littlefield and Bunkerville (Mesquite reach) due to the confined floodplain, whereas distribution in the Mormon Mesa reach is more expansive due to the broad, low-lying floodplain, shallow groundwater, and side channels present. Along the upper river (between the north- and east-fork confluence in Utah and the head of the Virgin River Gorge in Utah), a total of 665 acres (269 hectares) of potentially suitable restoration were identified, which represents approximately 18% of the riparian corridor. These areas are generally isolated due to floodplain confinement, particularly in the St. George reach by urban encroachment and in the upper Virgin Valley by canyons and upland terraces.

These potentially suitable restoration areas were presented at a stakeholder workshop attended by representatives of resource agencies, municipalities, and conservation groups. The attendees collectively discussed and further vetted the feasibility of implementing active restoration to involve some combination of strategic tamarisk treatment and native vegetation planting to chiefly enhance existing SWFL habitat, and to avoid any short-term impacts associated with implementation activities. A total of 12 sites were identified during this process for near-term implementation.

Next Steps

While the results of the Ecohydrological Assessment are helping watershed managers with prioritizing sites where active tamarisk treatment and native vegetation planting may soon be suitably applied, additional environmental factors will likely be needed to refine implementation plans at the site-scale (<100 acres). The other physical and ecological attributes of the river that are important for restoration planning include local soil conditions and salinity, groundwater levels, and wildlife habitat use and distribution, which can be economically assessed based on available remote-sensing data and focused field surveys.

1 INTRODUCTION

This technical summary report summarizes the methods and results of the initial phase of an integrative ecohydrological assessment of the entire Virgin River. The assessment was conducted within the broader Virgin River Watershed Restoration Framework by Stillwater Sciences, with close collaboration with members from the Virgin River Watershed Restoration Science Team (Science Team), to deliver science-based guidance on suitable riparian restoration actions within the ecologically sensitive, flood-prone river corridor. This report expands on our 2012 flood-scour analysis summary report (Stillwater Sciences 2012) by including vegetation information and priority areas for active restoration. The overall study need and focus area are described below. Figure 1 shows the Virgin River watershed and our focus area along the mainstem river corridor.

1.1 Need for an Integrative Ecohydrological Assessment

A "concept paper" compiled by the Tamarisk Coalition[1] (2011) outlined a framework for determining how Virgin River stakeholders and their representative partnership groups can identify and implement feasible opportunities for riparian habitat restoration along the Virgin River, with a focus on recovery actions for the endangered southwestern willow flycatcher[2] (SWFL; *Empidonax traillii extimus*). This framework is intended to allow a collaborative group of scientists, resource managers, and stakeholders to take a comprehensive approach toward restoration. To date, there have been numerous restoration efforts implemented throughout the river corridor by various entities across the different states, counties, and municipalities. The challenges inherent to this piece-meal approach are compounded by the recent establishment of the tamarisk leaf beetle (*Diorhabda carinulata*) within the critical habitat of the flycatcher, making the Virgin River the only watershed where the two are known to co-occur. This condition is particularly problematic here because much of the river's riparian corridor has been densely infested by tamarisk (saltcedar; *Tamarix ramosissima* and *T. parviflora*) and, accordingly, the success of the beetle biocontrol measure has unfortunately impacted flycatcher habitat in these tamarisk-rich areas due to beetle-induced defoliation during the flycatcher nesting period. Other exotic invasive plants similarly targeted for removal on the river include Russian olive (*Elaeagnus angustifolia*) and giant reed (*Arundo donax*).

Another significant, but natural stressor in the watershed, is flooding. In 2005 and 2010, the river and its major tributaries experienced large flood events that shifted the active channel path and scoured riparian vegetation—both invasive tamarisk and native riparian species stands. The December 2010 floods inundated much of the beetle-occupied habitat causing a temporary delay in the beetle expansion. Despite the recent floods, the beetle continued to colonize downstream to Lake Mead and more recently has established just below Hoover Dam (T. Dudley, personal communication), increasing the likelihood that it will expand into the lower Colorado River region. Flood scour also destroyed riparian restoration trials in Mesquite, St. George, and elsewhere (Figure 2) that were recently initiated in this ecosystem, including sites recently occupied by the flycatcher, illustrating why sustainable restoration must be based on sound hydrological assessment to ensure that suitable habitat will be sustained in key areas throughout the river corridor, rather than being susceptible to destruction once again by the next natural flood events.

[1] For more information, visit: http://www.tamariskcoalition.org/
[2] For more information, see: http://sbsc.wr.usgs.gov/cprs/research/projects/swwf/cprsmain.asp

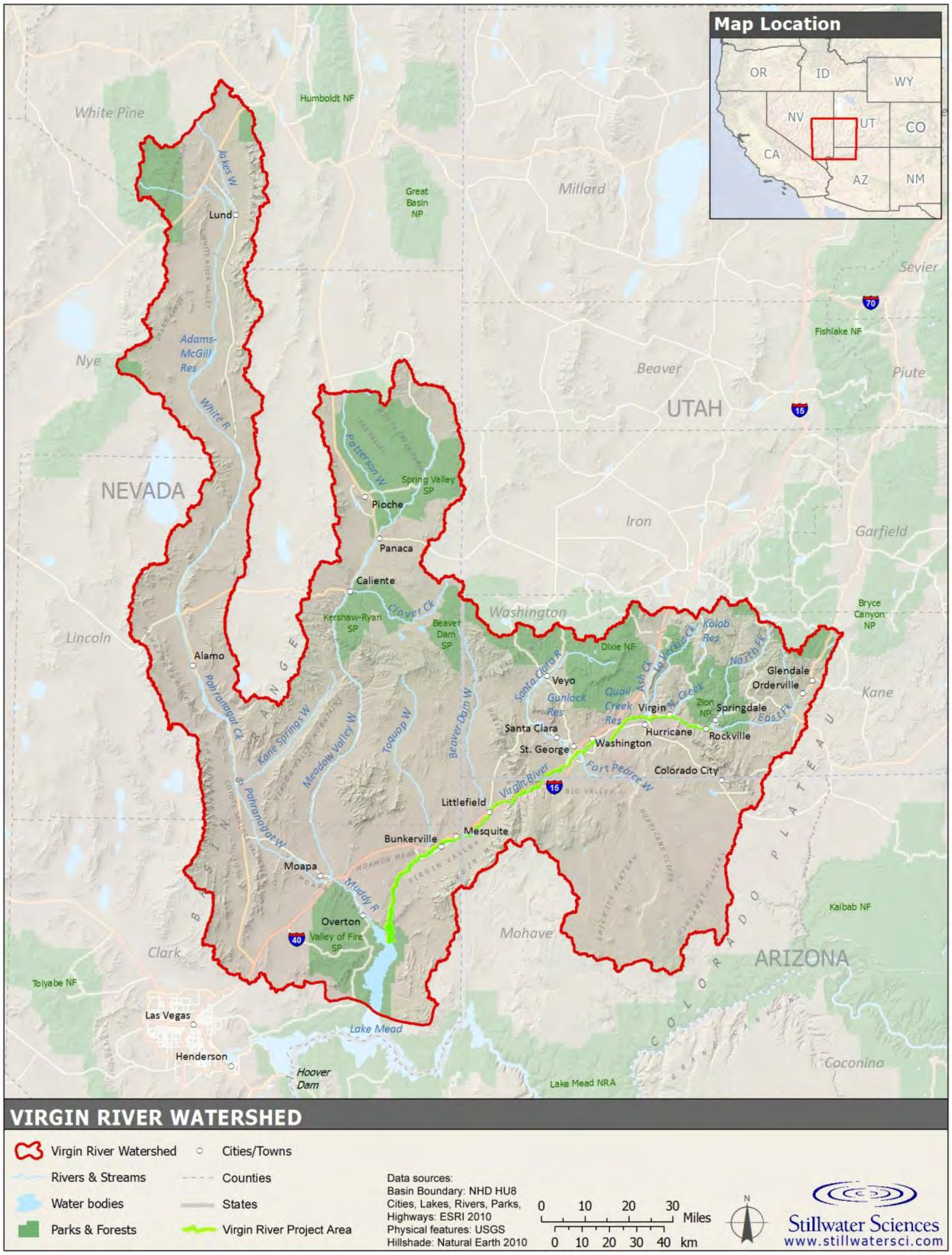


Figure 1. The Virgin River watershed and vicinity. The focus area of the ecohydrological assessment is shown in green along the mainstem river channel between Zion National Park and Lake Mead.


Figure 2. Views of the Hughes Middle School restoration site in the City of Mesquite, Nevada before (left photo) and after (right photo) the December 2010 flood that scoured much of the channel, including the restoration efforts. Project implemented by City of Mesquite, Partners in Conservation, and U.C. Santa Barbara after the 2005 flood event. (Photos by T. Dudley, UCSB)

In response to the issues described above, the overarching goal of the Restoration Framework for the Virgin River watershed is to promote recovery of native riparian habitat and subsequent local increases in flycatcher populations, and, ultimately, to re-establish their metapopulation structure across the greater Colorado River Basin. Satisfying this goal will enable sustained survival of this endangered species (and other sensitive riparian and aquatic wildlife) and subsequently lead to its de-listing based on quantitative evidence of species recovery. Meeting this goal therefore requires the Restoration Framework to maximize the likelihood of creating sustainable native riparian vegetation in a cost-effective manner, while simultaneously building the capacity of local communities to support and participate in achieving restoration success.

As part of the framework, the Tamarisk Coalition's concept paper outlined a primary objective to conduct a restoration action feasibility assessment that identifies appropriate locations in the Virgin River watershed for long term, sustainable riparian restoration, based on ecological and hydrological factors. Specifically, the objective stated:

> *"This assessment would compile available information on Virgin River hydrology, geomorphology, soil conditions and salinity, and vegetation as they relate to potential for successful plant growth and riparian recovery. Where important data gaps are identified samples will be collected and processed to provide a watershed-wide framework for implementing restoration actions. Remote sensing and other imagery would be used to construct flood path models that identify safe sites for revegetation in the face of future flood scour events so that the December 2010 loss of restoration efforts would not be repeated. These data would then be integrated into an ecohydrological framework for targeting suitable locations for revegetation with appropriate plant species, with the goal of establishing interconnected patches of high quality riparian habitat to enhance and sustain the SWFL metapopulation across the Virgin River watershed. The results of the Ecohydrological Restoration Feasibility Assessment will also provide the template for site-specific restoration actions, and the Science Team will work with stakeholders to identify the most appropriate locations and methods for specific restoration actions."*

We have begun to address this objective by initiating the first phase of the Virgin River Ecohydrological Assessment with mapping of historical flood-scour, existing vegetation types, and other environmental factors to identify those areas more suitable for sustainable restoration implementation. One of the most important aspects of this assessment is the identification of the primary "Flood Reset Zone." In concept, mapping of the historical floods gives insight into river dynamics, identifies those areas that are most likely to be reset (by scour and/or deposition) during the next flood event, and helps guide decisions about where passive versus active restoration is most appropriate. The location of a non-native invasive vegetation stand within or outside the Flood Reset Zone is an important factor in determining the best strategy for invasive plant removal and riparian revegetation. We have previously implemented this full approach in southern California, where semi-arid climate, flood-related issues, and sensitive ecosystem concerns are very similar to those of the Virgin River (see Stillwater Sciences 2004, 2008, 2011, and Orr et al. 2011).

In practice, the identification and use of the Flood Reset Zone may provide the single biggest cost saving opportunity in planning and implementing invasive plant treatment projects on the Virgin River, particularly when compared to conventional site-specific, bottom-up invasive removal programs that do not take landscape-scale processes into consideration. The primary Flood Reset Zone was defined to identify areas suitable for invasive plant treatment projects, the type of treatment methods that will be appropriate, and the level of revegetation that may be necessary. The physical removal of non-native invasive plant biomass greatly increases the cost of treatment projects. Floods, as well as fires, are effective at clearing large swaths of invasive plant biomass, and present obvious opportunities for cost effective treatment. The Flood Reset Zone provides an estimate of the infested areas that are highly likely to be scoured and have invasive plant biomass removed naturally during a high-flow event. This zone is also the area that is most likely to be successfully revegetated through natural recruitment, rather than expensive active planting, although it also poses a higher probability of being scoured away by a subsequent high-flow event. Major invasive plant treatment or revegetation expenditures in the primary Flood Reset Zone could be undone quickly by the introduction and reinfestation of invasive plants from upstream sources in the watershed, further limiting the utility of treatment methods that require biomass removal or revegetation that requires active planting. Understanding riparian vegetation dynamics both within and outside of the Flood Reset Zone is critical to ensuring that restoration efforts will result in a sustainable but shifting mosaic of suitable habitat patches throughout the river corridor.

1.2 Study Area

The Restoration Framework study area effectively includes the entire watershed, while the principal area of interest is the active river channel and floodplain where hydrological, geomorphological, and biological processes directly interact to compose the dynamic, ecologically rich river corridor. Our current Ecohydrological Assessment, accordingly, is focused on the mainstem river, from the confluence of the North and East forks near Zion National Park down to the Overton Arm of Lake Mead, with minimal inclusion of the lower reaches of key tributaries.

The Virgin River, a major tributary to the Colorado River, flows southwesterly across Utah, Arizona, and Nevada to its terminus in the Lake Mead reservoir (Figure 1). Nearly half of the watershed lies in Utah, where it includes portions of Kane, Iron, and Washington counties, and the lower half includes portions of Mohave County in Arizona and White Pine, Nye, Lincoln, and Clark counties in Nevada. Much of the watershed is under public management by the Bureau of

Land Management (BLM), Bureau of Reclamation (BOR), National Park Service (NPS), U.S. Forest Service (USFS), and assorted state, municipal, and tribal entities (USACE 2008).

The 13,750 mi^2 (35,600 km^2) watershed also spans two large geomorphic provinces: the high elevation Colorado Plateau on the eastern half; and the arid Basin and Range on the western half (Figure 1). Through these regions, the 150-mi (240-km) river and its major tributaries flow from steep, moderately well-vegetated mountainous terrain downstream to broad, arid valley bottoms where vegetation is concentrated primarily along the larger, perennial stream corridors. Native riparian tree and shrub species include Goodding's willow (or black willow, *Salix gooddingii*), coyote or sandbar willow (*S.exigua*), Fremont cottonwood (*Populus fremontii*), velvet ash (*Fraxinus velutina*), and honey and screwbean mesquite (*Prosopis glandulosa* and *P. pubescens*). Valley width is highly influenced by geologic controls, where the mainstem river alternates several times from coursing through narrow, bedrock-constrained canyons to expansive alluvial floodplain valleys. A single-thread channel dominates in the former reach type, while a multi-thread ("braided") channel dominates the latter reach type. Riparian habitats are most abundant and channel migration is greatest in the valley reaches.

With bi-seasonal precipitation conditions and few urban developments in the watershed, the mainstem river is mostly free-flowing and generally retains its historic discharge regime until joining Lake Mead tens of miles above the river's historic confluence with the Colorado River. Annual reservoir levels fluctuate greatly due to regional water supply and demand, which causes the reservoir backwater to shift longitudinally along approximately 10 miles of the lower river valley and, when levels are high, disconnects the Muddy River from the river. Diversion structures on the mainstem river are the Quail Creek Diversion Dam (between the towns of Virgin and Hurricane in Utah), the Washington Fields Diversion Dam (between Quail Creek Reservoir and the town of Washington in Utah), and the Bunkerville Ditch Diversion Dam (in Mesquite, Nevada). Several small, fish-exclusion barriers are also present near the Arizona-Utah state line and in the Virgin River gorge (or "Narrows"). Notable, albeit small, reservoir impoundments are present on the river's major tributaries, including Kolob Reservoir on the North Fork Virgin River above Zion National Park, Quail Creek Reservoir on Quail Creek near Hurricane, Gunlock Reservoir on the Santa Clara River between the towns of Santa Clara and Veyo, and a series of controlled ponds and lakes above Muddy River on Pahranagat Creek-White River. The dam of Quail Creek Reservoir failed catastrophically on January 1, 1989 causing massive flooding along the river down to Lake Mead. Additional details on the river discharge dynamics and long-term record are summarized below. Hydrogeomorphic reaches delineated along the mainstem river for this study are also described below.

In addition to the southwestern willow flycatcher, several other federally listed species are known to be present along the Virgin River. Other avian species include the northern goshawk (*Accipiter gentilis*), western burrowing owl (*Athene cunicularia hypugaea*), yellow-billed cuckoo (*Coccyzus americanus*), bald eagle (*Hallaeetus leucoephalus*), American Peregrine falcon (*Falco peregrinus anatum*), spotted owl (*Strix occidentalis*) and Mexican spotted owl (*Strix occidentalis lucida*). Listed fish species and other fish species of conservation interest include the desert sucker (*Catostomus clarkii*), flannelmouth sucker (*Catostomus latipinnis*), White River springfish (*Crenichthys baileyi baileyi*), Hiko White River Springfish (*Crenichthys baileyi grandis*), roundtail chub (*Gila robusta*), Virgin River chub (*Gila seminuda*), Virgin spinedace (*Lepidomeda mollispinus*), woundfin (*Plagopterus argentissimus*), and speckled dace (*Rhinichthys osculus*).

2 ECOHYDROLOGICAL ASSESSMENT

The Ecohydrological Assessment considers reach-scale river hydrology, geomorphology, and vegetation conditions along with SWFL-habitat needs to identify areas of the Virgin River's riparian corridor where active riparian restoration, involving some form of tamarisk treatment and native vegetation planting, may be suitably implemented. Here we describe methods and results of the Ecohydrological Assessment, beginning with remote-sensing data collection, flood-scour analysis, and vegetation characterization, and concluding with identification of the "potentially suitable restoration areas."

2.1 Remote-Sensing Data Collection

Remote sensing data collection and processing conducted in support of restoration planning for the Virgin River was performed by Utah State University's Remote Sensing/Geographical Information Systems Laboratory (USU RS/GIS). The entire length of the river was flown in November 2011 to obtain high-resolution aerial imagery and topographic data. The products specifically included color and multispectral orthoimagery, and LiDAR surfaces (first-return and bare-earth). A vegetation-classification layer depicting the dominant native and non-native, invasive plant species, as well as land-cover/-use types, was generated based on the multispectral imagery. These datasets provide an excellent spatial representation of river conditions following the December 2010 flood. A copy of the technical documentation authored by USU RS/GIS is presented in Appendix A.

2.2 Flood-Scour Analysis

This section describes our methods used to perform the flood-scour analysis along the mainstem Virgin River. To accomplish this, we first performed a brief evaluation of the hydrogeomophic character of the river corridor to understand the historic flood hydrology and contemporary channel morphology. From there we performed a detailed aerial photographic analysis to delineate flood-induced channel disturbance. The hydrogeomorphically active channel, or "active channel width," is considered here as that part of the mainstem channel bed that carried a significant part of the flood and sediment discharge during the recent flood event.

2.2.1 Hydrogeomorphic characterization

Characterization of the Virgin River's hydrology and geomorphology, along with riparian ecology, relied on review of available literature and remote sensing products, in addition to field reconnaissance along much of the river. Key technical studies utilized here included Carlson and Meyer (1995), Hereford et al. (1995), CH2M Hill (1996), NDEP (2003), BOR (2004), UDEQ (2004), JE Fuller (2005), and Beck and Wilson (2005), along with historic flow records held by the U.S. Geological Survey and geologic maps published by the USGS and state geologic divisions (e.g., Billingsley and Workman 2000, Biek et al. 2010).

2.2.1.1 Flood hydrology

Historic discharge data from the five long-term gauging stations along the mainstem Virgin River were obtained from the U.S. Geological Survey's National Water Information System website: http://waterdata.usgs.gov/nwis (Table 1). These spatially distributed stations provide a reliable characterization of the river's episodic hydrologic regime responsible for driving the flood-scour processes and geomorphic expression that are the subject of our Ecohydrological Assessment. Streamflow data were downloaded for all available years through water year (WY) 2011.

The river's hydrologic nature is bi-seasonal, with greater flows in winter and spring resulting from rainstorms and snowmelt, and monsoon-type thunderstorms in summer and fall. Annual peak flows occur most frequently in the summer-fall seasons, however, the largest floods of record most often occur in winter. As with most riverine systems, discharge increases downstream as a product of greater drainage area, which is evident in examination of the average annual flows calculated at the five gauges, where mean annual flows at the gauges in Virgin and Littlefield are about 200 and 240 cubic feet per second (cfs), respectively (Table 1). The one exception to this trend is at the gauge station "near St. George" which is due to a large data gap (i.e., 1956–1988).

Flood magnitude along the river also increases downstream, but to a substantially greater degree. For example, the 9,840 cubic feet per second (cfs) of peak discharge recorded at Virgin, UT during the January 2005 flood event accreted nearly four-fold to 37,000 cfs at Littlefield, AZ. The 15 largest floods recorded to date occurred in WY 1911, 1913, 1920, 1938, 1953, 1955, 1961, 1966, 1969, 1978, 1980, 1989, 1995, 2005, and 2010, based on gauge data from the two longest running stations: near Virgin, UT (USGS 09406000) and Littlefield, AZ (USGS 09415000). Of particular importance here is that these peak flows are massive compared to the average annual flows (e.g., 200 cfs versus 37,000 cfs) and usually span only a few hours to days indicating the flashy nature of this river. A graphical plot of peak discharge measured at the five gauges is presented below as Figure 3, which was used to help select appropriate remote sensing data for this study (see Section 2.1.2: Remote-sensing Analysis).

Table 1. USGS discharge gauging stations on the Virgin River used in this study through water year 2011.

USGS gauging station [A] [upstream to downstream]	Period of record in water years [B]	Drainage area [C]		Average annual discharge over period of record (cfs)	Location on river (RM) [D]
		(mi^2)	(km^2)		
09406000 Virgin River at Virgin, UT	1910–present (missing 1972–1978)	956	2,476	199	Near North Creek at RM 141.5
09408150 Virgin River near Hurricane, UT	1967–present (none missing)	1,493	3,867	216	On SR-9 bridge near Quail Creek Reservoir at RM 123
09413200 Virgin River near Bloomington, UT	1978–present (none missing)	3,853	9,979	224	In St. George near Santa Clara River and I-15 bridge at RM 107.5
09413500 Virgin River near St. George, UT	1951–present (missing 1956–1988)	4,123	10,679	194	Near upstream end of Narrows at RM 98
09415000 Virgin River at Littlefield, AZ	1930–present (none missing)	5,090	13,183	243	In Littlefield near Beaver Dam Wash at RM 73

[A] Weblink:
[1] http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=09406000&target=_
[2] http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=09408150&target=_
[3] http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=09413200&target=_
[4] http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=09413500&target=_
[5] http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=09415000&target=_
[B] Water year (WY) is the 12-month period for any given year from October 1 through September 30.
[C] Drainage areas from USGS station information.
[D] River miles (RM) based on system displayed on USGS topographical quadrangle maps for majority of the Virgin River; intermediate RM locations were interpolated between those displayed on quadrangle maps in a GIS.

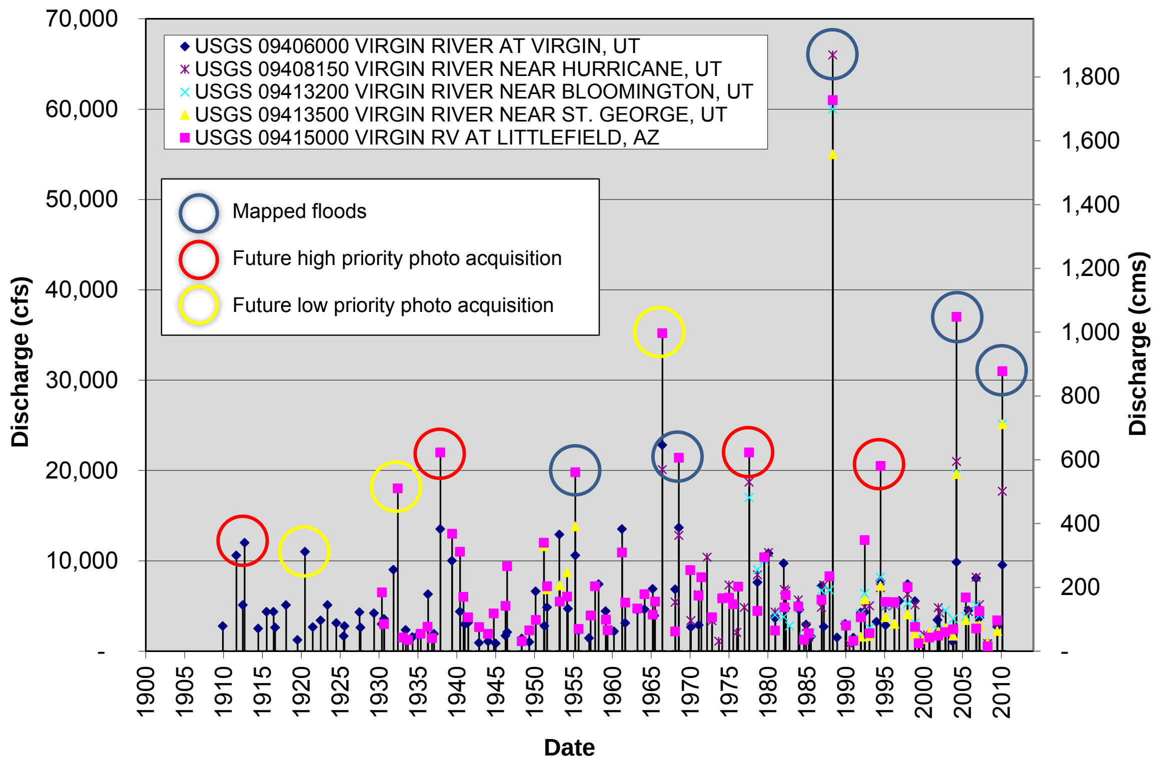


Figure 3. Historical peak flows at stream gauges on the mainstem Virgin River. Peaks are shown in comparison to known aerial photography acquisition dates.

To further characterize the river's flood hydrology for this study, we have calculated the flood recurrence intervals at the five gauges using all available data through WY 2011, which encapsulates the most recent large flood event of December 21, 2010 (Figure 4). These data individually provide a statistical basis of flood-level prediction for a given recurrence interval at each gauging station. The data can in turn be used to determine the recurrence interval (RI) value per flood event, such as those considered in our study. Using the Littlefield gauge data to represent the largest events experienced throughout the watershed, the computed (Log-Pearson III) recurrence intervals per flood are as follows:

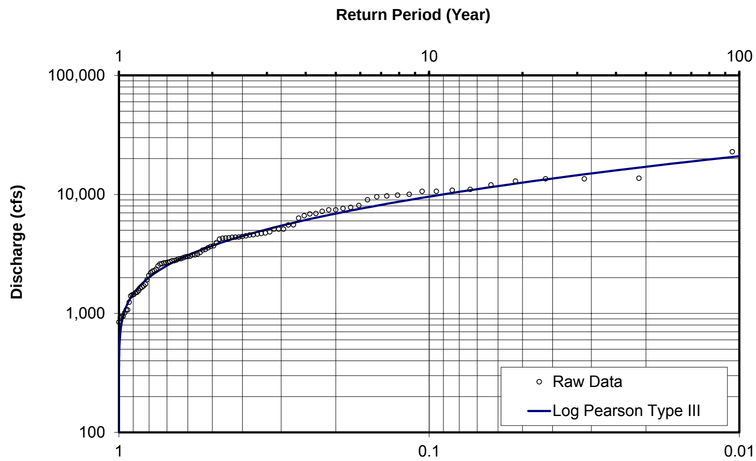
- August 25, 1955: 19,800 cfs RI≈17 yrs
- December 6, 1966: 35,200 cfs RI≈48 yrs
- January 26, 1969: 21,400 cfs RI≈20 yrs
- January 1, 1989 (Quail Creek Dam failure): 61,000 cfs RI >200 yrs
- January 11, 2005: 37,000 cfs RI≈52 yrs
- December 21, 2010: 31,000 cfs RI≈39 yrs

The largest flood of record occurred on January 1, 1989 as a direct result of man-made rather than natural causes. Soon after dam construction and reservoir filling, Quail Creek Reservoir Dam, located between the towns of Hurricane and Washington in Utah, failed catastrophically releasing 25,000 acre-feet (~30 million cubic meters) of water directly into the Virgin River and causing a massive flood that reached all the way to Lake Mead (Carlson and Meyer 1995). Since this event, the river recently experienced two large back-to-back floods in 2005 and 2010, both greater than

35-year recurrence-interval events (as measured at the Littlefield gauge), which underscores the rarity of such events occurring so close together.

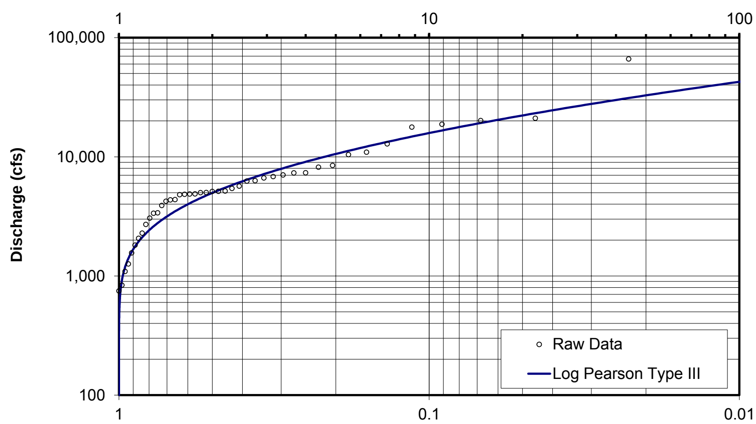
Overall, the Virgin River naturally experiences a wide variation of flows, punctuated episodically by short-duration but intensive flood events. These traits are common to large, dryland riverine systems that periodically experience dramatic geomorphic change resulting from their flashy discharge dynamics (Graf 1988).

a)



Return Period	Discharge (cfs)
1.2	1,800
1.5	2,700
2	3,700
5	6,900
10	9,600
50	17,100
100	21,000
500	31,600
1000	36,900

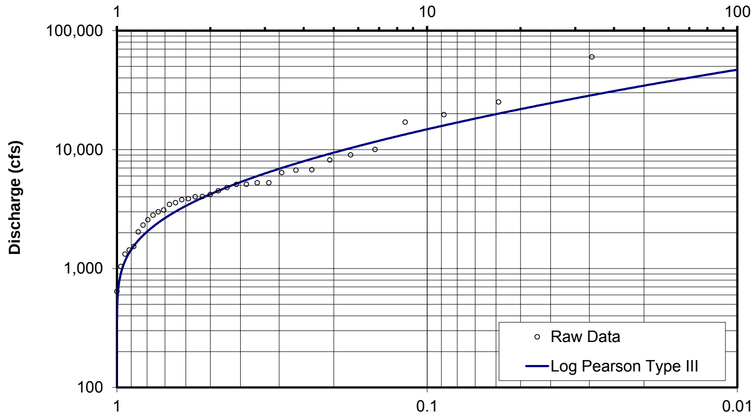
b)



Return Period	Discharge (cfs)
1.2	2,200
1.5	3,400
2	5,000
5	10,600
10	15,800
50	32,800
100	42,600
500	72,500
1000	88,600

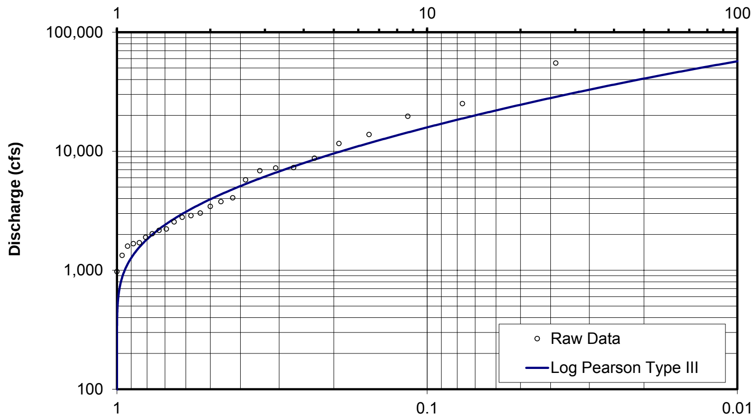
(Figure 4 is continued on the next page.)

c)



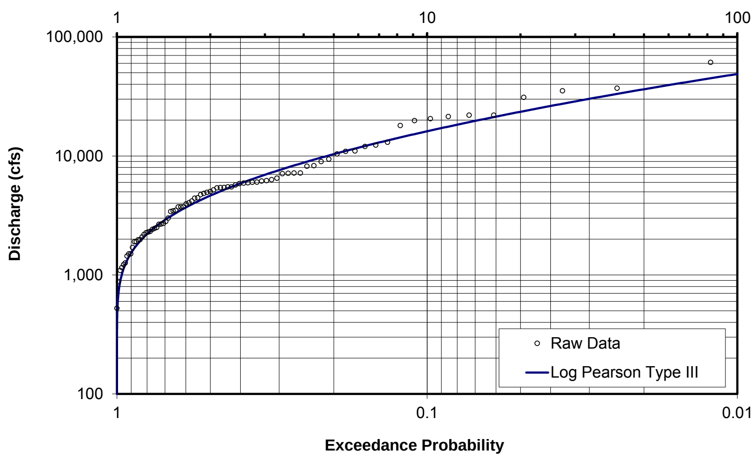
Return Period	Discharge (cfs)
1.2	1,800
1.5	2,900
2	4,200
5	9,400
10	14,800
50	34,500
100	46,900
500	86,300
1000	105,900

d)



Return Period	Discharge (cfs)
1.2	1,600
1.5	2,600
2	3,900
5	9,600
10	15,900
50	40,800
100	57,000
500	102,300
1000	119,400

e)



Return Period	Discharge (cfs)
1.2	2,000
1.5	3,200
2	4,600
5	10,400
10	16,100
50	36,400
100	48,800
500	87,300
1000	106,600

Figure 4. Flood frequency [Log-Pearson III] for the five USGS discharge gauges on the mainstem Virgin River through water year 2011. Gages include (from upstream to downstream): “at Virgin, UT” (a), “near Hurricane, UT” (b), “near Bloomington, UT” (c), “near St. George, UT” (d), and “at Littlefield, AZ” (e).

2.2.1.2 Sub-reach delineation

The hydrogeomorphic character of the river varies widely along the river's length between its origin at the North and South forks near Rockville, UT and its terminus at Lake Mead. Reach-level differences in channel morphology are quite apparent and, accordingly, have strong influence on the types of management and restoration actions that may be suitably applied. For example, the expansive river-floodplain areas in the Virgin Valley between Littlefield, AZ and Lake Mead can provide substantive capacity and accommodate many different types of restoration actions compared with the narrower river reaches upstream of Hurricane, UT. However, as is shown below, it is often these broader reaches of the river corridor where flood-scour has been greatest.

To assist our Ecohydrological Assessment, we sub-divided the mainstem Virgin River into discrete, physically similar reaches based on dominant hydrologic, geomorphic, and geologic characteristics. Reaches were designated in an upstream direction, beginning at Lake Mead, to allow for eventual continued designation farther upstream along the North and/or East forks. Reach locations are shown in Figure 5, and their salient attributes are summarized in Table 2. The following reaches correspond with The Nature Conservancy's (TNC's) broader restoration reaches of interest along the upper river in Utah:

- TNC Lower Reach (near St. George and Washington): 4c and 4d
- TNC Middle Reach (near Washington and Hurricane): 5b, 5c, 6a, and 6b
- TNC Upper Reach (near Virgin and Rockville): 8a, 8b, and 8c

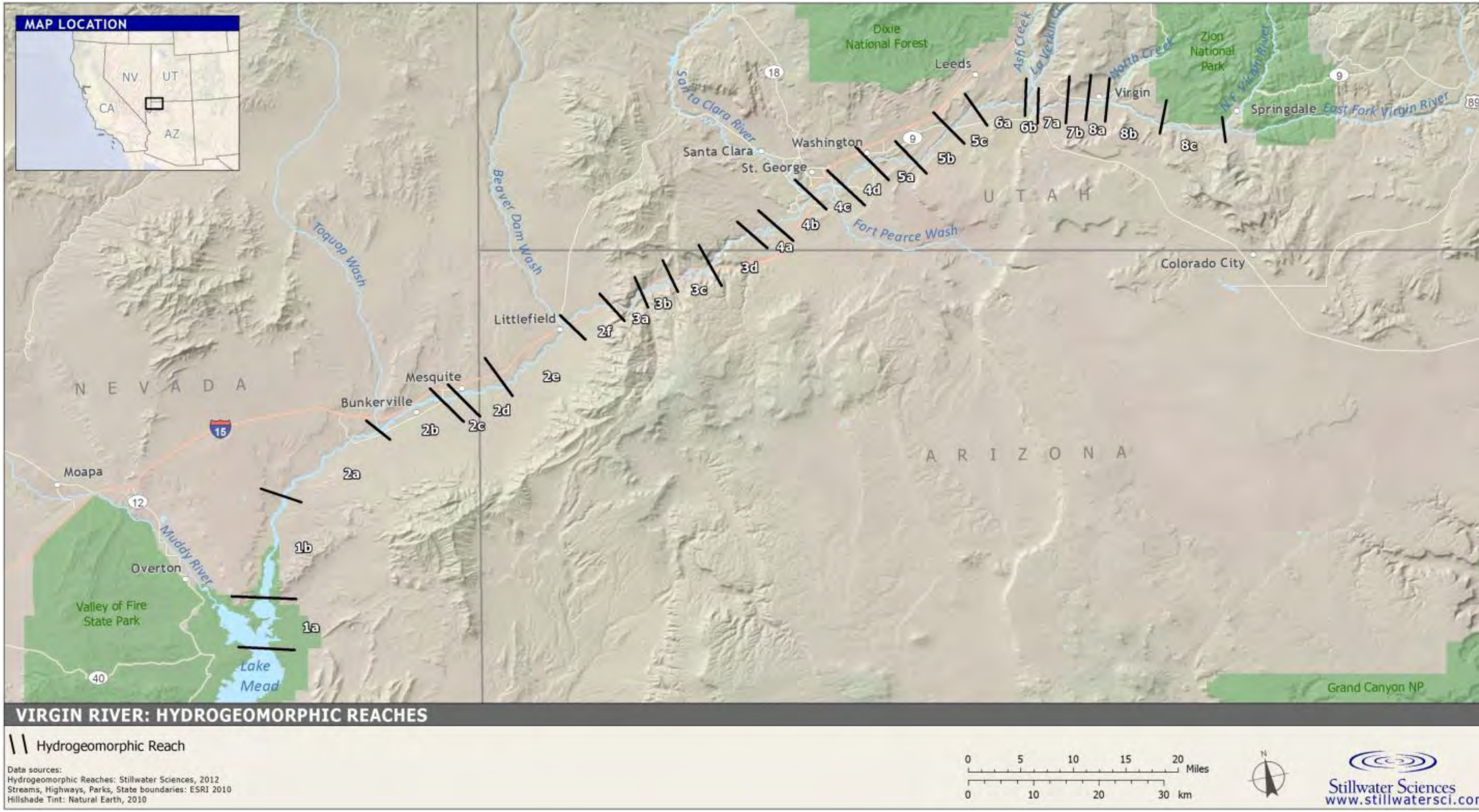


Figure 5. Hydrogeomorphic reaches delineated along the entire mainstem Virgin River for this study. See Table 2 for reach attributes.

Table 2. Hydrogeomorphic reaches of the mainstem Virgin River delineated for this study. See Figure 5 for sub-reach locations.

Reach group	Sub-reach number	Sub-reach name	Sub-reach end features (upstream limit)		River length [A]		Sub-reach description
			RM [A]	Feature [B]	(mi)	(km)	
Lake Mead	0	Overton Arm	26.0	Muddy River confluence	26.0	41.8	Reservoir-drowned, lowermost reach of Virgin River downstream of Muddy River confluence; fed by short washes and alluvial fans from mountain ridges and cliffs on both banks (east and west sides)
Virgin Valley-Mormon Mesa	1a	Mormon Mesa: Lake Mead Backwater	35.5	Black Ridge	9.5	15.3	Alternating broad and constricted, densely vegetated, alluvial, lower floodplain valley below maximum reservoir elevation; fed by Virgin Mountains' (Black Ridge) bajadas on left-bank (east) side and cliffs of Mormon Mesa on right-bank (west) side
	1b	Mormon Mesa	41.5	Halfway Wash	6.0	9.7	Broad, densely vegetated, alluvial, lower floodplain valley above maximum reservoir elevation; fed by Virgin Mountains' bajadas on left-bank (east) side and cliffs of Mormon Mesa on right-bank (west) side
Virgin Valley-Mesquite Basin	2a	Riverside	52.0	Toquop Wash	10.5	16.9	Sinuous valley bottom, alluvial, meandering-braided channel, with some agriculture on floodplain; fed by Virgin Mountains' bajadas on left-bank (south) side and longer, mesa washes on right-bank (north) side
	2b	Bunkerville	58.5	Riverside Road Bridge	6.5	10.5	Broad floodplain valley bottom, alluvial, meandering-braided channel, with dense agriculture and some urban developments on floodplain; fed by Virgin Mountains' bajadas on left-bank (south) side and longer, mesa washes on right-bank (north) side; also fed by urban and agricultural run-off
	2c	Mesquite: Urban Encroachment	60.0	Bunkerville Ditch Diversion Dam	1.5	2.4	Broad floodplain valley bottom with confined alluvial reach by urban encroachment on right bank (north) side from City of Mesquite, with active meander belt bordered by Virgin Mountains' bajadas on left-bank (south) side; also fed by urban and agricultural run-off
	2d	East Mesquite	64.0	East End of Mesquite Valley	4.0	6.4	Broad floodplain valley bottom, alluvial, meandering-braided channel, with some agriculture and some urban developments on right-bank (north side) floodplain, with active meander belt bordered by Virgin Mountains' bajadas on left-bank (south) side; also fed by agricultural run-off
	2e	Littlefield	74.0	Beaver Dam Wash	10.0	16.1	Sinuous valley bottom, alluvial, meandering-braided channel, with some agriculture on floodplain; fed by Virgin Mountains' bajadas on left-bank (south) side and longer, mesa washes on right-bank (north) side; primarily fed by the large Beaver Dam Wash tributary (draining to the south), and urban and agricultural run-off from Littlefield
	2f	East End of Virgin Valley	79.0	West End of The Narrows	5.0	8.0	Sinuous valley bottom, alluvial, meandering-braided channel; fed by Virgin Mountains' bajadas on left-bank (south) side and Beaver Dam Mountains' bajadas on right-bank (north) side
The Narrows	3a	Interstate 15 Confinement	83.5	Sullivans Canyon	4.5	7.2	Confined bedrock gorge reach through Virgin and Beaver Dam mountains, closely bordered by Interstate 15 (Veterns Memorial Highway)
	3b	Black Rock Mountain Meanders	88.0	Grand Wash Fault	4.5	7.2	Sinuous canyon bottom with alluvial channel; fed by steep canyon washes and fans from Black Rock Mountains on left bank (south) side and Beaver Dam Mountains on right bank (north) side
	3c	Yellow Knolls	93.5	Black Rock Gulch	5.5	8.9	Confined, sinuous bedrock gorge with narrow alluvial channel; fed by steep canyon washes, fans, and cliffs from Lime Hills on left bank (south) side and Blakes Lambing Grounds on right bank (north) side
	3d	East End of The Narrows	99.0	West Mountain Valley Wash	5.5	8.9	Confined, bedrock gorge with narrow alluvial channel; fed by steep canyon washes, fans, and cliffs from Starvation Point on left bank (south) side and Blakes Lambing Grounds on right bank (north) side

Reach group	Sub-reach number	Sub-reach name	Sub-reach end features (upstream limit)		River length A		Sub-reach description
			RM A	Feature B	(mi)	(km)	
St. George Basin	4a	Round Valley	103.0	Curly Hollow and Atkinville washes	4.0	6.4	Sinuous valley bottom, alluvial, meandering-braided channel; fed by washes on both banks (north and south sides) at transition of Beaver Dam and Virgin Mountains (The Narrows) and St. George Basin
	4b	Bloomington	107.5	Santa Clara River and Fort Pearce Wash	4.5	7.2	Broad floodplain valley bottom with confined alluvial reach by close, urban levees and/or riprap on both banks; fed by mesa washes and urban run-off; primarily fed by the large Santa Clara River tributary from the north
	4c	St. George Fields	111.0	Middleton Black Ridge	3.5	5.6	Broad floodplain valley bottom, alluvial, meandering-braided channel partially confined by setback urban levees and/or riprap on both banks; fed by mesa washes and urban run-off
	4d	Washington Fields	114.5	Mill Creek and S 300 E Road Bridge	3.5	5.6	Broad floodplain valley bottom, alluvial, meandering-braided channel partially confined by setback urban levees and/or riprap on both banks; fed by mesa washes and urban and agricultural run-off
Washington-Harrisburg Dome	5a	Shinob Kibe	119.0	Washington Fields Diversion Dam	4.5	7.2	Confined bedrock canyon with narrow, alluvial floodplain, meandering-braided channel, with some agriculture and urban development; fed by mesa washes and agricultural run-off
	5b	Quail Creek-Sand Hollow Reservoirs	123.0	Quail Creek Reservoir Overflow	4.0	6.4	Confined bedrock canyon with very narrow, straight, alluvial channel with minimal natural floodplain, with some agriculture and urban development on terrace and dome-mesa; fed by mesa cliffs and washes, and agricultural run-off; impacted by 1989 Dam Failure of Quail Creek Reservoir
	5c	Quail Creek Historic	126.5	East Reef	3.5	5.6	Confined bedrock canyon with narrow, alluvial floodplain, meandering-braided channel, with aggregate mining and some agriculture on floodplain; fed by mesa cliffs and washes, and agricultural run-off
Hurricane Bench	6a	Sandstone Mountain	133.0	La Verkin and Ash Creeks	6.5	10.5	Sinuous canyon bottom with alluvial channel; fed by steep canyon cliffs, fans, and washes from Hurricane Bench and Fields on left bank (south) side and Sandstone Mountain on right bank (north) side; primarily fed by the large La Verkin Creek and Ash Creek tributaries (draining to the south), and some urban and agricultural run-off from Hurricane
	6b	Hurricane Fields	134.5	Hurricane Fault	1.5	2.4	Sinuous canyon bottom with alluvial channel; fed by steep canyon cliffs, fans, and washes from Hurricane Bench and Fields on left bank (south) side and La Verkin Bench on right bank (north) side; also fed by urban and agricultural run-off from Hurricane and La Verkin
Hurricane Cliffs and Mesa	7a	Pah Tempe Springs	137.5	Quail Creek Diversion Dam	3.0	4.8	Confined, bedrock gorge with narrow, coarse channel; fed by steep canyon washes, fans, and cliffs from mesa on both banks (north and south sides); also flow regulated by Quail Creek Diversion Dam
	7b	Quail Creek Diversion Dam Impoundment	139.5	West End of Virgin	2.0	3.2	Confined, bedrock gorge with narrow, coarse channel; fed by steep canyon washes, fans, and cliffs from mesa on both banks (north and south sides); flow impounded by Quail Creek Diversion Dam
Upper Virgin Valley	8a	Virgin	142.0	North Creek	2.5	4.0	Confined bedrock canyon with narrow, alluvial floodplain, meandering-braided channel, with agriculture and urban development on right-bank (north side) floodplain; fed by mesa washes and agricultural run-off; primarily fed from North Creek (draining to the south)
	8b	Gooseberry Mesa	148.0	Grafton Wash	6.0	9.7	Confined, sinuous bedrock canyon with alluvial floodplain, meandering-braided channel, with agriculture on both banks and Highway 9 on right-bank (northeast) side; fed by mesa washes and agricultural run-off
	8c	Rockville	154.0	North and South Forks Confluence	6.0	9.7	Confined, sinuous bedrock canyon with alluvial floodplain, meandering-braided channel, with agriculture on both banks and City of Rockville and Highway 9 on right-bank (north) side; fed by mesa washes and agricultural run-off; primarily fed by North and South Forks of the Virgin River via Zion National Park

[A] River miles (RM) based on system displayed on USGS topographical quadrangle maps for majority of the Virgin River; intermediate RM stations were interpolated between those displayed on quadrangle maps in a GIS.
[B] Names of physical features from USGS topographical quadrangle maps.

2.2.2 Aerial imagery analysis

Historical aerial imagery was utilized in a geographic information system (GIS) to delineate areas of flood disturbance for selected historical floods along the mainstem Virgin River. For the entire length of river, three of the most recent, large flood events were selected: 1989, 2005, and 2010. As discussed above, the 1989 flood was not a natural hydrological event, but was still considered here because of its lasting effect on the river corridor. Two additional flood events in 1955 and 1966/69 were selected for the TNC reaches in Utah: Reaches 4c, 4d, 5b, 5c, 6a, 8a, 8b, and 8c. Many aspects of this analysis were modeled on similar work done by Graf (2000), Tiegs et al. (2005), and Tiegs and Pohl (2005). Details of the methods employed here and the mapping products are presented in Appendix B.

For purposes of aerial-photographic interpretation, the flood-scour areas were defined as follows:

High disturbance: These areas were characterized by distinct channel and floodplain areas severely disturbed by flow (i.e., scoured to bare substrate), typically with 10% or less apparent remaining riparian vegetative cover.

Medium disturbance: These areas were characterized by distinct areas of low to moderate apparent disturbance by flow, typically defined as areas with more than 10% but less than 80% apparent riparian vegetative cover.

Low disturbance (riparian vegetation): These areas were characterized by distinct zones of apparently natural riparian vegetation with little to no apparent disturbance by flood, typically containing more than 80% riparian vegetation.

All flood-scour areas were then classified as being either within or outside of the "active channel," with the active channel defined as areas of medium to high disturbance. Areas of riparian or non-riparian vegetation with no apparent disturbance were excluded.

2.2.3 Results of flood-scour analysis

The results of our flood-scour analysis are presented graphically in two sets of maps: "Width of active channel in successive floods" and "Frequency of active channel position" (see Appendix B). The first set of maps represents the active-channel areas during the 1983, 1993, and 2005 flood events. The second set of maps highlight those channel areas most frequently disturbed by repeat flood events.

As a predominantly braided but dryland river, the mainstem channel of the Virgin River largely comprises a primary low-flow channel and various short-lived secondary channels. The flood-scour analysis performed here reveals that the low-flow channel boundary changes rapidly and completely during flood events according to the magnitude of the event and other factors, whereas the boundary of the larger mainstem channel changes less frequently.

The "Flood Reset Zone" was then identified to partially inform restoration area suitability as part of the Ecohydrological Assessment—suitable restoration areas are considered to be found safely outside of the Flood Reset Zone. This zone includes areas having both >33% flood-scour frequency (i.e., scoured in 2 out of the 3 mapped events [1989, 2005, and 2010]) *and* "high" flood-disturbance activity—areas severely disturbed by flow, typically scoured to bar substrate retaining <10% apparent riparian vegetation cover—during the most recent flood of 2010. The apparent trajectory of the active channel's position was also considered (i.e., lateral-migration direction).

The maps presented in Appendix B are meant to guide restoration planning and implementation at multiple scales, ranging from restoration strategy development at the full river corridor and reach levels to site-specific restoration design and implementation. However, the maps are only one tool and need to be combined with a variety of other information to develop the most effective and efficient strategies and designs for riparian restoration, such as riparian vegetation classification (see below). In particular, more detailed field-based information and geomorphic interpretation may be warranted to refine the fine-scale delineation of the Flood Reset Zone and predictions of likely future flood paths when designing and implementing site-specific plans for invasive species removal and revegetation of native riparian species.

2.3 Vegetation Characterization

Riparian vegetation composition and distribution patterns were characterized along the Virgin River based on a combination of remote sensing and field-based surveys and mapping. The primary goal of the vegetation characterization was to inform the selection of suitable restoration areas by providing an understanding of the physical conditions that do, or could, support the establishment and growth of native riparian trees and shrubs.

2.3.1 Remote sensing and pixel-based classification

Dominant native and non-native, invasive vegetation types were classified by USU RS/GIS using their November 2011 multispectral orthoimagery[3]. This process entailed interpreting the unique pixel values contained in the multispectral imagery to assign the following classes (see Appendix A for more details of this process):

- Defoliated tamarisk
- Tamarisk
- Cottonwood, willow, ash
- Agriculture
- Wetland and aquatic vegetation
- Sand/soil
- Soil
- Upland vegetation
- Water
- Shadow (typically from tall trees or canyon walls)

USU RS/GIS also attempted to delineate a "Russian olive" class along the upper river near Virgin and Rockville, UT, but ultimately this class was assigned manually based on discrete field observations rather than from interpretation of the multispectral imagery. Therefore, occurrences of Russian olive in the USU RS/GIS mapping products are incomplete and do not capture the full extent of this species along the river (although field-based mapping provided a more

[3] Classification of vegetation in the Virgin River Gorge, which roughly runs between Littlefield, AZ and Bloomington, UT, has not been completed.

comprehensive inventory of Russian olive and other vegetation types in three focal reaches in Utah; see Section 2.3.2).

Figure 7 presents an index to the vegetation-classification maps that are presented in Figure 8.1–8.23 (a, b). The individual maps are grouped by location, and presented in downstream to upstream order beginning in Reach 1 near Lake Mead. In reviewing these maps, several general patterns emerge:

- native riparian vegetation dominated by cottonwood and willow (and occasionally velvet ash) is relatively common in the upper river (Utah), although non-native, invasive species (Russian olive and tamarisk) are often dominant or co-dominant;
- the middle river (Arizona) tends to be dominated by tamarisk, although smaller patches of native vegetation still persist; while
- the lower river (Nevada) is more strongly dominated by dense, nearly mono-specific stands of tamarisk.

2.3.2 Refined vegetation mapping in Utah reaches

TNC provided supplemental funding for more detailed vegetation classification and mapping and more in-depth flood-scour mapping (see Section 2.2.1.2) along three reaches of the upper Virgin River in Utah, which are the focus of TNC conservation and restoration planning efforts:

- TNC Lower Reach: (approximately 7 river miles near St. George and Washington)
- TNC Middle Reach (approximately 15.5 river miles near Washington and Hurricane)
- TNC Upper Reach (approximately 14.5 river miles near Virgin and Rockville)

The TNC Lower Reach extends from the Interstate 15 bridge and Santa Clara River confluence upstream to the South Washington Fields Road bridge. This reach contains critical habitat for the endangered southwestern willow flycatcher. Vegetation mapping was conducted along the full length of this reach.

The TNC Middle Reach extends from the Washington Field Diversion upstream to Quail Creek Diversion (just above Pah Tempe Hot Springs), and provides important habitat for two endangered fish species, the woundfin and Virgin River chub. Vegetation mapping in this reach was focused on the broader alluvial floodplain areas that were more accessible and appeared to have more revegetation/restoration potential than the more confined canyon areas that tend to be more thoroughly reset (scoured) during flood events.

The TNC Upper Reach extends from the eastern edge of the town of Virgin upstream to the confluence with the North Fork and East Fork (east of the town of Rockville). This reach provides valuable habitat for native fish, including the Virgin spinedace, flannelmouth sucker, desert sucker, and speckled dace. Vegetation mapping was conducted along the full length of this reach.

2.3.2.1 Classification and Mapping Methods

The nature of the Virgin River system poses a number of challenges to riparian vegetation mapping. Like the river itself, vegetation in the corridor is dynamic, exhibiting dramatic fluctuations in extent and composition in response to large flood events, such as the December 2010 flood (as previously described in Section 2.2.1.1). Significant areas of riparian vegetation within the active channel were removed by the floods, dramatically altering the character and pattern of vegetation within the study area, particularly in the lower and middle TNC reaches (and much of the lower river in Arizona and Nevada). In addition, the tamarisk leaf beetle now occurs throughout the river corridor and is likely to result in substantial mortality of tamarisk, thereby leading to pronounced changes in vegetation composition and structure. The complex and dynamic nature of vegetation communities present within the Virgin River corridor required modifications to traditional approaches for vegetation mapping; thus, this project utilized a combination of field-based vegetation classification and mapping, and traditional photo-interpretive techniques, as described below. The vegetation classification approach follows the U.S. National Vegetation Classification (NVC) system (http://usnvc.org/), with most vegetation types classified and mapped at the NVC alliance level. In some cases we used mapping unit types, such as floodplain wetland and riverwash (herbaceous), that are not part of the NVC system and may include one or more NVC vegetation alliances. For readers unfamiliar with species' scientific names and/or NVC classification terminology, in the text below we also provide a common name equivalent for each vegetation type listed.

Vegetation classification and mapping efforts were focused on capturing conditions that existed 1–2 years after the December 2010 flood event. Initial field surveys were conducted June–August 2012, with supplemental surveys in August–September 2013, and final roadside and binocular verification surveys in February 2014. Imagery used for the surveys included the November 2011 natural color and multispectral orthoimagery developed by USU RS/GIS, supplemented by natural color imagery available on Google Earth, and the pixel-based vegetation classification developed by USU RS/GIS. The vegetation types and mapping units used in the Zion National Park Vegetation Mapping Project (BOR 2004) were also reviewed to help interpret vegetation types in the upper reach.

Based upon the available imagery and the results of initial field reconnaissance, a minimum mapping unit (MMU) to be applied in both field-based and photo-interpretation efforts for each vegetation type was derived. The desired target was a 1-acre MMU for most types, with finer resolution (0.50-acre MMU) for more unusual types that were discernable from the aerial photography. A coarser resolution (5-acre MMU) was generally used for cover types such as agriculture and development.

Field crews utilized high-resolution maps (11x17 inches, color printed at 600 dpi, 1:4000 scale) with mylar overlays to document the boundaries of stands of vegetation observed in the field. To create the digital vegetation map data set, the mylar overlays were scanned at 600 dpi and georeferenced in GIS to the November 2011 orthoimagery. The scanned and georeferenced field delineated stands, or mapping units, were then digitized using a polygon representation, with additional on-screen editing conducted as needed to refine the polygon coverage. Features were generally delineated at a scale of 1:4,000.

For areas of riparian vegetation that were inaccessible to field crews during the field mapping effort, and for extensive areas of upland land cover within the floodplain, on-screen photo interpretation was conducted using the November 2011 orthoimagery and Google Earth imagery (primarily 2011 and 2013). A field-experienced photo interpreter delineated and classified each identifiable vegetation stand or land cover area using the MMUs discussed above.

The 541 mapped polygons were then attributed with the following information:

- **Vegetation type (or other cover type):** using the types listed in Table 3

- **Assessment Method:** field (assessed from within or at boundary of the polygon), binocular (remotely assessed from roads and overlooks using binoculars), or office (assessed using USU RS/GIS or Google Earth digital imagery)
- **Total Vegetative Cover:** total amount of vegetative cover (by cover class), generally derived from aerial imagery and confirmed/supplemented by field observations where feasible. Six cover classes were used: <1%, 1 to <5%, 5 to <15%, 15 to <33%, 33 to <67%, and 67–100% absolute cover.
- **Percent Cover of Target Invasive Species:** the abundance (by cover class) of each of the three main target non-native, invasive species—tamarisk, Russian olive, and giant reed—was estimated for each polygon, generally derived from aerial imagery and confirmed/supplemented by field observations where feasible. In addition, the cover class of a fourth target invasive species, perennial pepperweed (*Lepidium latifolium*), was recorded if it was observed in field assessed polygons (this species was not detectable via binoculars or remote sensing).
- **Notes:** miscellaneous notes on dominant or characteristic native and non-native plant species present, and other site characteristics

The principal investigator reviewed draft versions of the classification and digital vegetation map to ensure consistency in stand delineation and classification within the study area. Mapping unit boundaries were revised in some cases to better match the November 2011 orthoimagery base map and ensure consistency with the final classification scheme presented in this report. This effort was necessary to ensure that the final vegetation map (GIS coverage) represents an accurate "snapshot" of the dynamic vegetation mosaic in the first few years following the December 2010 flood. This product, therefore, will provide a good foundation for detecting future changes in riparian vegetation in the study area.

Although a formal accuracy assessment was not conducted due to limited resources, the extensive field-based nature of this effort has been used to the greatest extent possible to provide a highly accurate vegetation map of the study area.

2.3.2.2 Vegetation types and distribution patterns

The detailed vegetation map of the TNC reaches, which presents the 35 mapping units documented during field-based and photo-interpreted mapping (including vegetation alliances and associations, and other land use and land cover types), is included in the GIS files delivered to TNC. The abundance (in acres) and distribution (by reach) of these mapping units is summarized in Table 3. A more generalized version of the vegetation map, with the vegetation alliances, associations, and more detailed cover types aggregated into vegetation/cover types (as shown in Table 3), is provided in Appendix C.

Table 3. Vegetation and other cover types in the three TNC conservation reaches along the upper Virgin River, Utah.

Vegetation/Cover type	Vegetation alliance/Detailed cover type	Area (acres)			
		Upper Reach	Middle Reach	Lower Reach	Total
Tree-dominated Vegetation					
Native Woodland	*Populus fremontii - Fraxinus velutina* Woodland	3.9	0.5	5.4	9.8
	Populus fremontii - Salix gooddingii Woodland	0	0	1.5	1.5
	Populus fremontii Woodland Complex	99.3	3.4	9.3	112.0
	TOTAL	103.2	3.9	16.2	123.3
Mixed Native and Invasive Woodland	*Populus fremontii - Fraxinus velutina/ Tamarix* Woodland-Wetland complex	0	0	26.4	26.4
	Populus fremontii- (Salix gooddingii) - Eleagnus angustifolia Woodland	324.5	12.1	11.8	348.4
	Populus fremontii- (Salix gooddingii)/ Tamarix Woodland	52.3	94.0	79.4	225.7
	Populus fremontii/ Tamarix Woodland-Wetland Complex	0	3.5	8.6	12.1
	Salix gooddingii/ Salix exigua-Tamarix Woodland-Wetland Complex	0	0	11.2	11.2
	TOTAL	376.8	109.6	137.4	623.8
Invasive Woodland	*Ailanthus altissima* Semi-natural Stand	0.9	0	0	0.9
	Eleagnus angustifolia Semi-natural Woodland	28.9	0	0	28.9
	Eleagnus angustifolia/Tamarix Semi-natural Woodland	16.1	0	0	16.1
	TOTAL	45.9	0	0	45.9

Vegetation/Cover type	Vegetation alliance/Detailed cover type	Area (acres)			
		Upper Reach	Middle Reach	Lower Reach	Total
Shrub-dominated Vegetation					
Native Shrubland	*Artemisia filifolia* Shrubland	8.1	0	0	8.1
	Atriplex lentiformis Shrubland	0	0	10.1	10.1
	Ericameria nauseosa Shrubland Complex	62.5	14.5	0.6	77.6
	Mixed Native Riparian Scrub	0	24.6	0	24.6
	Pluchea sericea Shrubland	0.3	0	0.7	1.0
	Prosopis glandulosa Shrub land	0	21.3	4.2	25.5
	Salix exigua Shrubland	0.9	14.5	26.0	41.4
	TOTAL	71.8	74.9	41.6	188.3
Mixed Native-Invasive Shrubland	*Salix exigua-Tamarix* Mixed Scrub	0	59.5	65.7	125.2
	TOTAL	0	59.5	65.7	125.2
Invasive and Disturbed Shrubland	*Tamarix* Semi-natural Shrubland	42.8	167.6	236.0	446.4
	Disturbed Scrub	37.2	24.6	21.6	83.4
	TOTAL	80.0	192.2	257.6	529.8
Herbaceous Vegetation and Sparsely Vegetated Floodplain and Riverwash					
Herbaceous Vegetation	Floodplain Wetland	0	4.1	22.7	26.8
	Disturbed Grassland	4.2	0	0	4.2
	TOTAL	4.2	4.1	22.7	31.0
Sparsely Vegetated Floodplain and Riverwash	Floodplain Herbaceous	0	0	1.3	1.3
	Floodplain Scrub	28.4	10.4	128.4	167.2
	Riverwash (Herbaceous)	0.9	10.4	72.2	83.5
	Riverwash (Bare)	3.6	9.8	19.4	32.8
	TOTAL	37.1	34.7	244.0	315.8
Other Cover Types					
Agriculture	Agriculture (croplands and pasture)	470.0	30.4	2.2	502.6
	Agriculture (orchards, groves, vineyards)	7.9	0	0	7.9
	Old Field (fallow field, old agricultural field)	21.9	20.5	0	42.4
	TOTAL	499.8	50.9	2.2	552.9
Disturbed/Developed	Developed (mixed urban, residential, roads)	113.8	4.1	0	117.8
	Disturbed (graded, dirt roads, etc)	22.9	6.5	16.8	46.2
	Quarries and Gravel Pits	0	79.7	0	79.7
	TOTAL	136.7	90.3	16.8	243.7

Vegetation/Cover type	Vegetation alliance/Detailed cover type	Area (acres)			
		Upper Reach	Middle Reach	Lower Reach	Total
Water	Water (river)	188.6	68.6	0	257.2
	Water (stock ponds, reservoirs)	25.8	17.4	2.6	45.8
	TOTAL	214.4	86.0	2.6	303.0
GRAND TOTAL		***1570***	***707***	***807***	***3084***

Tree-dominated Vegetation

Native Woodland—this vegetation type includes stands of open to dense native woodlands with tree canopy greater than 10%, typically dominated by Fremont cottonwood (*Populus fremontii*). These stands usually contain a sparse to dense shrub understory, dominated mainly by native species but may include some tamarisk. Ground cover is often sparse, especially in dense woodlands, but can be well developed in more open stands. The native woodland vegetation type represents about 4% of the total mapping area, and is best developed in the upper reach where it comprises just under 7% of the total area mapped (Table 3).

Three alliances or potential associations were recognized in the native woodland vegetation type:

- *Populus fremontii* Woodland Complex (Fremont Cottonwood Woodland Complex)—stands with a tree canopy dominated by Fremont cottonwood
- *Populus fremontii–Fraxinus velutina* Woodland (Fremont Cottonwood–Velvet Ash Woodland)—stands with a tree canopy co-dominated by Fremont cottonwood and velvet ash.
- *Populus fremontii–Salix gooddingii* Woodland (Fremont Cottonwood–Goodding's Willow Woodland)—stands with a tree canopy co-dominated by Fremont cottonwood and velvet ash.

Mixed Native and Invasive Non-native Woodland—this vegetation type includes stands with tree canopy greater than 10%, dominated by native trees, mainly Fremont cottonwood but with Goodding's willow or velvet ash sometimes present, or co-dominated by native trees and non-native, invasive Russian olive. The shrub layer is typically dominated or co-dominated by tamarisk. Understory conditions are variable. In some cases, trees and shrubs are interspersed with wetlands containing a mix of open water and aquatic or emergent wetland vegetation. This vegetation type covers approximately 624 acres, or 20% of the mapped area, and is most common in the upper reach where it covers 24% of the mapped area (Table 3).

Five alliances or potential associations were recognized in the mixed native and invasive non-native woodland vegetation type:

- *Populus fremontii–Fraxinus velutina/Tamarix* spp. Woodland-Wetland Complex (Fremont Cottonwood–Velvet Ash/Tamarisk Woodland-Wetland Complex)—stands with a tree canopy co-dominated by Fremont cottonwood and velvet ash, with tamarisk dominant in the shrub layer, and wetlands interspersed throughout the mapped stand.
- *Populus fremontii (Salix gooddingii)–Eleagnus angustifolia* Woodland (Fremont Cottonwood (Goodding's Willow)–Russian Olive Woodland)—stands with a tree canopy co-dominated by Fremont cottonwood and Russian olive. Goodding's willow is sometimes present as a co-dominant in the tree layer. Shrub and understory layers are variable.

- *Populus fremontii (Salix gooddingii)/Tamarix* spp. Woodland (Fremont Cottonwood (Goodding's Willow)/Tamarisk Woodland)—stands with a tree canopy dominated by Fremont cottonwood, with Goodding's willow sometimes present as a co-dominant, and tamarisk dominant in the shrub layer. The understory layer is variable.
- *Populus fremontii/Tamarix* spp. Woodland-Wetland Complex (Fremont Cottonwood/Tamarisk Woodland-Wetland Complex)—stands with a tree canopy dominated by Fremont cottonwood, with tamarisk dominant in the shrub layer, and wetlands interspersed throughout the mapped stand.
- *Salix gooddingii/Salix exigua–Tamarix* spp. Woodland-Wetland Complex (Goodding's Willow/Narrowleaf Willow–Tamarisk Woodland-Wetland Complex)—stands with a tree canopy dominated by Goodding's willow, with narrowleaf willow (*Salix exigua*) (also known as coyote willow) and tamarisk co-dominant in the shrub layer, and wetlands interspersed throughout the mapped stand.

Invasive Woodland—this vegetation type includes woodland stands dominated by non-native, invasive trees. These are primarily Russian olive but two small stands of tree of heaven (*Ailanthus altissima*) were also mapped in the upper reach. Tamarisk is sometimes dominant in the shrub layer. This vegetation type was only mapped in the upper reach, where it covers 46 acres, or 3% of the total area mapped (Table 3).

Three semi-natural woodland stand types (the non-native equivalent of alliances) were recognized in the invasive woodland vegetation type:

- *Ailanthus altissima* Semi-natural Stand (Tree of Heaven Semi-natural Stand)—two small stands dominated by tree of heaven were mapped along Utah State Highway 9 near the upstream end of the upper reach.
- *Eleagnus angustifolia* Semi-natural Stand (Russian Olive Semi-natural Stand)—stands with Russian olive dominant in the tree canopy. This type most often occurs in narrow, linear strips along the river banks.
- *Eleagnus angustifolia/Tamarix* spp. Semi-natural Stand (Russian Olive/Tamarisk Semi-natural Stand)—stands with Russian olive dominant in the tree canopy and tamarisk dominant in the shrub layer. This type often occurs in narrow, linear strips along the river banks, or in broader patches on point bars.

Shrub-dominated Vegetation

Native Shrubland—this vegetation type includes stands dominated by a variety of native shrub species. Tamarisk may be present, but is not co-dominant. Shrub canopy cover in this vegetation type varies from 20 to almost 100%. A few scattered emergent trees may be present, but total tree canopy is less than 10%, and usually well under 5%. The understory is variable. Native shrublands are scattered throughout the three reaches and cover a total of 188 acres (about 6% of the total area mapped) (Table 3).

The native shrubland vegetation type contains seven groups, alliances, or potential associations:

- *Artemisia filifolia* Shrubland (Sand Sagebrush Shrubland)—a few small stands in the upper reach dominated by sand sagebrush (*Artemisia filifolia*).
- *Atriplex lentiformis* Shrubland (Big Saltbush Shrubland)—a few stands in the lower reach dominated by big saltbush (*Atriplex lentiformis*).
- *Ericameria nauseosa* Shrubland Complex (Rabbitbrush Shrubland Complex)—shrubland stands, mainly in the upper and middle reaches, that contain rabbitbrush (*Ericameria*

nauseosa) and various other native shrubs. This type is often found along disturbed roadsides and other disturbed areas.

- Mixed Native Riparian Scrub—stands dominated by a diverse mix of native shrubs, found in the middle reach. These stands typically have a noticeable amount of bare riverwash (sands and gravels) in between shrubs, and are generally found in locations likely to experience at least modest amounts of scour or deposition during high flows. Of particular botanical interest is the occurrence of species such as desert willow (*Chilopsis linearis*) that were not recorded elsewhere in the mapping area.
- *Pluchea sericea* Shrubland (Arrowweed Shrubland)—a few small stands in the lower and upper reaches dominated by arrowweed (*Pluchea sericea*). This species is often present in variable amounts in other vegetation types, but rarely occurs in monospecific stands large enough to map.
- *Prosopis glandulosa* Shrubland (Honey Mesquite Shrubland)—stands dominated or co-dominated by honey mesquite (*Prosopis glandulosa*). This type was most common in the middle reach, but also occurs in the lower reach.
- *Salix exigua* Shrubland (Narrowleaf Willow Shrubland)—small stands dominated by narrowleaf willow, typically on point bar surfaces and other areas affected by scour and deposition during high flow events. This type was found in all three reaches, but is more common in the middle and lower reaches.

Mixed Native and Invasive Shrubland—this vegetation type includes stands co-dominated by native (mainly willows) and non-native, invasive (mainly tamarisk) shrubs. Shrub canopy cover in this vegetation type varies from 20 to 75%. A few scattered emergent trees may be present, but total tree canopy is less than 10%, and usually well under 5%. The understory is variable, but patches of bare riverwash (sand or gravel) are typically present in the stand. This vegetation type was only mapped in the middle and lower reaches (Table 3), but some very small stands (below the MMU) may also occur in the upper reach.

Only one alliance was recognized in this vegetation type:

- *Salix exigua–Tamarix* spp. Mixed Scrub (Narrowleaf Willow–Tamarisk Mixed Scrub)—stands co-dominated by narrowleaf willow and tamarisk. This type typically occurs on point bar surfaces and other areas affected by scour and deposition during high flow events.

Invasive and Disturbed Shrubland—this vegetation type includes stands dominated by non-native, invasive shrubs (mainly tamarisk) or showing high levels of disturbance and sparse shrub cover. A few scattered trees may occur, but at very low cover. This vegetation type occurs in all three reaches and covers a total of 530 acres, or 17% of the total area mapped. It is particularly common in the lower reach where it covers 32% (258 acres) of the mapped riparian corridor (Table 3).

One semi-natural stand type was recognized in the invasive and disturbed shrubland vegetation type:

- *Tamarix* spp. Semi-natural Shrubland (Tamarisk Semi-natural Shrubland)—shrub stands dominated by tamarisk. A few scattered native shrubs may be present, but these stands often have very dense, nearly monospecific cover of tamarisk.

Herbaceous and Sparsely Vegetated Floodplain and Riverwash

Herbaceous Vegetation—this relatively uncommon vegetation type (only 31 acres mapped in the three reaches) includes stands dominated by herbaceous species that met the MMU.

Two vegetation groups were recognized in the herbaceous vegetation type:

- Floodplain Wetland—wetlands occurring in the floodplain that support a mix of open water, aquatic and emergent vegetation. Cattails (*Typha* spp.) and common reed (*Phragmites australis*) are common emergent marsh species along the river. This group was most common in the lower reach, but was also mapped in the middle reach. Smaller, more ephemeral patches of floodplain wetland (below the MMU of 0.5 acres) may occur elsewhere in the study area in wet low-lying areas within the flood reset zone.
- Disturbed Grassland—a few patches of grassland, generally dominated by non-native species (e.g., *Bromus* spp.), were mapped in the upper reach in disturbed areas near Utah State Highway 9.

Sparsely Vegetated Floodplain and Riverwash—this vegetation type includes mapping units with generally less than 10% total vegetative cover, that are typically in areas likely to be reset by high flow events. It occurs in all three reaches (316 acres), but is most abundant in the lower reach where it covers 30% of the mapped riparian corridor (244 acres) (Table 3).

Sparsely vegetation floodplain and riverwash includes four cover types:

- Floodplain Herbaceous—areas dominated by riverwash (sands or gravels) with some scattered herbaceous vegetation, typically sweetclover (*Melilotus* spp.). This type was only mapped in small amounts in the upper reach, but this may be an under-representation since it could only be mapped based on field survey observations.
- Floodplain Scrub—areas dominated by riverwash, but with some scattered shrubs or small patches of shrubs within the larger riverwash matrix. This type occurs in all three reaches, but is most common in the lower reach.
- Riverwash (Herbaceous)—low-lying areas of moist riverwash. Field observations indicated that these areas often support variable amounts of herbaceous vegetation, such as various grasses and rushes (*Juncus* spp.). This type occurs in all three reaches, but is most common in the lower reach.
- Riverwash (Bare)—patches of bare riverwash, typically found in drier and at higher relative elevations than the moister Riverwash (Herbaceous) cover type. This type occurs in all three reaches

Other Cover Types

Agriculture—this cover type includes areas currently being used for agriculture (croplands, pasture, orchards) or previously used for agriculture (fallow fields, old fields). This type occurs in all three reaches, but is most common in the upper reach (Table 2). This cover type includes:

- Agriculture (croplands and pasture)—areas which appeared to be in current or recent use as cropland or pasture, often with signs of irrigation. This type was mapped in all three reaches, but the greatest extent within the mapped corridor was in the upper reach.
- Agriculture (orchards, groves, and vineyards)—this type was only mapped in the upper reach, and included a commercial apple orchard.
- Old Field (fallow field, old agricultural field)—areas within the mapping corridor that had clearly been used for agriculture in the recent past, but that appeared to be fallow or undergoing secondary old field succession based on aerial imagery or field observations.

Disturbed/Developed—this cover type includes lands developed for residential or industrial use, roads, graded areas, quarries, and gravel pits. It was mapped in all three reaches (Table 3) and includes:

- Developed (mixed urban, residential, roads)—areas clearly developed for residential or commercial use, including roads.
- Disturbed (graded, dirt roads, etc.)—any mappable areas with bare surfaces created by or clearly associated with human land use.
- Quarries and Gravel Pits—areas developed as quarries or for gravel extraction.

Water—this cover type includes:

- Water (River)—the main river channel and any side channels with surface water present and visible in the aerial imagery.
- Water (Stock Ponds, Reservoirs)—stock ponds and small reservoirs within the mapping corridor that were visible in the aerial imagery.

2.3.2.3 Implications for Conservation and Restoration

The results of the vegetation classification and mapping effort can assist in developing conservation and restoration plans in the three TNC reaches and, in particular, have implications for developing strategies and priorities for control of the following invasive species that were observed:

- Giant reed currently occurs only as small isolated patches. It is most common in the middle reach, but it was mapped in all three reaches (1 observation in the upper, 15 in the middle, and 7 in the lower). Rapid, focused action to eradicate giant reed along the river corridor should be a high priority to eliminate this invasive species before it has the chance to become further established.
- Russian olive is well established in the upper reach, but also occurs to a more limited extent in the middle and lower reaches. Efforts to control this species upstream in Zion National Park have been successful, and efforts to remove or control this species in portions of the upper reach are currently underway. Focused efforts to remove this species in the middle and lower reaches may also be warranted, especially given the concern that Russian olive may expand as tamarisk abundance decreases over the next few years due to mortality caused by the tamarisk leaf beetle.
- Tamarisk occurs throughout the river corridor, but is especially dominant in the downstream reaches. Continued efforts to re-establish native woody species in the lower reach, in appropriate locations, warrants high priority to maintain or enhance SWFL habitat as tamarisk defoliation by the tamarisk leaf beetle continues.
- Two small stands of tree of heaven occur on private property next to Utah State Highway 9 in the upper reach. While there was no evidence of this species becoming naturalized within the active floodplain, it is recommended that tree of heaven be put on a watch list for future monitoring and action if it starts to invade.
- Perennial pepperweed was found during field surveys, generally in small patches that would be suitable for control or eradication (it was observed in one polygon the upper reach, none in the middle reach, and in 10 polygons in the lower reach). When site-specific restoration or other vegetation management actions are planned, this species should be considered as a high priority for control or, ideally, eradication.

2.4 Identification of Potentially Suitable Restoration Areas

Areas within the river's riparian corridor were evaluated for their apparent suitability to support active riparian restoration and directly benefit SWFL habitat. This process drew upon the results of the flood-scour and vegetation characterization efforts described above, in addition to a few other environmental factors. The "potentially suitable restoration areas" were based on the following criteria:

- Located within the riparian corridor (as determined from 2011 orthoimagery and LiDAR)
- Located outside of the Flood Reset Zone (see Section 2.2: Flood-Scour Analysis)
- Vegetation >20% native shrubs and trees and <80% tamarisk (see Section 2.3: Vegetation Characterization)
- Adjacency to known surface water sources (as interpreted from 2011 orthoimagery and LiDAR)
- Avoidance of urban development and other active land uses (as interpreted from 2011 orthoimagery, LiDAR, and county zoning maps)
- Proximity to known past or present SWFL habitat (from survey data provided by BOR and Utah Division of Wildlife Resources)
- Minimum site area of >10 acres (advised for promoting SWFL population growth)

Synthesis of these environmental factors was performed in a GIS where areas (polygons) representing potential suitability for active riparian restoration along the entire length of the Virgin River were generated (Figure 6). The potentially suitable restoration areas are shown on the maps in Figures 8.1 through 8.23 (c, d) (see Figure 7 for an index map).

Figure 6. Process of the ecohydrological assessment to identify potentially suitable restoration areas along the Virgin River. Example shown above is of the Hughes Middle School restoration project area in Mesquite, Nevada.

2.4.1 Lower River

The results of the assessment reveal a concentration of potentially suitable restoration areas in the lower river as compared to the upper river. Approximately 3,480 acres, or 45% of the riparian corridor, along the lower river between Lake Mead and the Virgin River Gorge are potentially suitable for restoration. The areas here are concentrated in the Mormon Mesa reach because of its broader, low-lying riparian corridor and proximity to surface water (i.e., low-flow channel and side-channels). Identified sites within this reach, however, do not strictly adhere to the >20%

native shrubs and trees and <80% tamarisk criterion, but are nevertheless considered suitable for restoration based on other environmental factors (e.g., low flood-scour potential, proximity to surface water, etc.). Farther upstream where native vegetation cover is greater, suitable restoration areas identified in the Bunkerville–Mesquite reaches are relatively scattered throughout the narrower floodplain, which is due in part to adjacent agriculture (near Bunkerville) and urban encroachment (in Mesquite). Only a few suitable areas are identified between Mesquite and Littlefield in the Littlefield reach; the two most notable are located at the "Big Bend" site and the Beaver Dam Wash confluence. No suitable areas are identified in the Virgin River Gorge due to the high potential for flood-scour within the confined reaches and limited potential to support SWFL habitat.

2.4.2 Upper River

Approximately 665 acres, or 18% of the riparian corridor, along the upper river between the Virgin River Gorge and the North-South Fork split in Utah are potentially suitable for restoration. The proportion of native vegetation to tamarisk and Russian olive generally increases, as does overall species diversity and structural complexity, in the upstream reaches (see Section 2.3: Vegetation Characterization). Suitable areas identified in the Bloomington-St. George-Washington reaches are generally isolated due to channel and floodplain confinement, particularly near Bloomington. More contiguous extents of potentially suitable areas are located in the St. George reach near several existing Virgin River Program restoration sites. The suitable areas identified upstream of Washington and continuing towards Rockville are limited to a few isolated locations along the narrow riparian corridor that is confined by valley-canyon topography and agricultural fields.

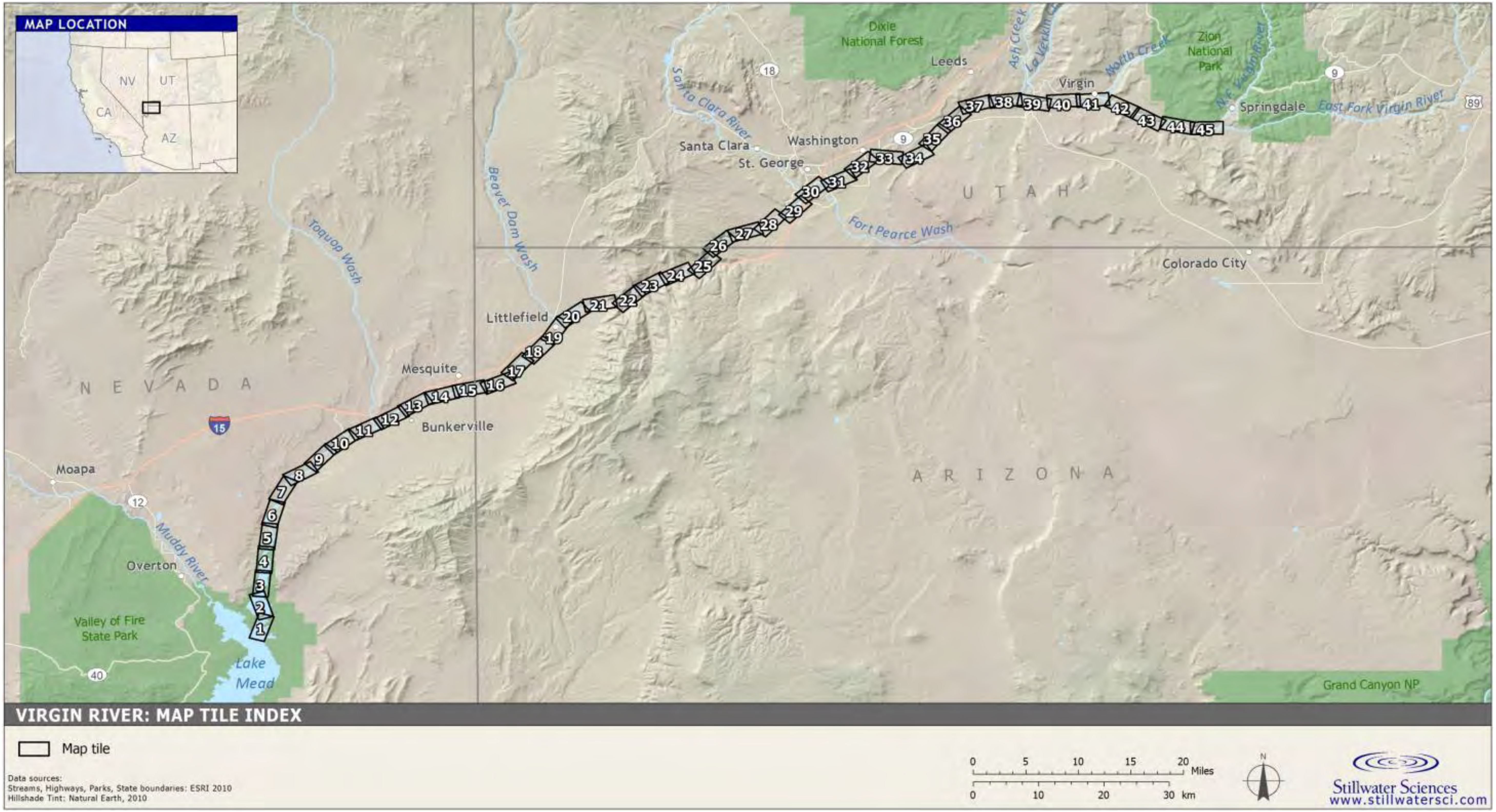


Figure 7. Index map for ecohydrological assessment map tiles along the mainstem Virgin River. See Figures B2.1 through B2-23 for individual map-tiles showing flood-scour activity and Figures 7.1 through 7.23 for showing vegetation classification (a, b) and potential priority areas for active restoration (c, d).

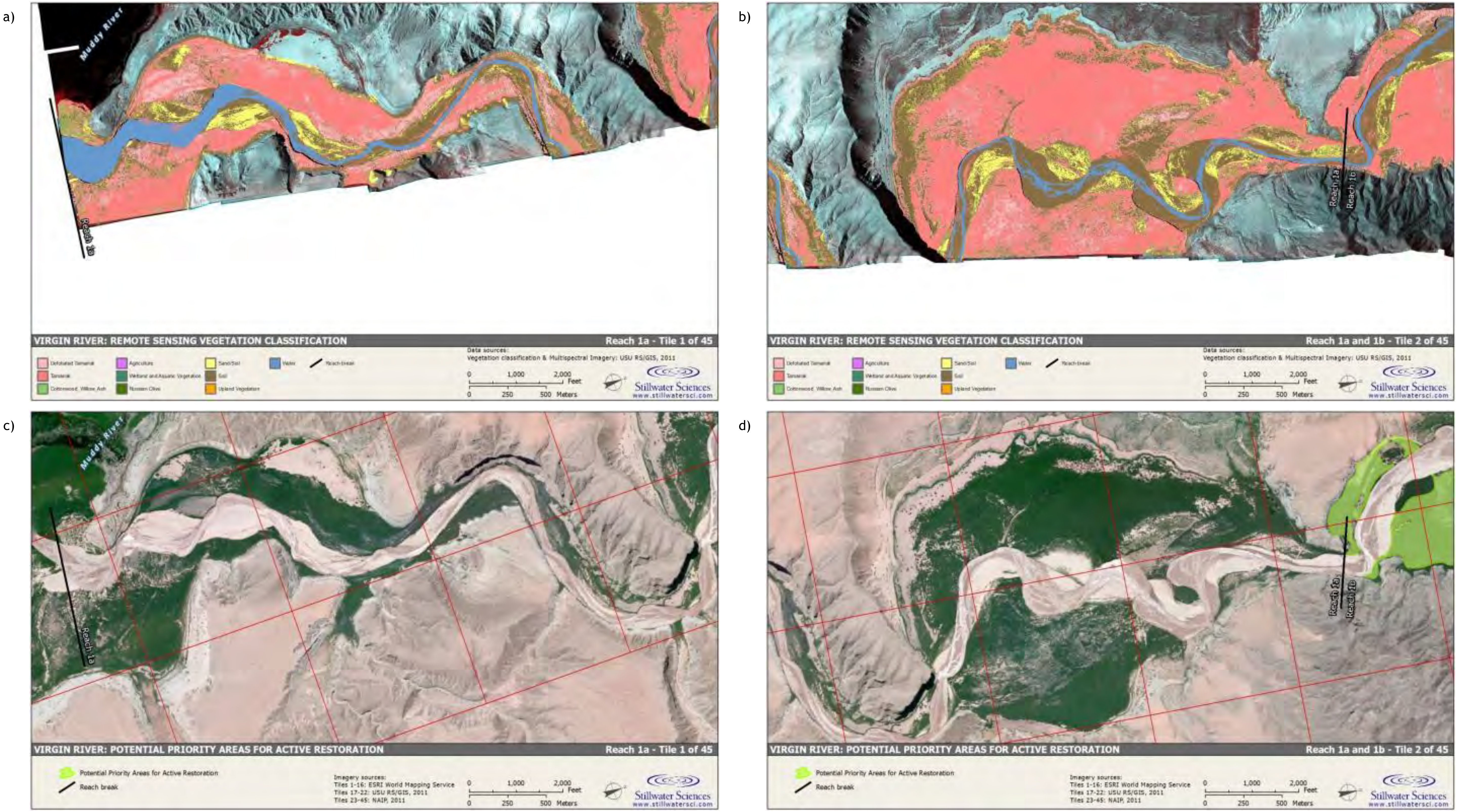


Figure 8.1. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reach 1a.

a) b) c) d)

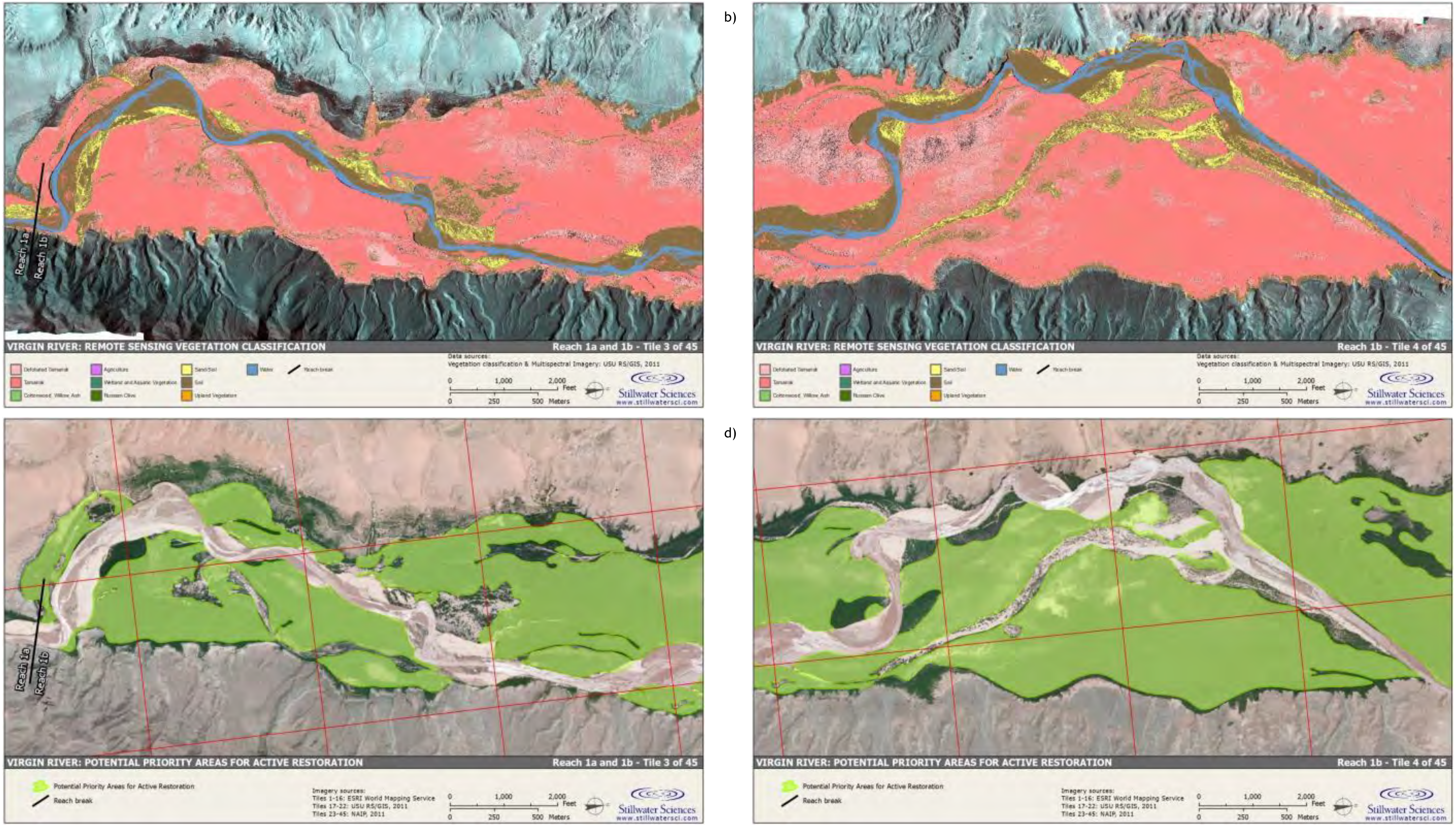


Figure 8.2. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reach 1b (lower).

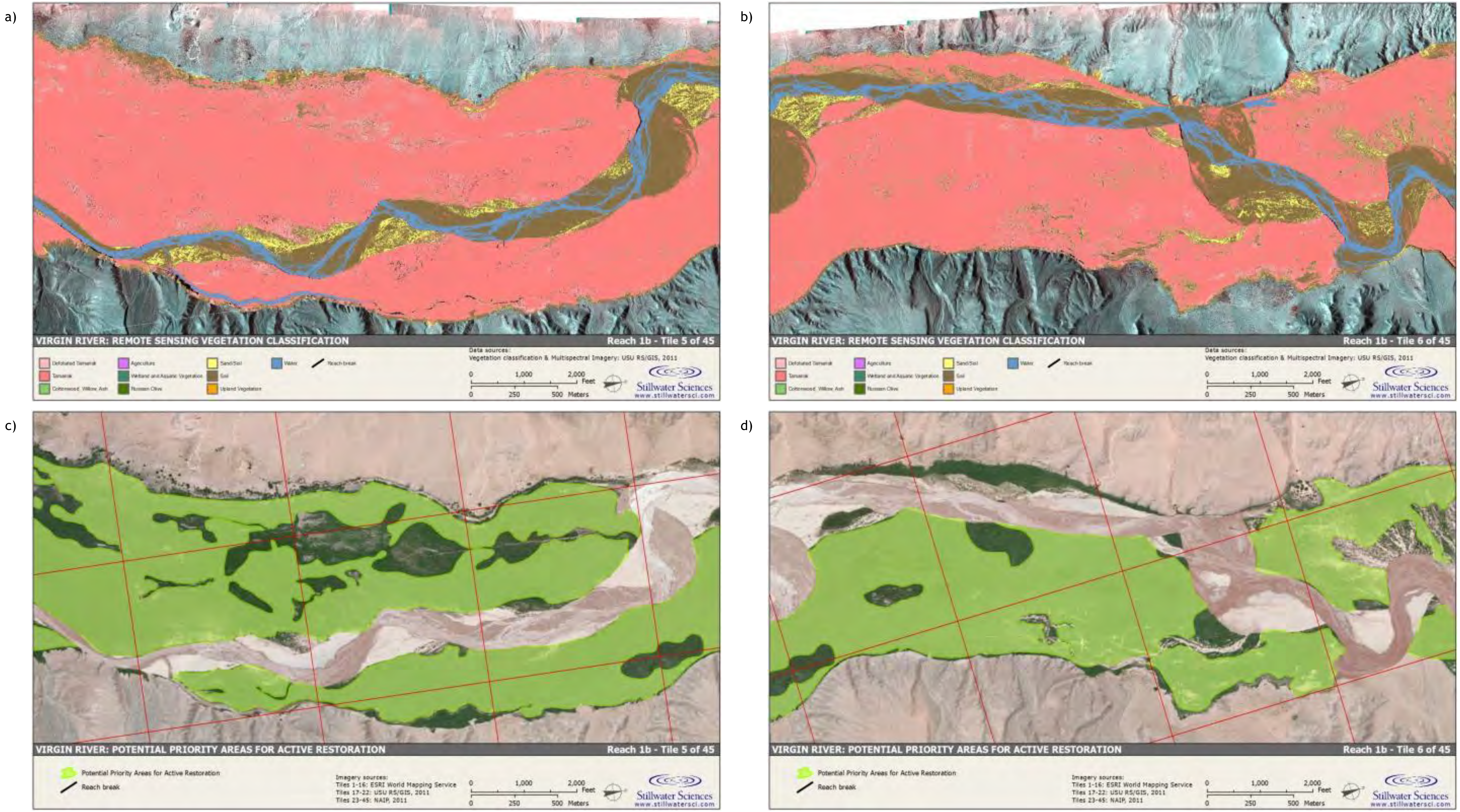


Figure 8.3. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reach 1b (upper).

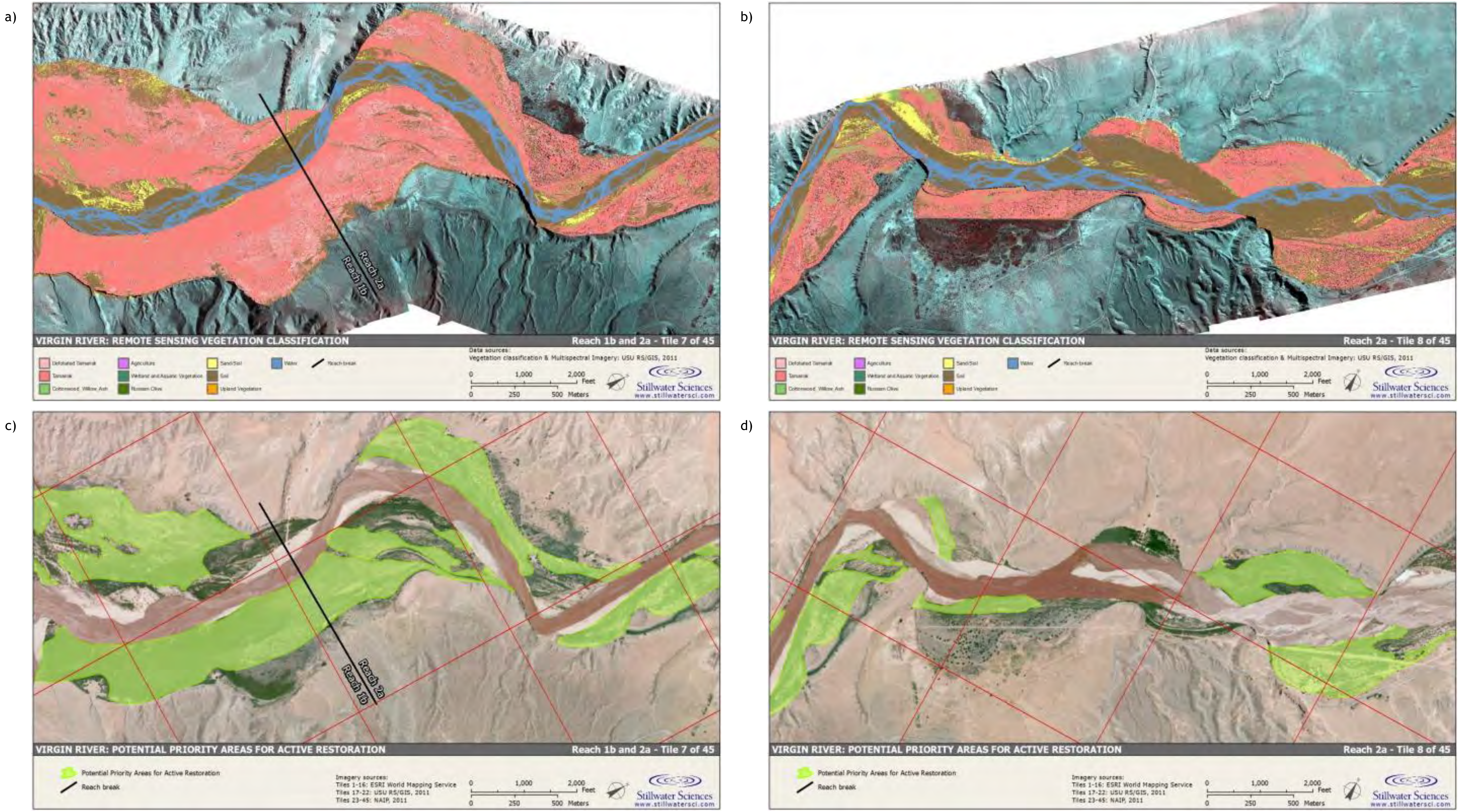


Figure 8.4. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 1b and 2a.

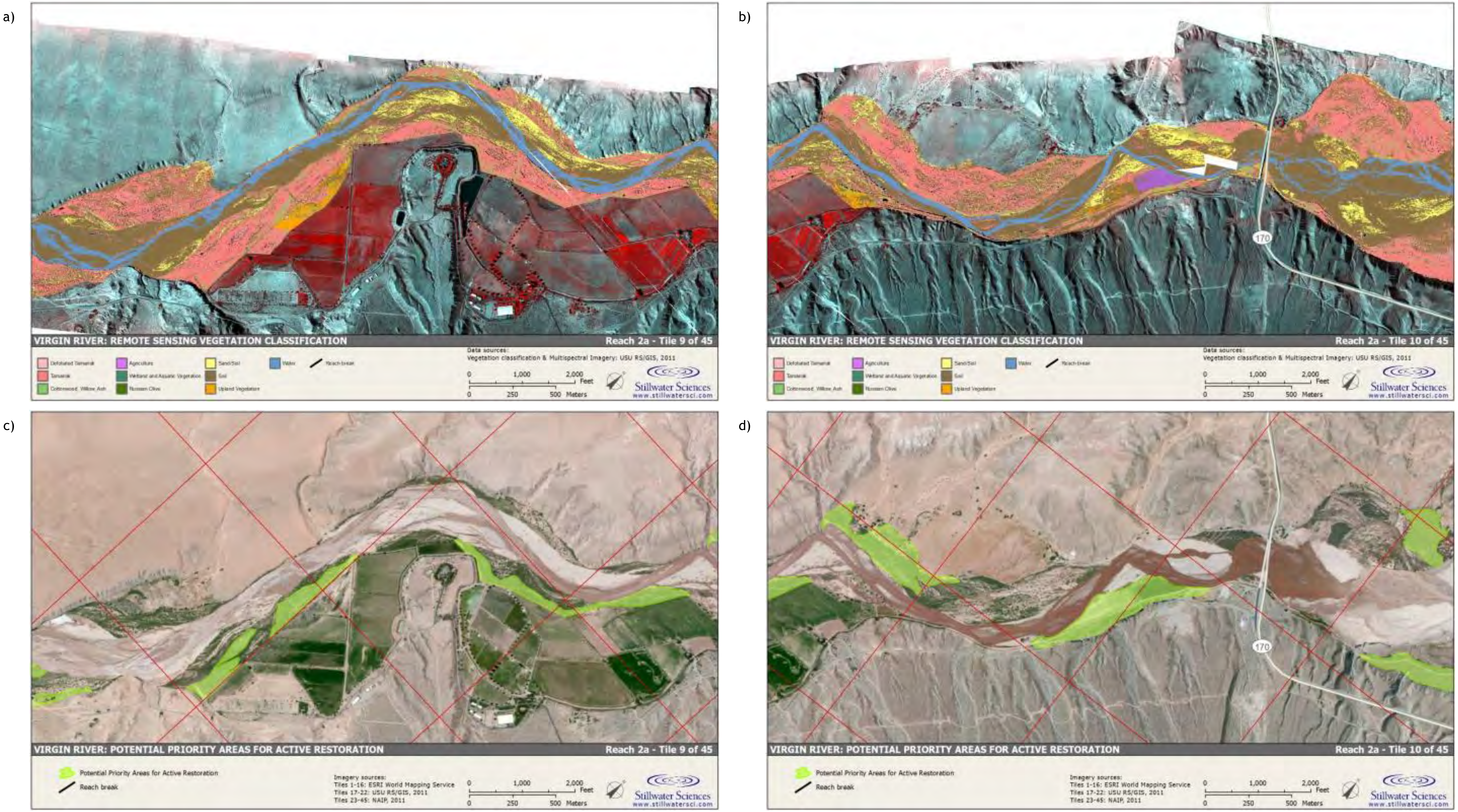


Figure 8.5. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 2a.

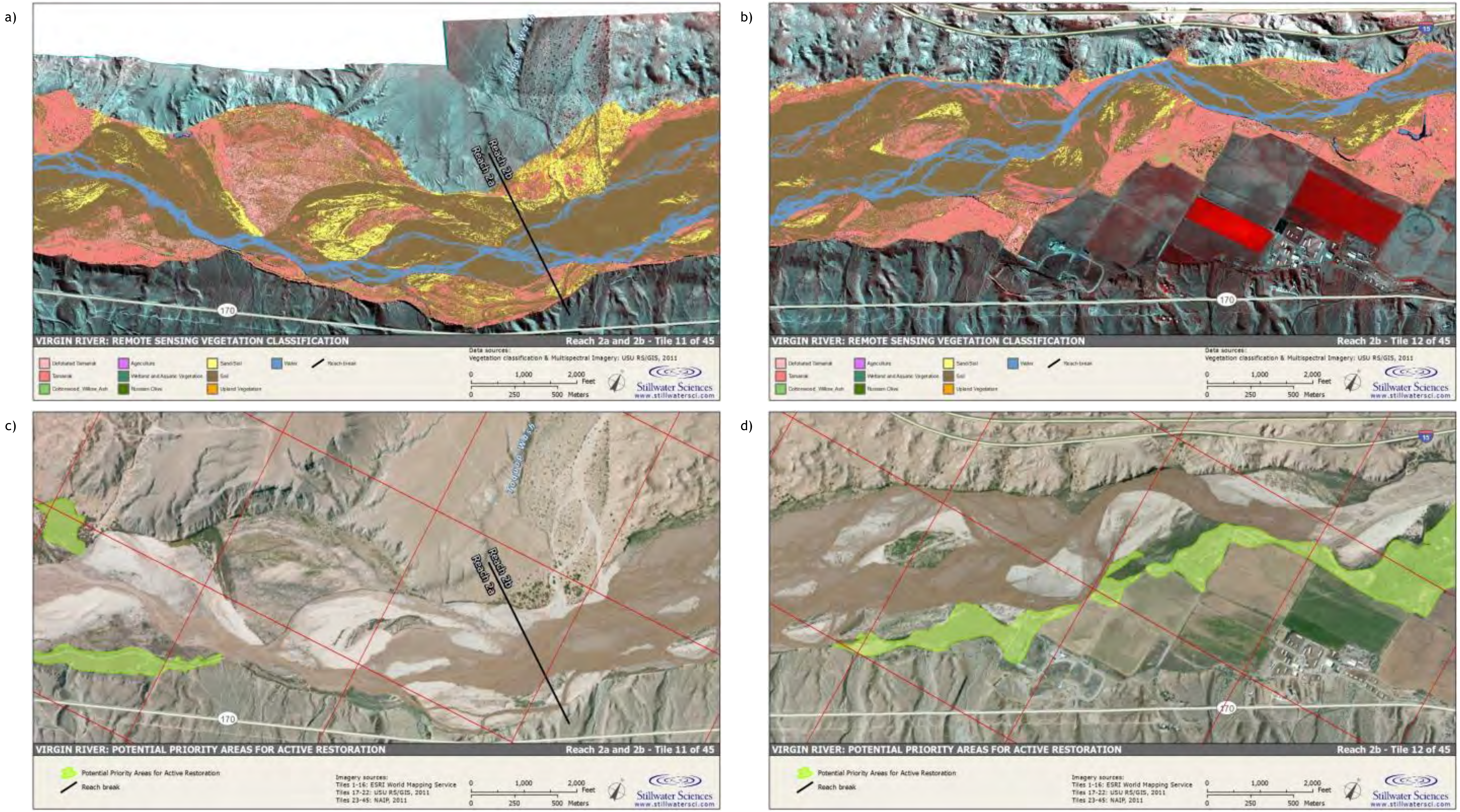


Figure 8.6. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 2a and 2b.

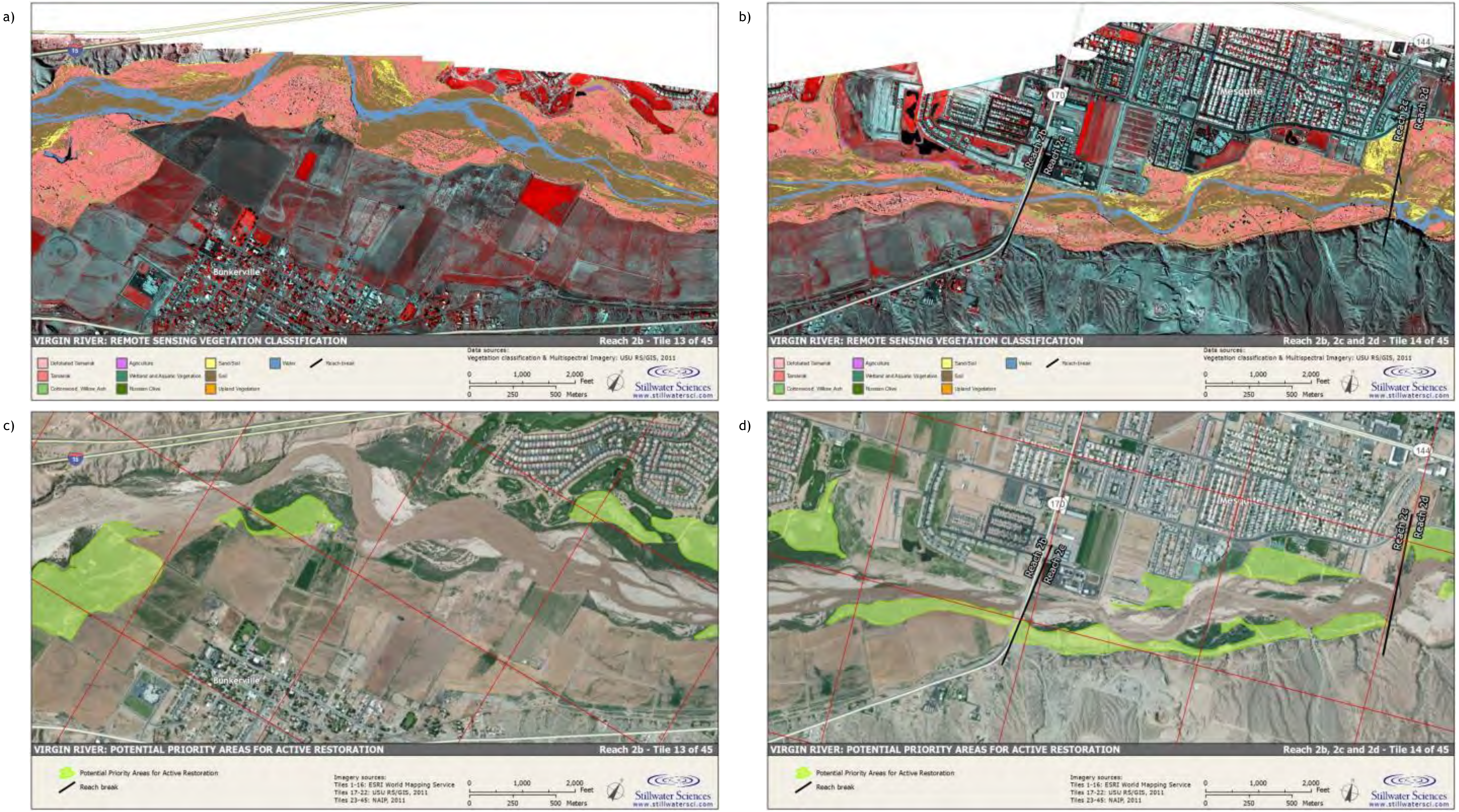


Figure 8.7. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 2b and 2c.

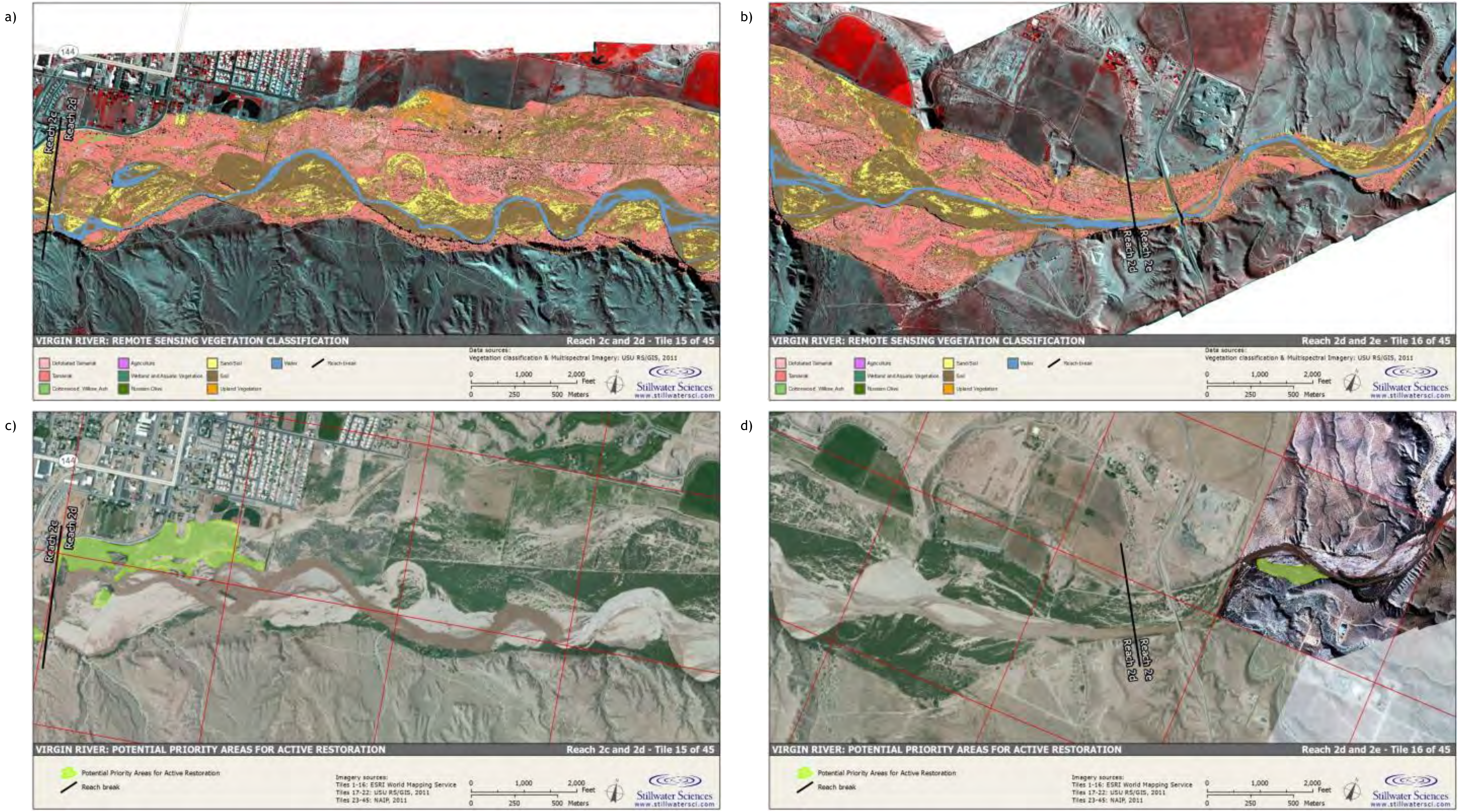


Figure 8.8. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 2d and 2e.

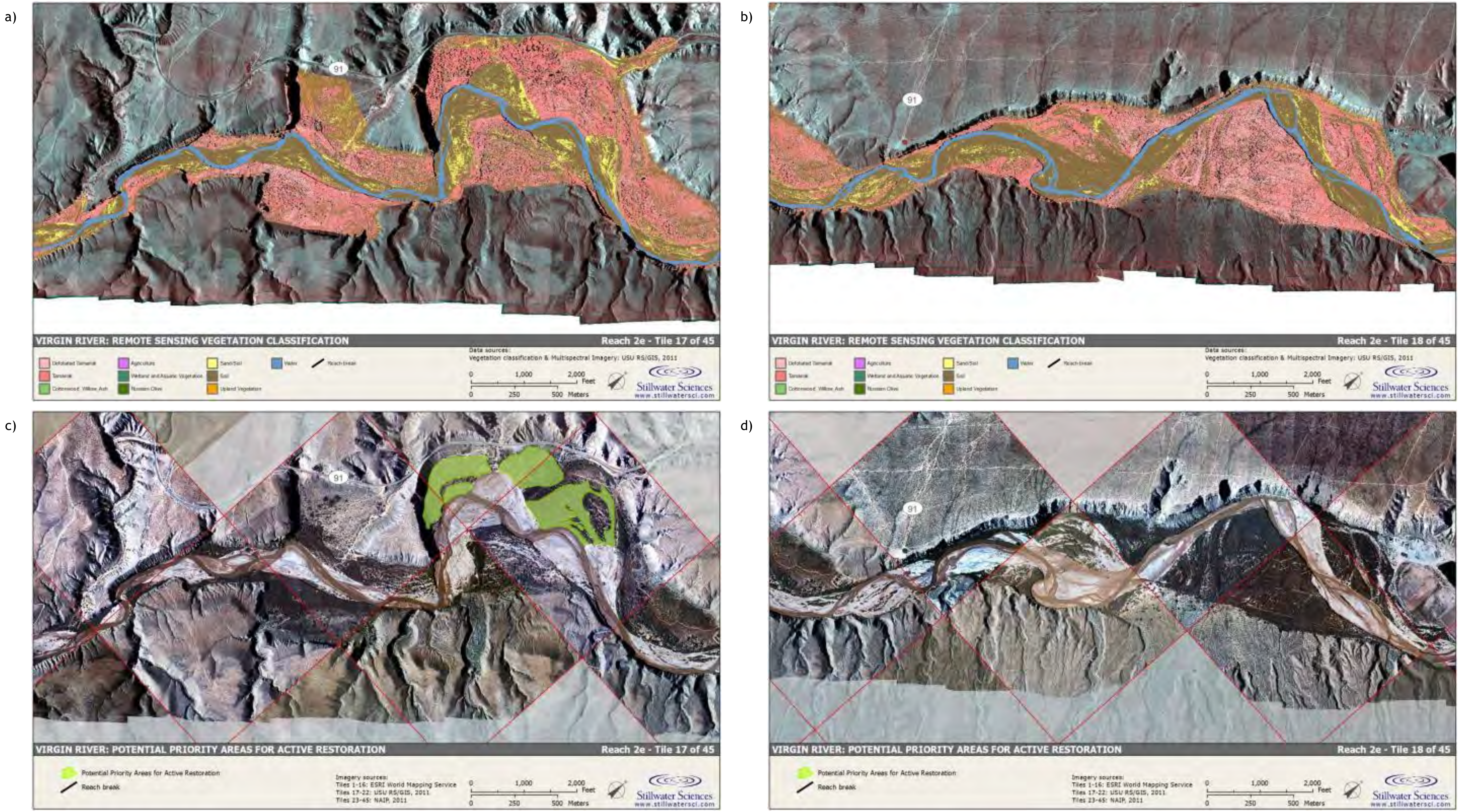


Figure 8.9. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reach 2e.

a) b) c) d)

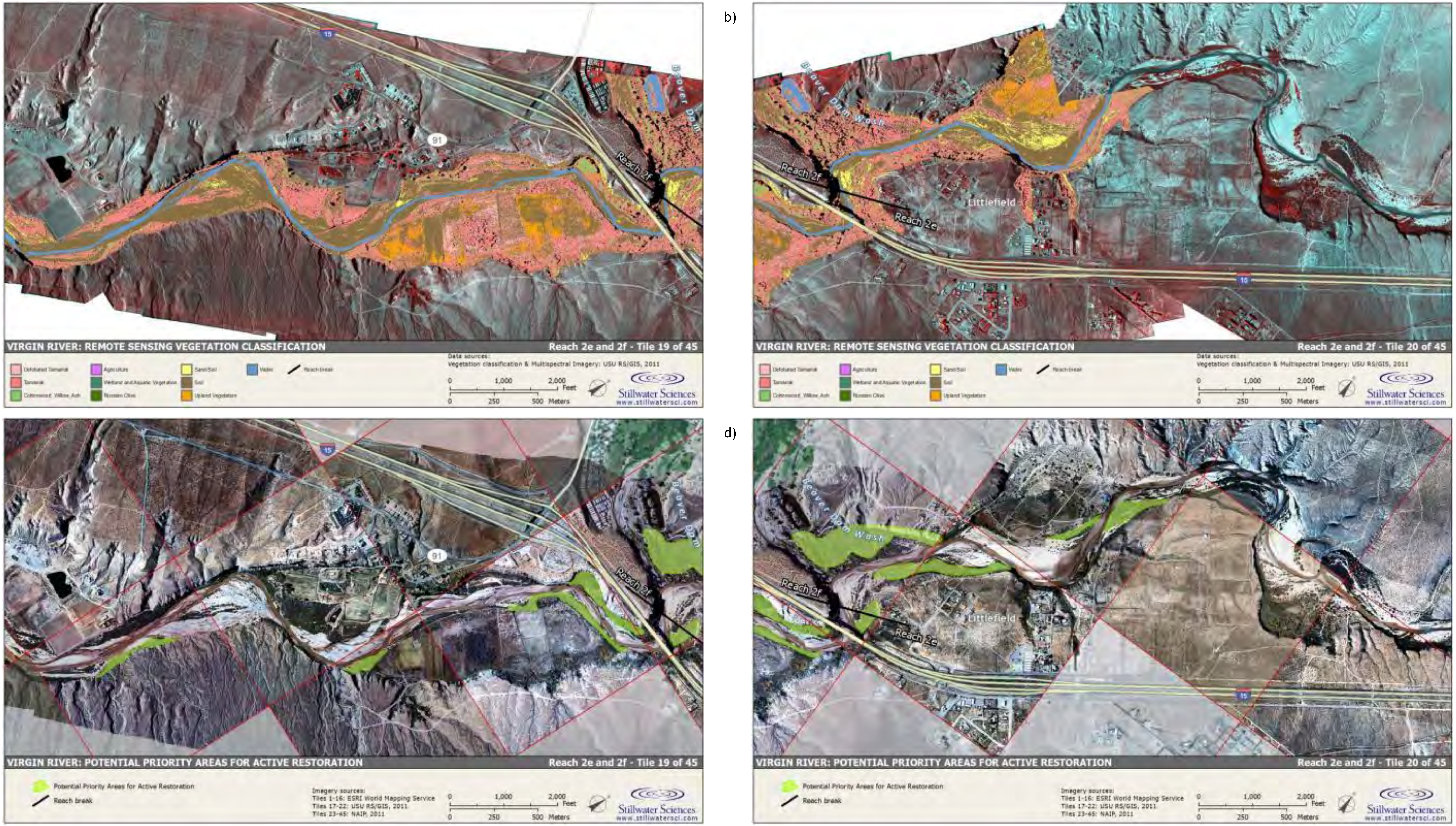


Figure 8.10. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 2e and 2f.

a) b) c) d)

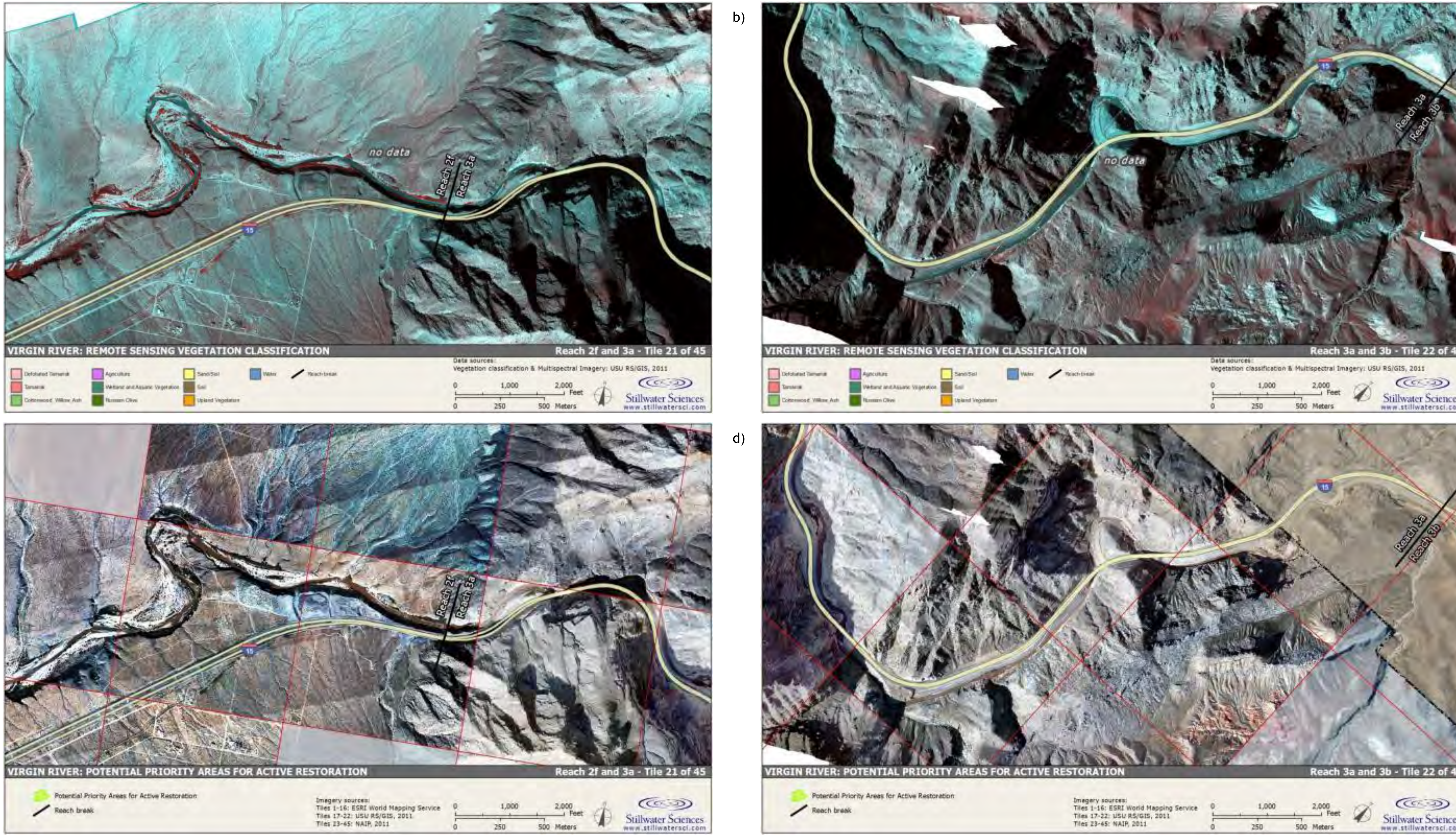


Figure 8.11. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 2f and 3a.

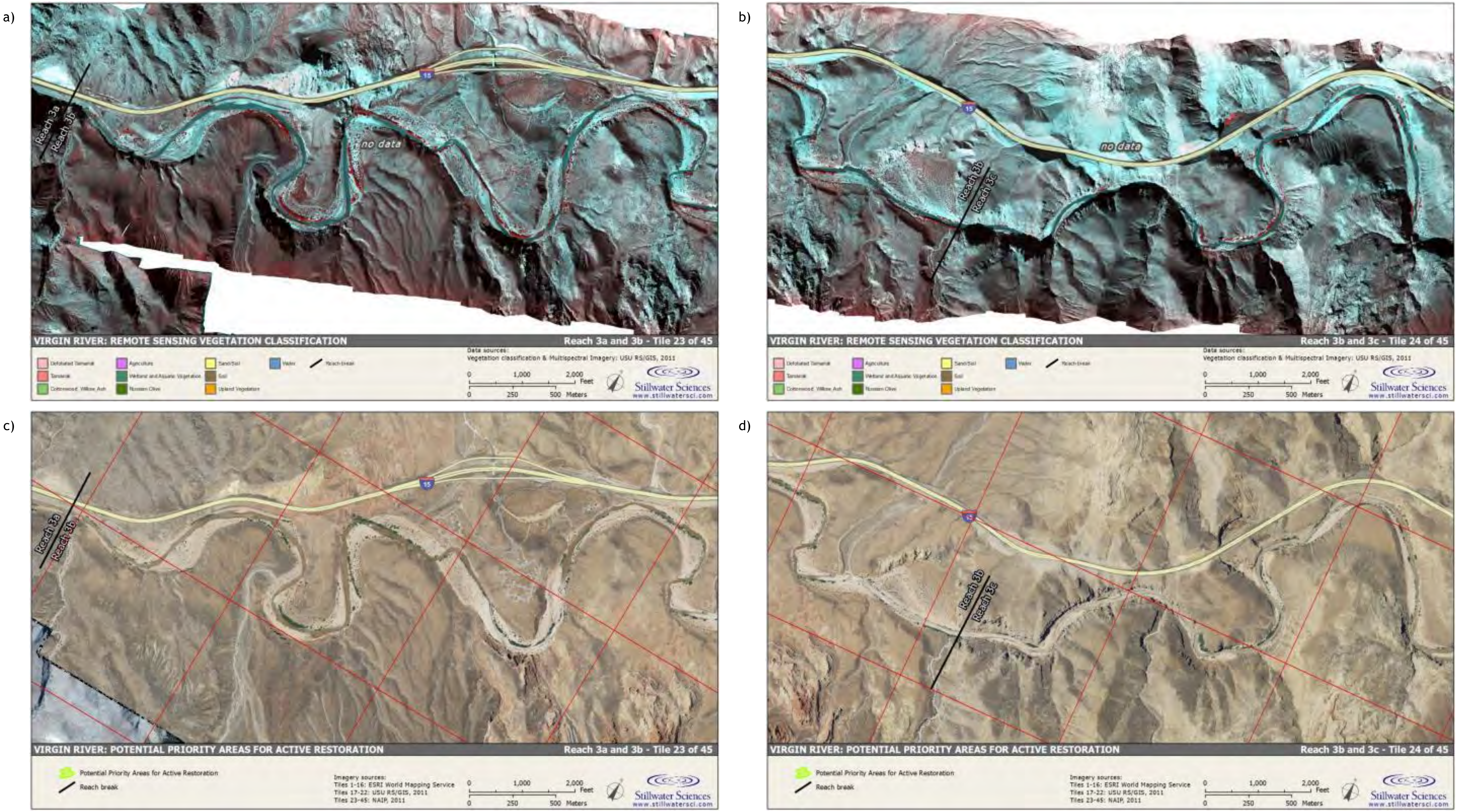


Figure 8.12. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 3b and 3c.

a) b) c) d)

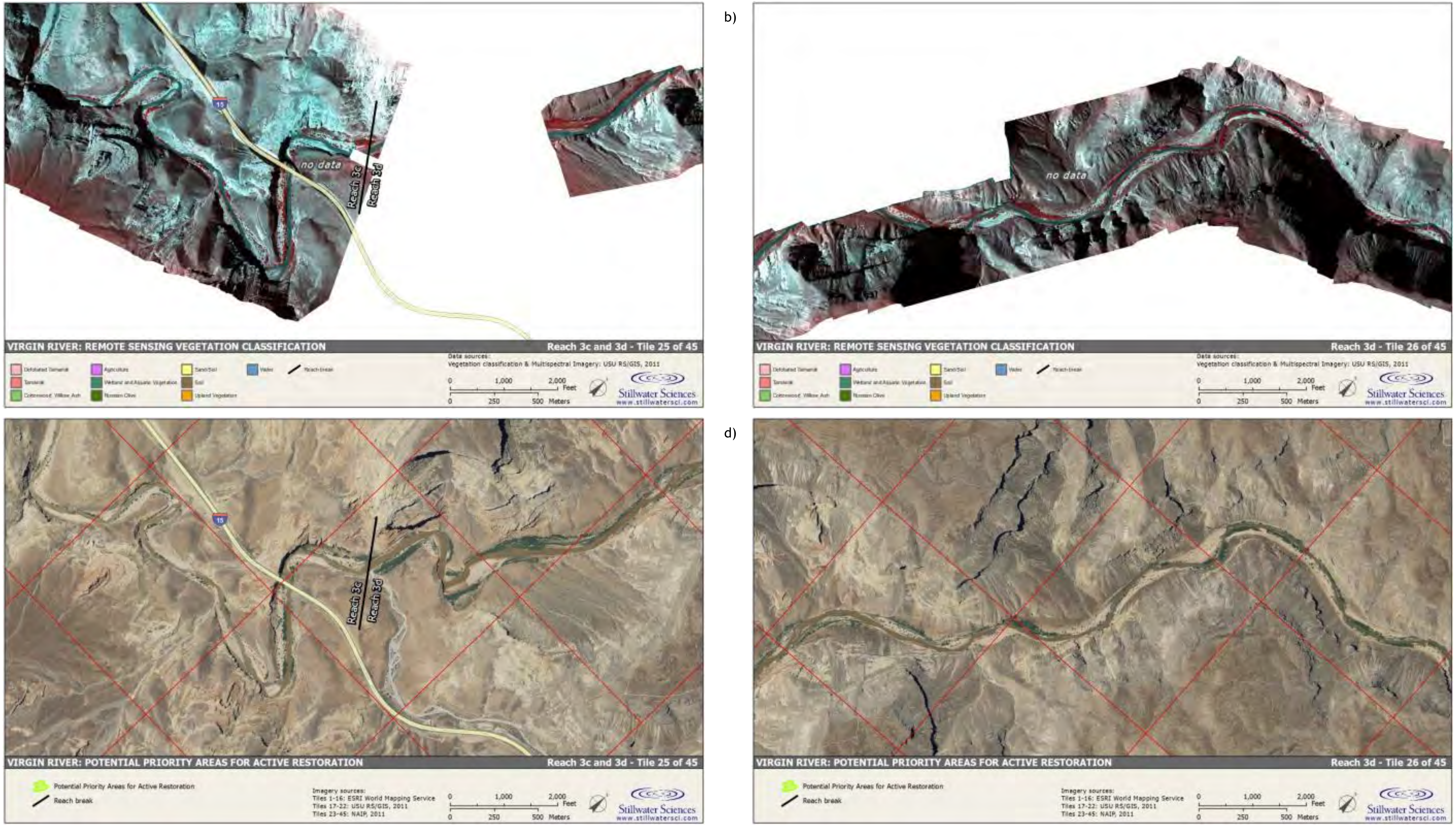


Figure 8.13. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 3c and 3d.

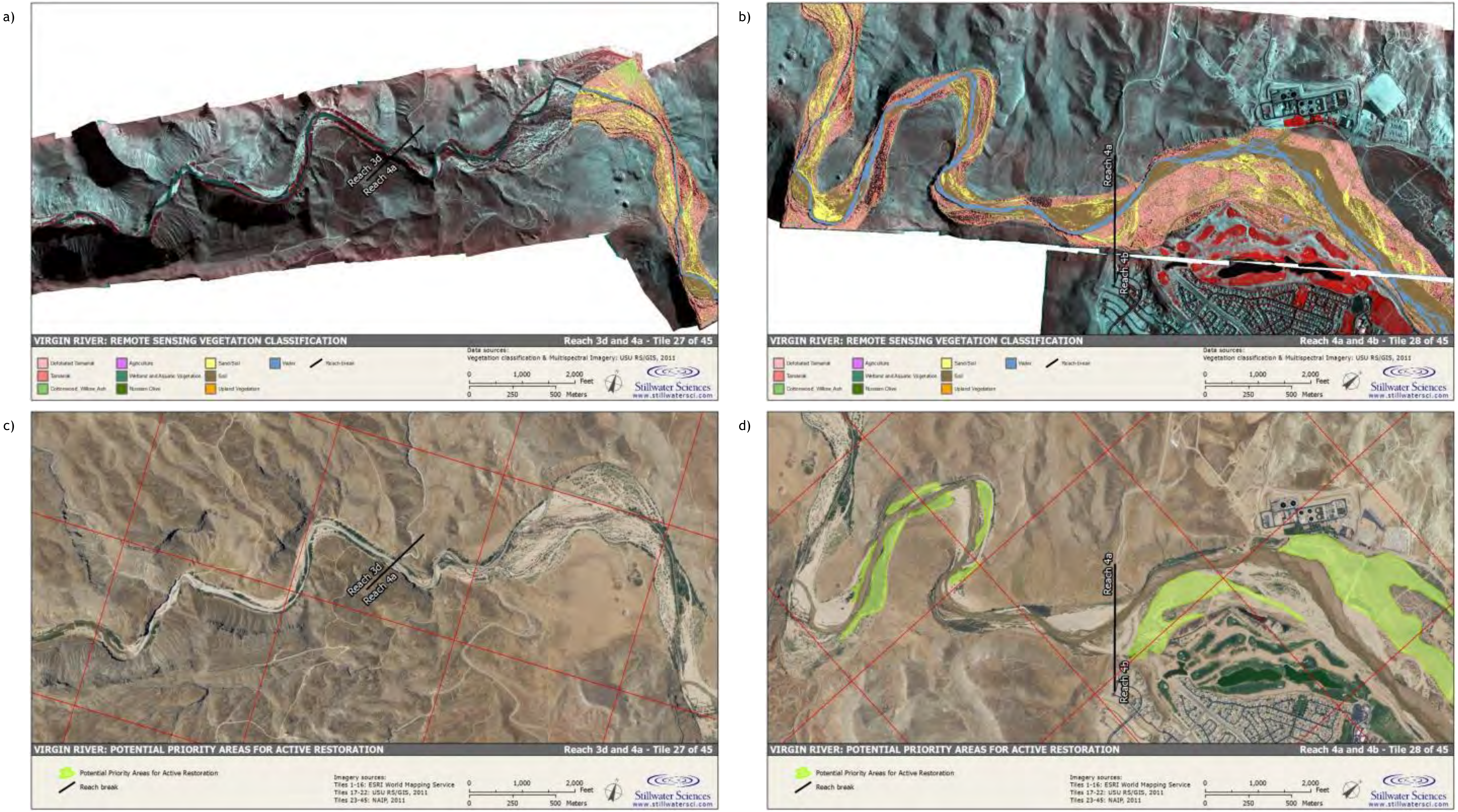


Figure 8.14. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 3d, 4a, and 4b.

a) b) c) d)

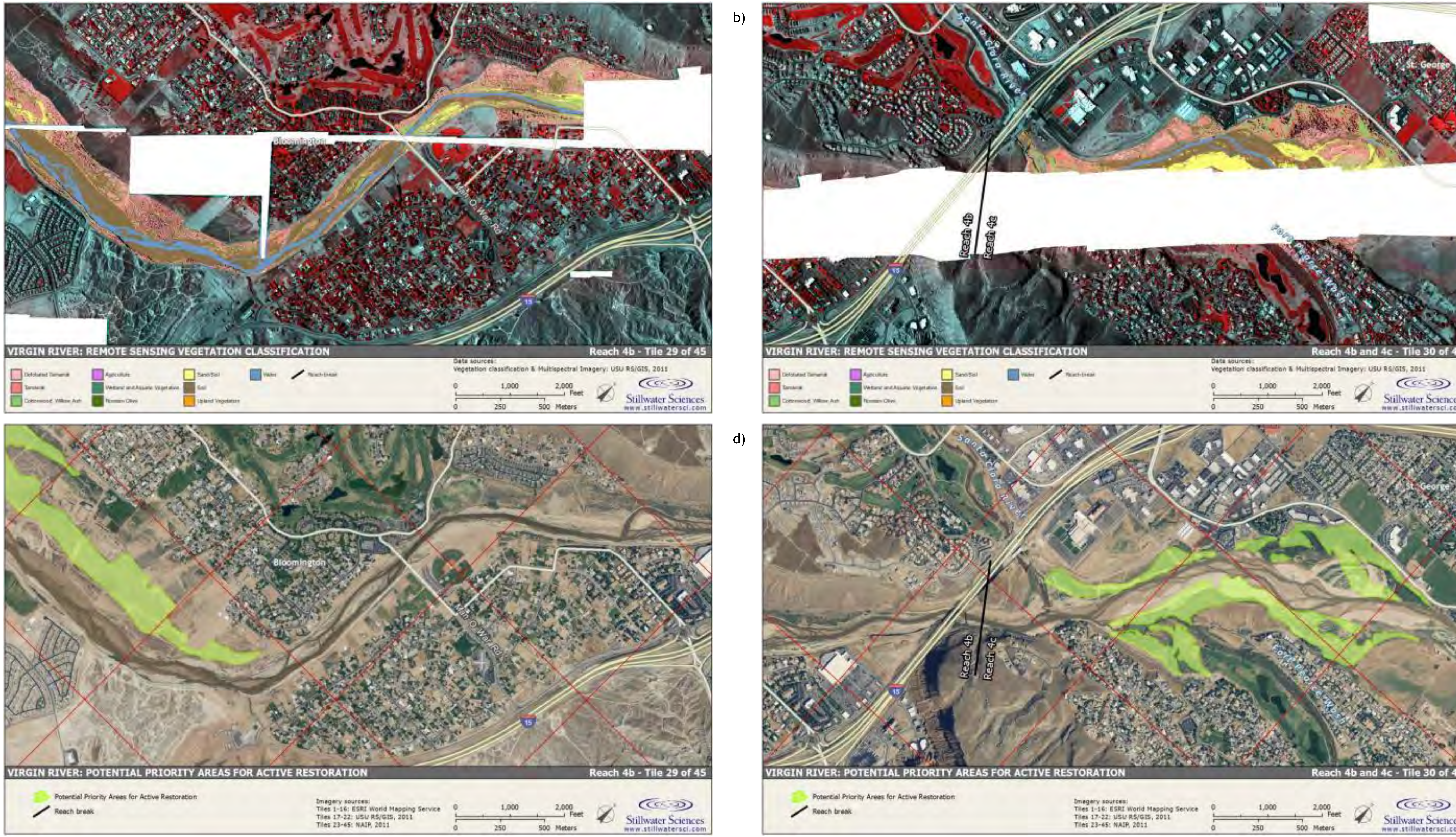


Figure 8.15. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 4b and 4c.

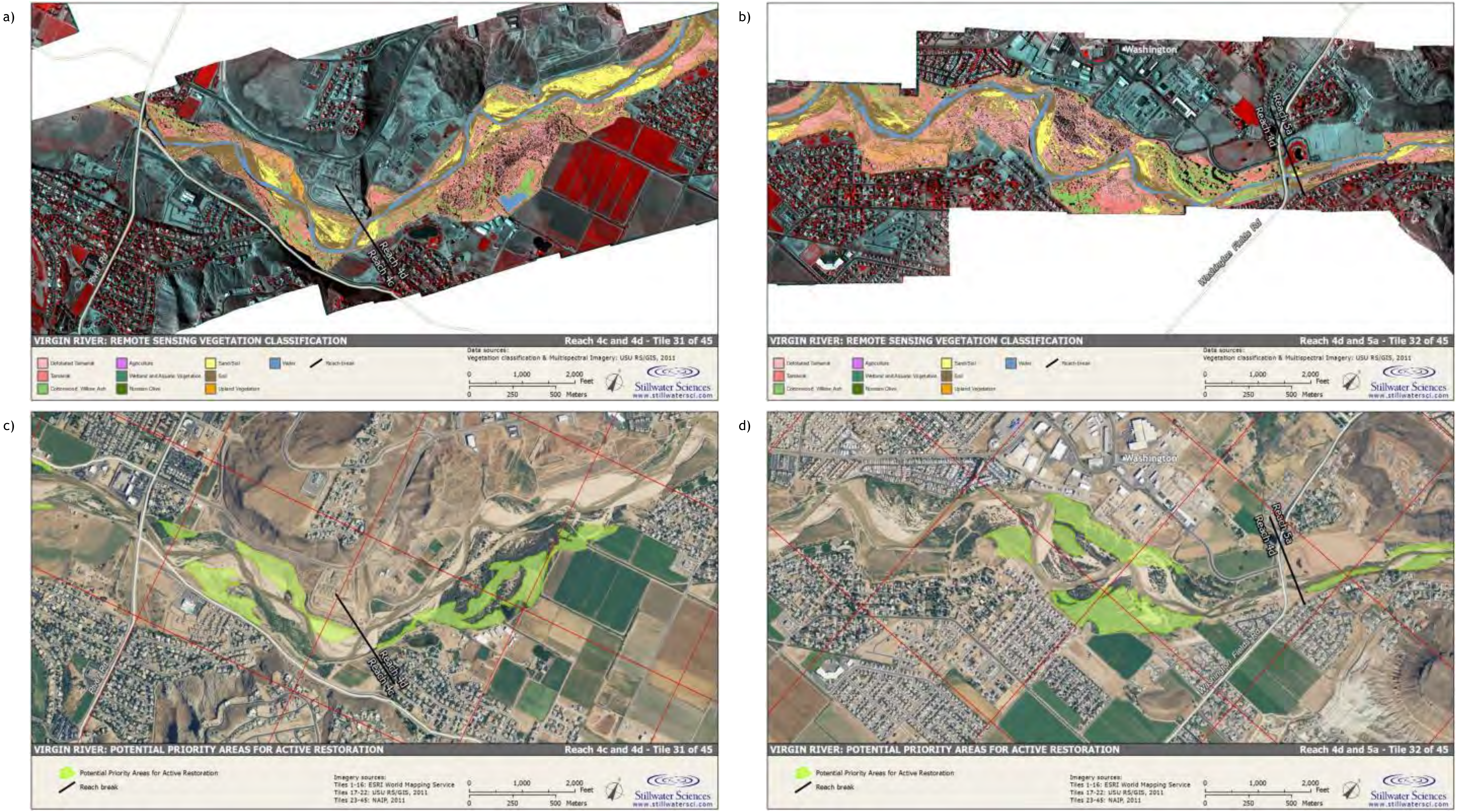


Figure 8.16. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 4c, 4d, and 5a.

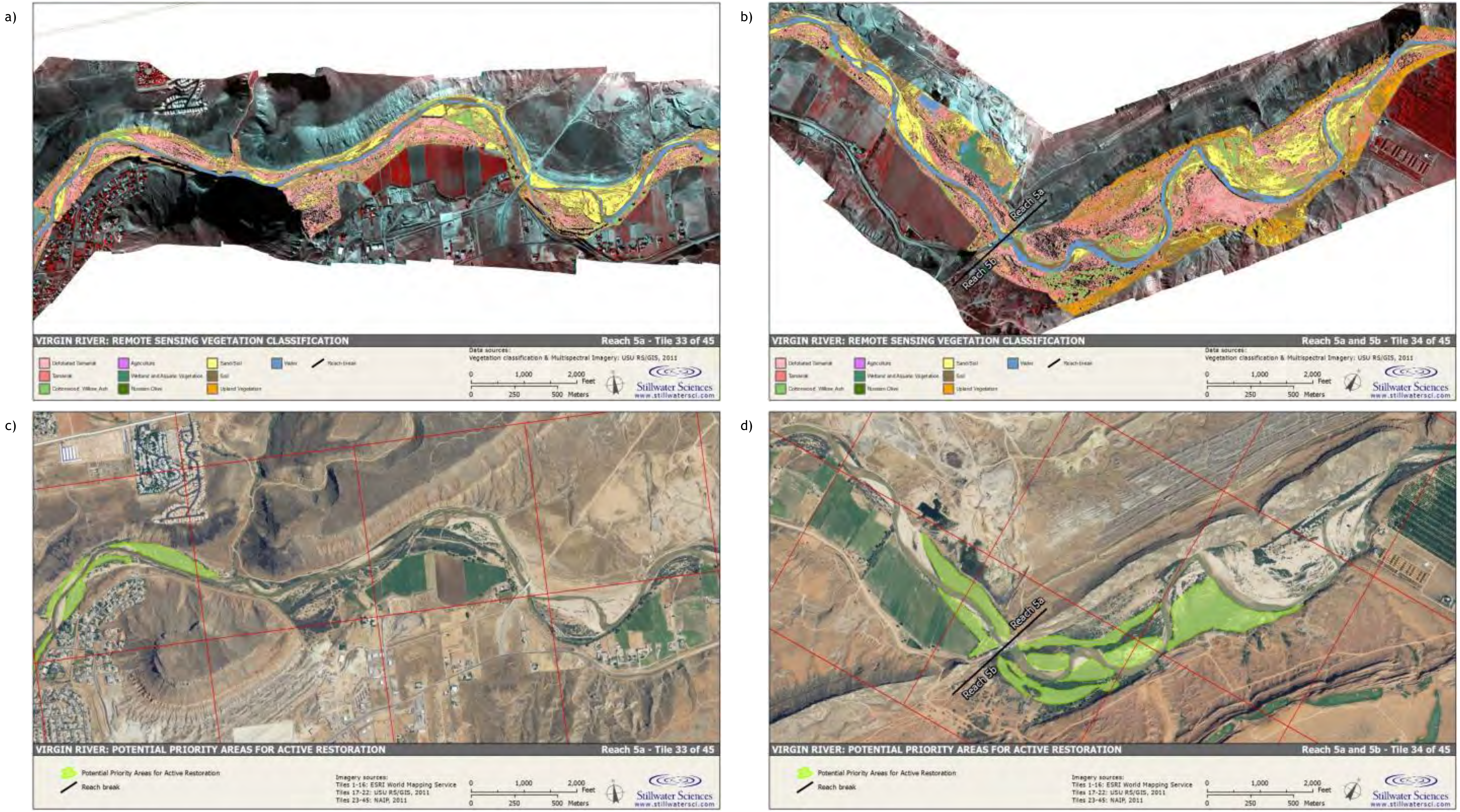


Figure 8.17. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 5a and 5b.

a) b) c) d)

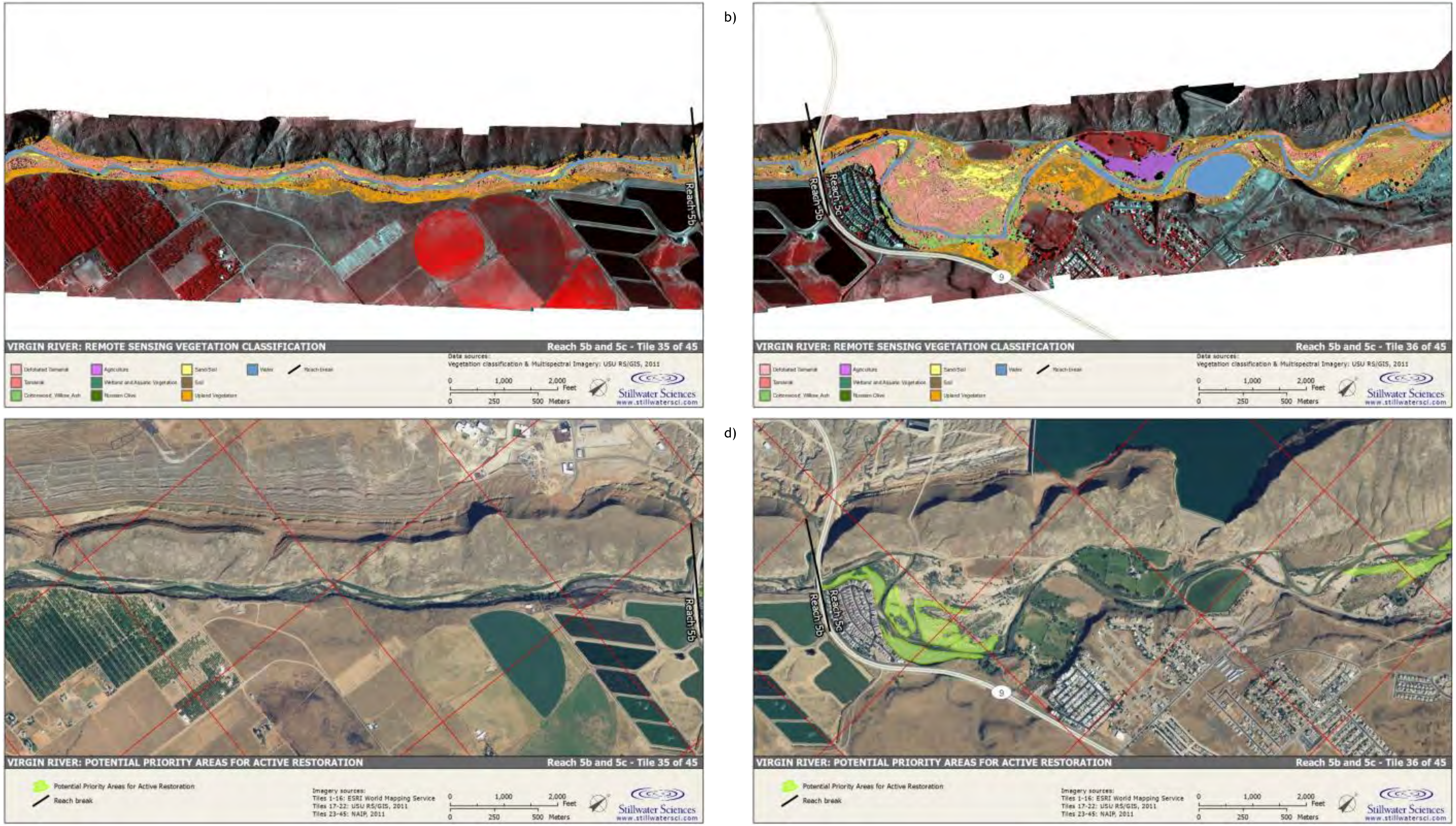


Figure 8.18. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 5b and 5c.

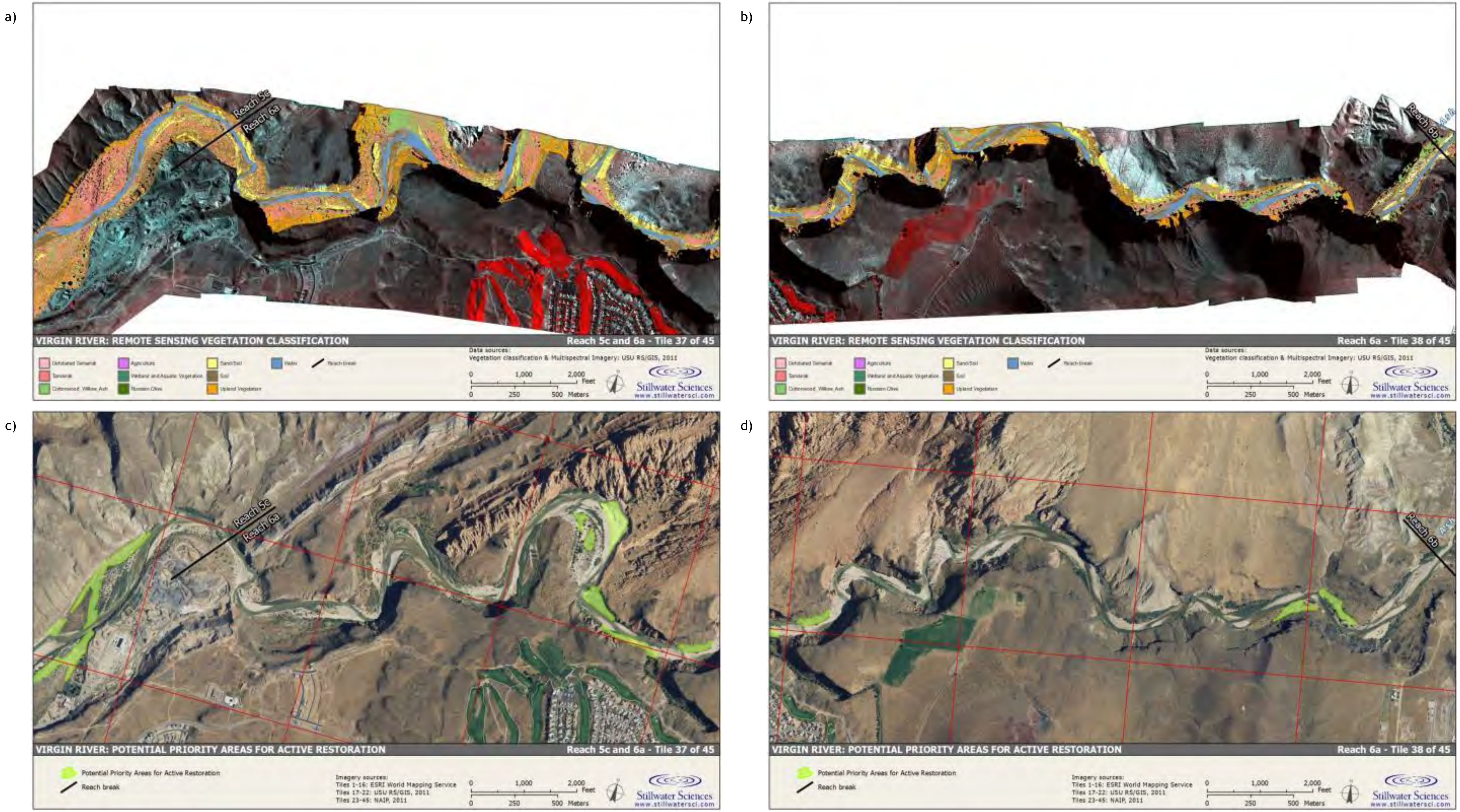


Figure 8.19. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 5c and 6b.

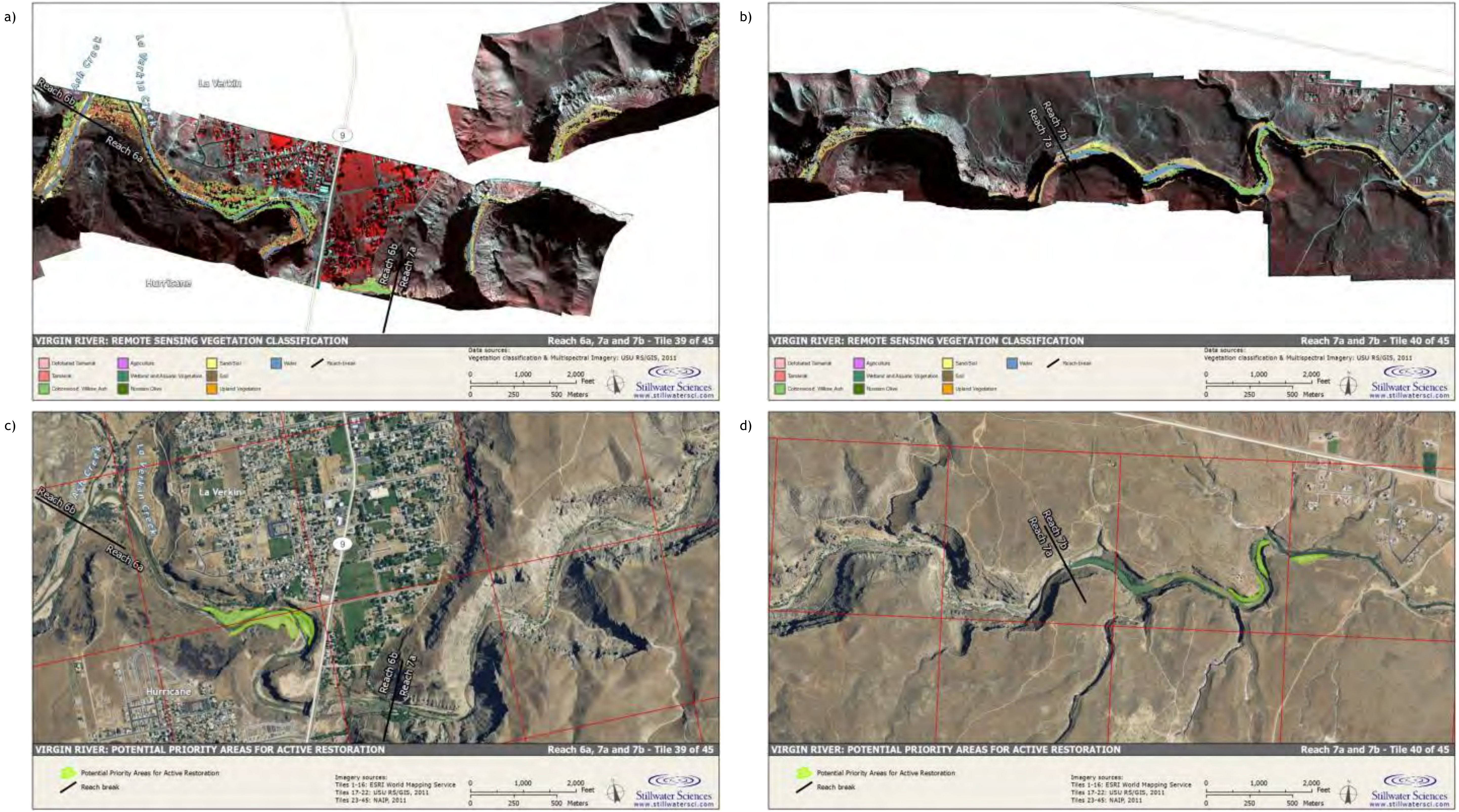


Figure 8.20. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 6b, 7a, and 7b.

a) b) c) d)

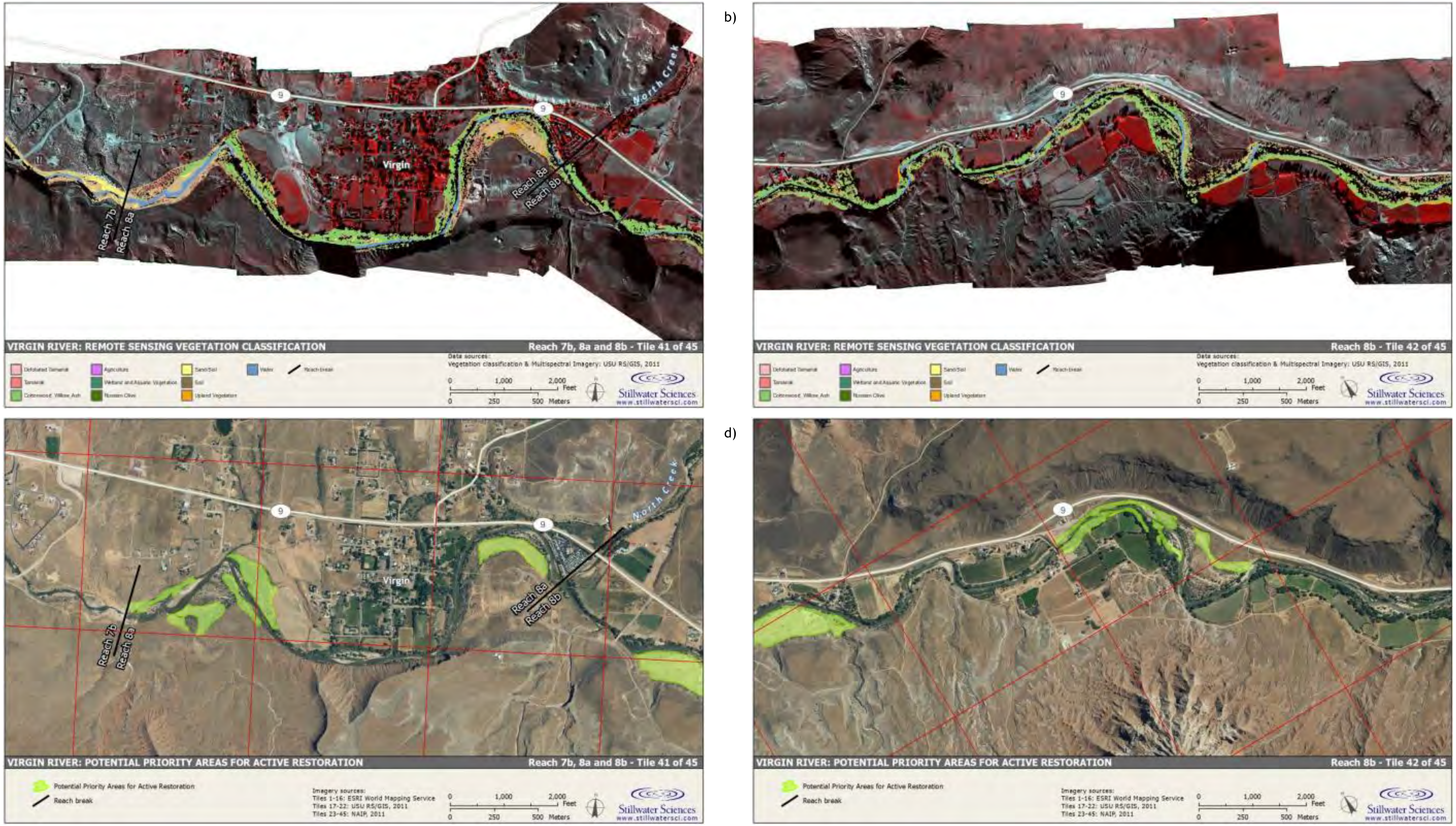


Figure 8.21. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 7b, 8a, and 8b.

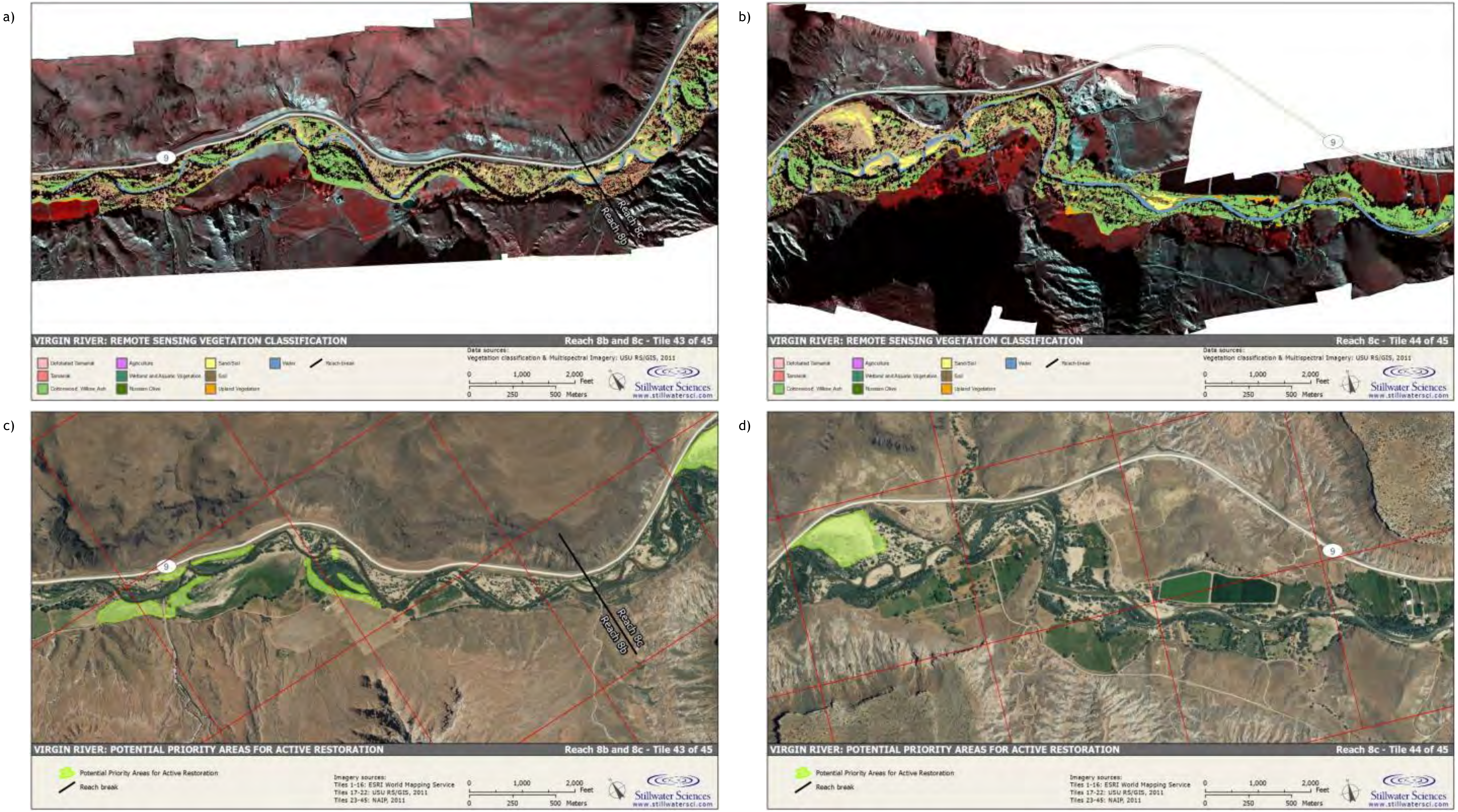
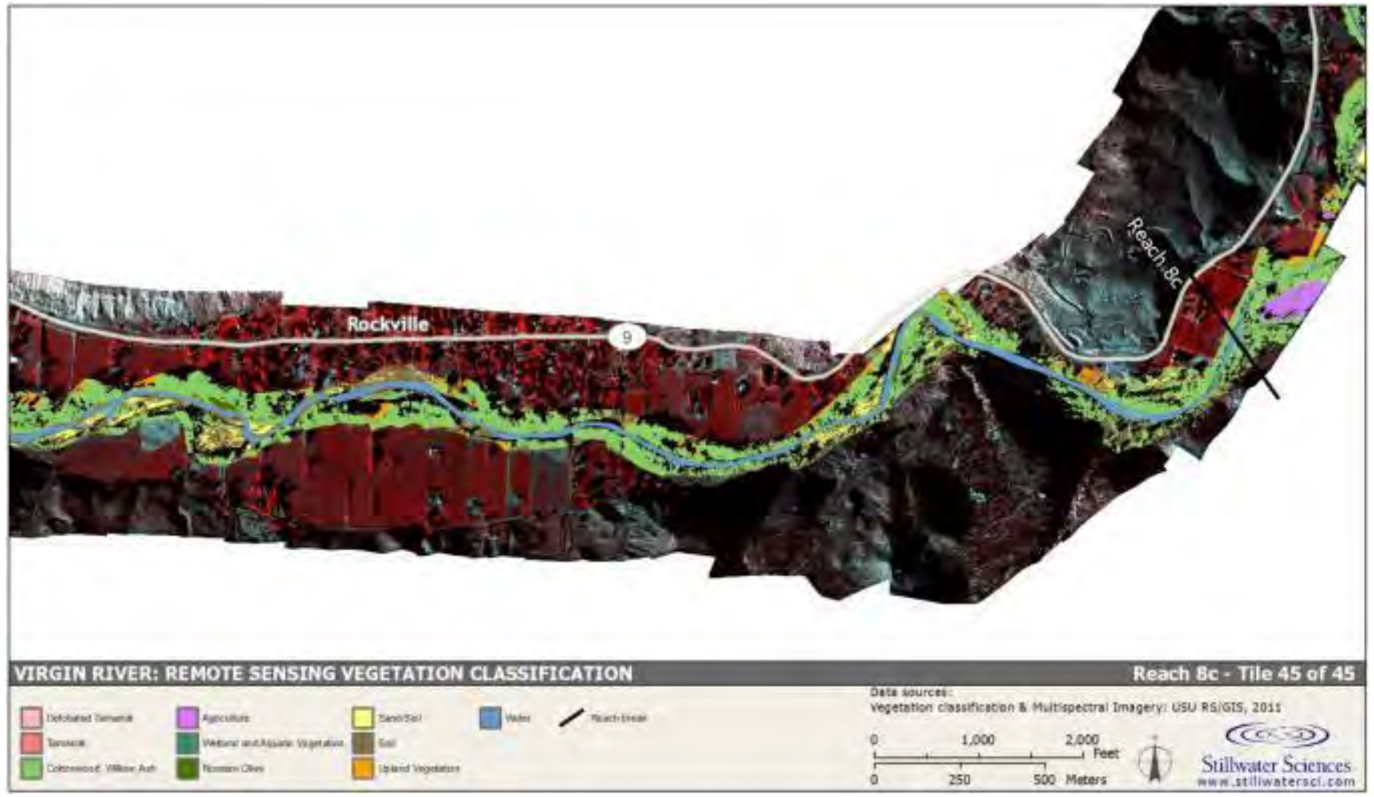


Figure 8.22. Virgin River vegetation classification (a, b) and potential priority areas for active restoration (c, d) in Reaches 8b and 8c.

a)



b)

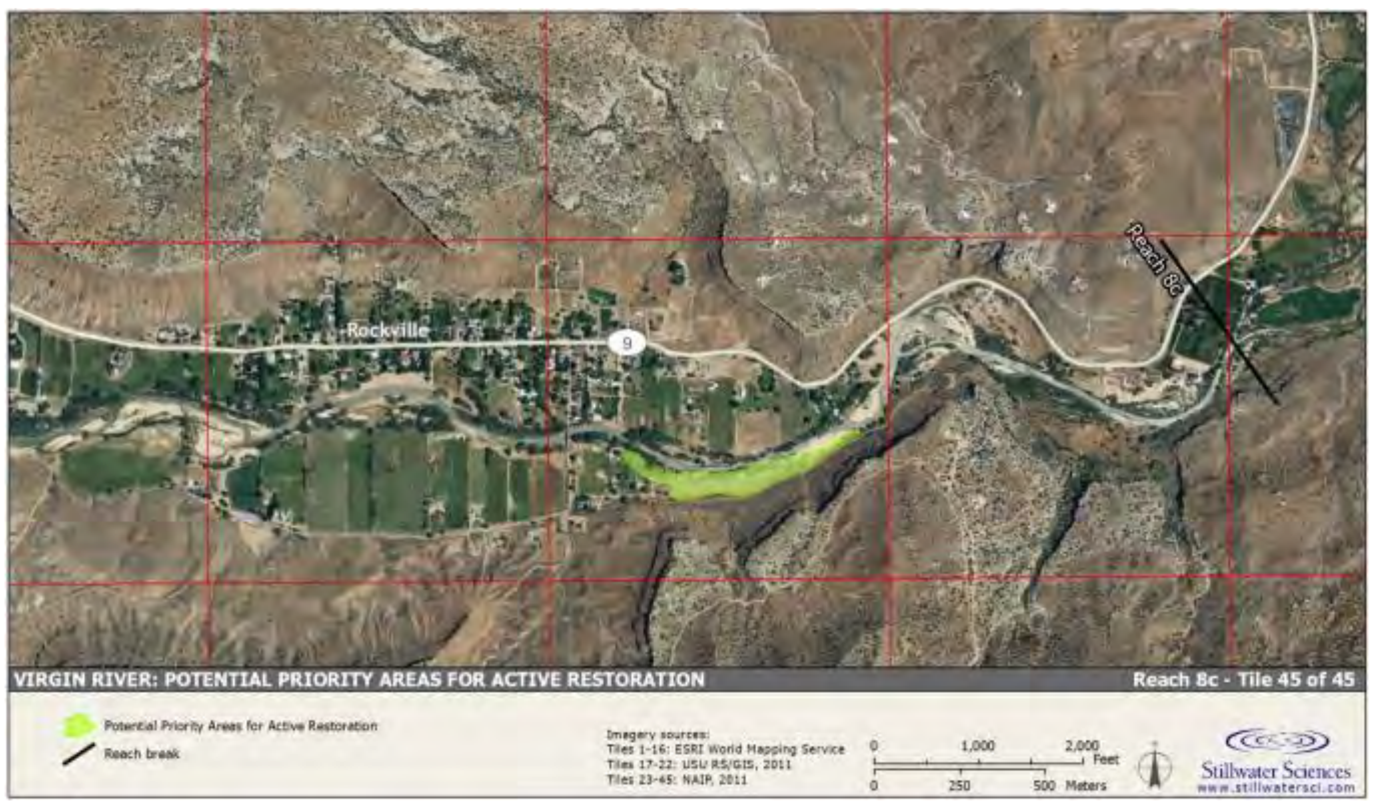


Figure 8.23. Virgin River vegetation classification (a) and potential priority areas for active restoration (b) in Reach 8c (upper).

3 STAKEHOLDER WORKSHOP

In May 2013 the Virgin River Southwestern Flycatcher Collaborative hosted a two-day workshop for stakeholders in the watershed to discuss riparian restoration strategies and priorities based on the initial findings of the Ecohydrological Assessment and other related studies conducted by the Restoration Science Team. The intention of the workshop was specifically to inform local land managers and wildlife agencies of the restoration suitability of potential sites, identify individual sites for near-term implementation, identify restoration requirements for sites, and prioritize those sites based on specific criteria established by workshop participants. The workshop was also intended to aid development of a resource guide for coordinated enhancement of SWFL habitat and population on the Virgin River.

Attendees included representatives from the following agencies and groups (listed alphabetically): Bureau of Land Management, Bureau of Reclamation, City of Mesquite, City of St. George, Clark County Desert Conservation Program, Great Basin Institute, National Park Service, Natural Resources Conservation Service, Nevada Department of Wildlife, Nevada Division of Forestry, Partners in Conservation, Southern Nevada Water Authority, Tamarisk Coalition, The Nature Conservancy, U.S. Fish and Wildlife Service, Utah Division of Wildlife Resources, Virgin River Program, and Walton Family Foundation.

Technical presenters and their topics included (listed alphabetically):

- Tom Dudley (UCSB) and Kevin Hultine (Desert Botanical Garden) – *Monitoring Ecosystem Recovery from Biocontrol and Restoration*
- Kevin Grady (NAU) – *Assisted Migration, Forest Restoration, and Climate Change*
- Shannon Hatch (Tamarisk Coalition) and Deborah Campbell – *Virgin River SWFL Collaborative Resource Guide*
- Jim Hatten (USGS) – *SWFL Breeding Habitat Modeling*
- Matt Johnson (NAU) and Rob Dobbs (UDWR) – *SWFL Critical Habitat and Restoration*
- Steve Meismer (VRP) – *Restoration/Mitigation as Part of Flood-Control Planning*
- Bruce Orr and Glen Leverich (Stillwater Sciences) – *Ecohydrological Assessment and Identification of Suitable Restoration Areas*

Well over 20 potential restoration sites were vetted during the workshop. Approximately 12 sites were identified as having the greatest potential for near-term, active implementation involving some combination of strategic tamarisk removal and native vegetation planting to enhance existing SWFL habitat, and to avoid any short-term impacts associated with implementation activities. The locations of the sites are not included in this report in order to respect owner and land-manager privacy. Additional details of the workshop were presented in the Resource Guide authored by the Virgin River SWFL Collaborative (2013).

4 RECOMMENDATIONS FOR NEXT STEPS

The results of the Ecohydrological Assessment help to highlight those portions of the Virgin River where riparian restoration might be suitably implemented based on several key environmental factors considered at the reach scale (see Figures 8.1 through 8.23). This information was subsequently evaluated by the Restoration Science Team members and several watershed stakeholders during a two-day workshop. The outcome of the workshop included identification of approximately 12 sites considered to offer the greatest potential for near-term implementation involving tamarisk treatment and native vegetation planting. As restoration planning efforts at these and any other sites move forward, certain environmental factors should be considered in more detail at the site-scale (<100 acres) to ensure restoration success and SWFL recovery.

4.1 Site-Scale Environmental Factors

Other physical and ecological attributes of the river that are equally important for restoration planning include soil conditions and salinity, groundwater levels, and wildlife habitat use and distribution. The details of these valuable attributes are as follows:

- Soil conditions, salinity, and groundwater – provide a spatially comprehensive analysis of pertinent soil conditions related to restoration potential:
  - Collate available shallow groundwater level data from monitoring wells operated by the Virgin Valley Water District, Southern Nevada Water Authority, and Washington County Water Conservancy District; install new monitoring wells (piezometers) with water-level recording sensors where geographic data-gaps exist;
  - Process recently collected soil samples and compile their data to characterize soil texture, salinity, and productivity/nutrient content; acquire samples from additional key locations to adequately characterize potential for native plant growth and restoration of key riparian plant species; and
  - Combine local empirical data with existing spatial data on soil characteristics (NRCS soils data), elevation (from 2011 LiDAR data), and groundwater to create updated composite GIS coverages of soils (texture, salinity) and depth to groundwater or relative elevation (as a proxy for depth to groundwater) for use in the final integrative analysis.
- Wildlife habitat use and distribution – identify contemporary and projected habitat distribution and population dynamics for SWFL and other sensitive wildlife species:
  - Create a geographic profile of SWFL habitat based on current and projected distribution and habitat associations;
  - Produce a conceptual model of SWFL population dynamics under current and expanded population sizes, including between-patch dispersal to describe potential metapopulation structure;
  - Build similar geographic profiles and conceptual models for other federally protected species (e.g., "Covered Species" of the Virgin River Habitat Conservation & Recovery Program, Clark County Multiple Species Habitat Conservation Plan, and Virgin River Program) potentially affected by tamarisk biocontrol and by riparian restoration actions; and
  - Identify riparian restoration locations, minimum/recommended stand size, and other habitat traits that will attract SWFL and other protected species, and that will maximize population increases, facilitate successful dispersal among suitable habitat

patches, and generate population stability that will promote sustainable populations with low risk of extirpations.

- Combine understanding of river and riparian vegetation dynamics with SWFL and other key wildlife habitat needs to help ensure that the final proposed mix of active and passive restoration actions is likely to result in a dynamic shifting mosaic of habitat patches in different successional stages sufficient to maintain the long-term viability of populations of SWFL and other key native species in the Virgin River corridor.

4.2 Hughes Middle School Case Study

Tamarisk removal and native vegetation plantings have been implemented by Partners in Conservation at the Hughes Middle School restoration site in Mesquite, Nevada on a regular basis since before the December 2010 flood. However, this flood severely disturbed restoration efforts here as the active channel adjusted abruptly, but not entirely unpredictably (see Figure 2). To aid future planning efforts at the site scale, we refined our Ecohydrological Assessment by including additional environmental factors pertinent to the site. These included soil texture and salinity based on the NRCS soils database, depth to shallow groundwater and in-channel depressions estimated from a relative-elevation surface produced from the November 2011 LiDAR (elevations are shown to be relative to the low-flow water surface in the river channel), changes in vertical elevations of the active river channel associated with the 2005 and 2010 floods (surface differencing of 3 repeat LiDAR datasets taken before and after each event), and vegetation structure and composition based on a combination of the LiDAR-based canopy-height surface, vegetation-classification layer, and field-based surveys (Figure 9). This type of information can feed directly into development of site restoration design and planting plans.

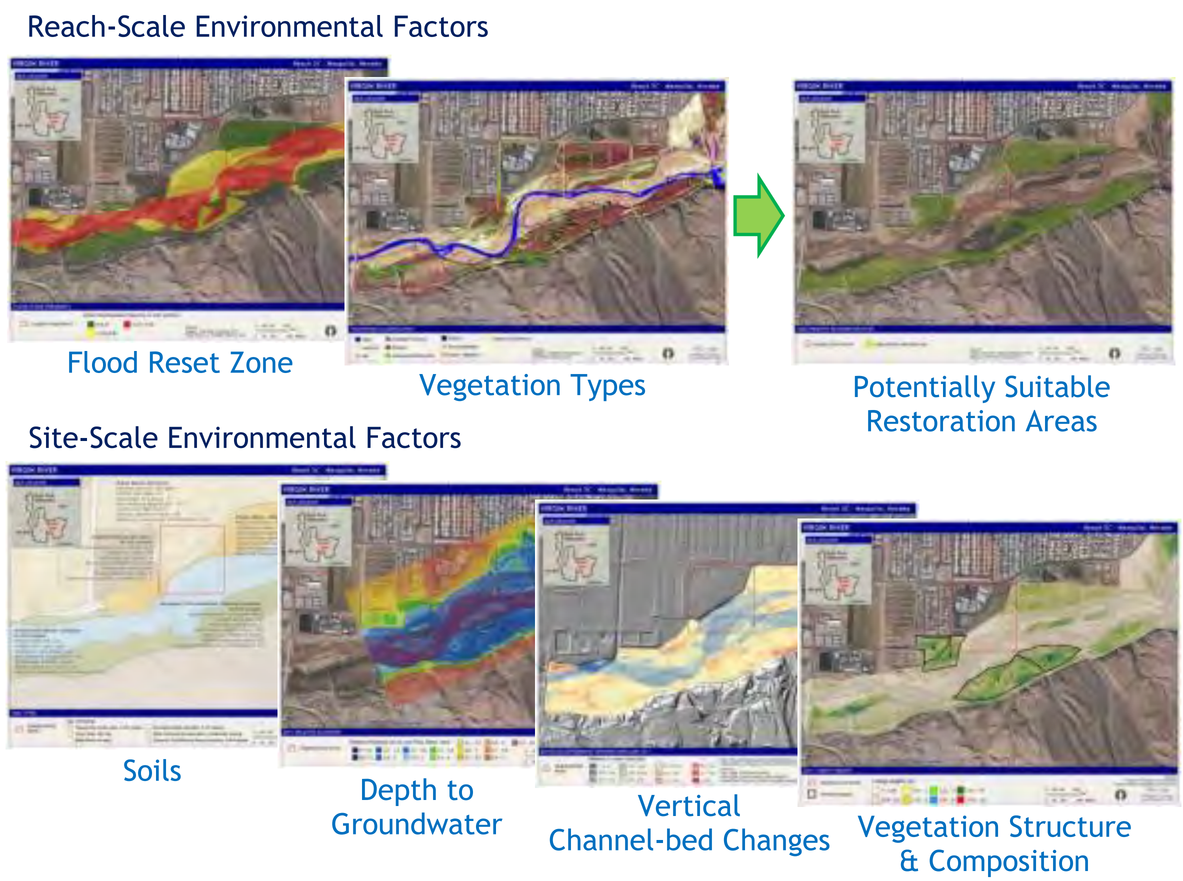


Figure 9. Process of refinement of the ecohydrological assessment at the site-scale to prioritize restoration at the Hughes Middle School restoration site in Mesquite, NV.

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Appendices

Appendix A

Technical Documentation for Remote-Sensing Data Collection by USU RS/GIS

Restoration Planning and Assessment for the Virgin River

Mapping the Geomorphology and Vegetation in the Virgin River Riparian Corridor Using Airborne High Resolution LiDAR and Multispectral Imagery

Final Report

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EXECUTIVE SUMMARY

The need for continuous monitoring of natural and invasive vegetation species and stream geomorphology in the Virgin River led to the sub-contract with Utah State University, as part of a larger project with Stillwater Sciences and U. of California Santa Barbara. The purpose was to acquire and use high resolution airborne multispectral imagery and Lidar data for monitoring post-2010 flood conditions. Due to delays in implementing the contract, the Virgin River was flown with the USU airborne multispectral and LASSI Lidar system in November 2011, to mainly obtain Lidar data before the following winter and potential spring floods that could have change the geomorphology of channel again. The Lidar data were processed to produce 3-D point clouds of returns and then classified into vegetation and surface returns. The surface returns were used to produce 1-meter digital elevation models (DEM) of the floodplain and surrounding areas. The canopy returns were used along with the DEM's to produce a canopy height layer, to be used in the vegetation classification. The multispectral imagery was processed into 3-band images and used along with the Lidar data to produce orthoimagery of the floodplain using a direct geo-referencing technique. Color digital imagery was also acquired and used to produce color orthoimages of the Virgin River floodplain and surrounding areas, matching the Lidar coverage. The multispectral imagery was classified using supervised classification techniques to produce a thematic layer of vegetation and surface cover types of the immediate floodplain of the Virgin River. The Methods section of the report describes the image and Lidar acquisition campaign, the processing methodology, and the image classification. Samples of the delivered products are shown in the Results and Discussion chapter.

The ultimate goal of this sub-contract was to provide high-resolution Lidar and image products for geo-morphological studies and obtain an up-to-date resource map of the Virgin River floodplain, identifying the main native and invasive vegetation species.

INTRODUCTION

Monitoring of vegetation species and geo-morphology of the Virgin River Canyon is important for understanding the changing nature of these systems as a response to floods and control of invasive vegetation species such as Salt Ceder or Tamarisk (*Tamarix spp.*), subject to attacks by the Asian beetle (*Diorhabda elongata*).

This final report describes the data and methodology used in the monitoring program of 2011, presenting samples of the products and the vegetation resources classification results. Approximately 130 river miles of the Virgin River were covered in the effort starting south of Zion National Park downstream to Lake Mead.

METHODS

Description of the Airborne Remote Sensing System

Multispectral Image Acquisition and Processing

The multispectral portion of the airborne system consisted of three Kodak Megaplus 4.2i digital cameras with interference filters forming spectral bands in the green (0.545-0.555 μm), red (0.665-0.675 μm) and near infrared (NIR) (0.790-0.810 μm) wavelengths. The cameras are mounted along side the Lidar through a porthole in a Cessna TP206 aircraft, dedicated for remote sensing missions (Figure 1). The cameras are controlled through special software using Epix boards in a fast desktop computer, mounted in the equipment rack. The system digital cameras are calibrated against a radiance standard using a method described by Neale and Crowther (1994). On the day of the flight, a standard reflectance panel with known bi-directional properties was set up in a central location to the study area. An Exotech 4-band radiometer was mounted looking down onto the panel from nadir, measuring incoming irradiance at one-minute intervals. This information was used to calculate the reflectance of the pixels in the spectral imagery. The panel was mounted either at the Saint George, Utah airport or the Mesquite, Nevada airport depending on what section of the river was being flown.

The shortwave images were acquired at a nominal pixel resolution of 0.4 meters with an overlap of 80% along the flight lines which were planned to cover the river corridor. The 800 m swath width overlapped laterally at least 30% with the adjacent flight lines. The individual spectral band images were radiometrically adjusted for lens vignetting effects (Neale and Crowther, 1994) and registered into 3 band images, used along with the the Lidar data to produce the orthomosaics. The 3-band images were ortho-rectified, using the geometric calibration parameters of the cameras and Lidar instrument obtained by flying a calibration pattern over the USU campus prior to the mission. The Terraphoto and Microstation software were used for this task. The direct geo-registration technique used a TIN obtained from the Lidar terrain parameters and point cloud date along with the positioning information from the Lidar Novatel navigation system supported with appropriate ground control. The rectified images were mosaicked into larger image blocks following the flight line pattern. The rectified image blocks were calibrated in terms of reflectance prior to the formation of the final mosaic covering sections of the floodplain.

Figure 1. Details of the USU airborne multispectral remote sensing system and LASSI Lidar system installed on the USU Cessna TP206 remote sensing aircraft.

Lidar Data and Color Image Acquisition and Processing

The Lidar system uses a full-waveform Riegl Q560 lidar transceiver, a Novatel SPAN LN-200 GPS/IMU Navigation System. The lidar is capable of working at up to 1200m above ground level (agl) and, depending on the flying height, at a pulse rate of up to 250,000 shots per second. It has beam divergence of less than 0.5 mrad and therefore has a footprint size of about 0.5 m at 1000 m agl. The average flying height above the Virgin River was 800 m, which, given the pulse rate of 100,000 shots per second, a flight speed of 180 Km/h and a scan rate of 115 Hz, resulted an average shot density of 2 shots per square meter. Given a 50% side-lap specification, an average shot return of greater than 4 shots per square meter was obtained in the overlap zones. The waveform for each shot was digitized at a rate of 500 MHz which yielded a volume spacing of 0.6 m for each single shot within the vegetation. Based on the availability of GPS satellites and the locality of differential GPS base-stations, an absolute vertical and horizontal accuracy of 8 cm and 15 cm respectively, was achieved. A single ground base-station collecting GNSS data on one-second epochs was occupied during the flight.

Color digital images were collected by a Cannon EOS 5D Mark II camera at 21.1 megapixels generating .jpg images with a resolution of 5616 (width) x 3744 (height) pixels.

The processed Lidar point clouds return data were classified using a special routine to separate the ground returns from the vegetation returns. The ground returns were used to produce a triangular irregular network and 1-meter digital elevation models for the covered area.

Image and Lidar Data Acquisition Campaign

The airborne data acquisition campaign occurred on November 8, 2011 between the hours of 12:30 pm to 2:30 pm MST and on between the times of 11:00 am and 2:45 pm MST on November 9th. The sky conditions were sunny and clear on both days. Figure 2 shows the 84 flight lines covered where Lidar and color/multispectral image data were acquired. A list of the raw Lidar data files collected is shown in the Appendix section. The lines in red (Figure 2) indicate missing data due to malfunction of the multispectral cameras, a condition that was not noticed at the time by the system operator. On the first day of the flight there was a failure of the Near-Infrared camera. In order not to compromise the mission and the need to acquire Lidar data before the winter, the filter of the Near-IR camera was swapped with the Green band camera and the data acquisition flights proceeded with two cameras, acquiring the more important spectral bands for image classification: the Red and Near-infrared bands.

Lidar and color imagery were acquired normally with no problems. Prior to the mission and before leaving Logan, UT, the aircraft conducted flyovers and acquisition of lidar and image data over known targets in the area to provide information for Lidar/camera calibration. These data were used to calibrate the scanner and bore sight the cameras. This is routinely done as a part of each mission to ensure the highest accuracy possible. During the data collection, in-flight quality assurance was conducted by monitoring the lidar data swath to avoid any data gaps between the flight lines caused by air turbulence which can lead the aircraft to wander, pitch or roll.

The actual local flight times and duration of flights were controlled by weather, fuel consumption of the aircraft and safety of flight operations in this mountainous region. This limited our flexibility in planning for times when the GNSS constellation was most favorable thereby producing the highest number of satellites visible in the best geometric configuration relative to the GNSS receivers onboard the aircraft as well as at the base station on the ground.

Specifications for Lidar data and color imagery are shown in the Appendix section.

Figure 2. Schematic of the flight lines flown during the data acquisition flights. Red lines indicate missing multispectral imagery.

Project Area Extents and Project Tile Index

Figure 3 illustrates the tile layout and project extents for the LiDAR survey. Tiles were designed on a 1000 m by 1000 m grid. The tile numbers were automatically generated'

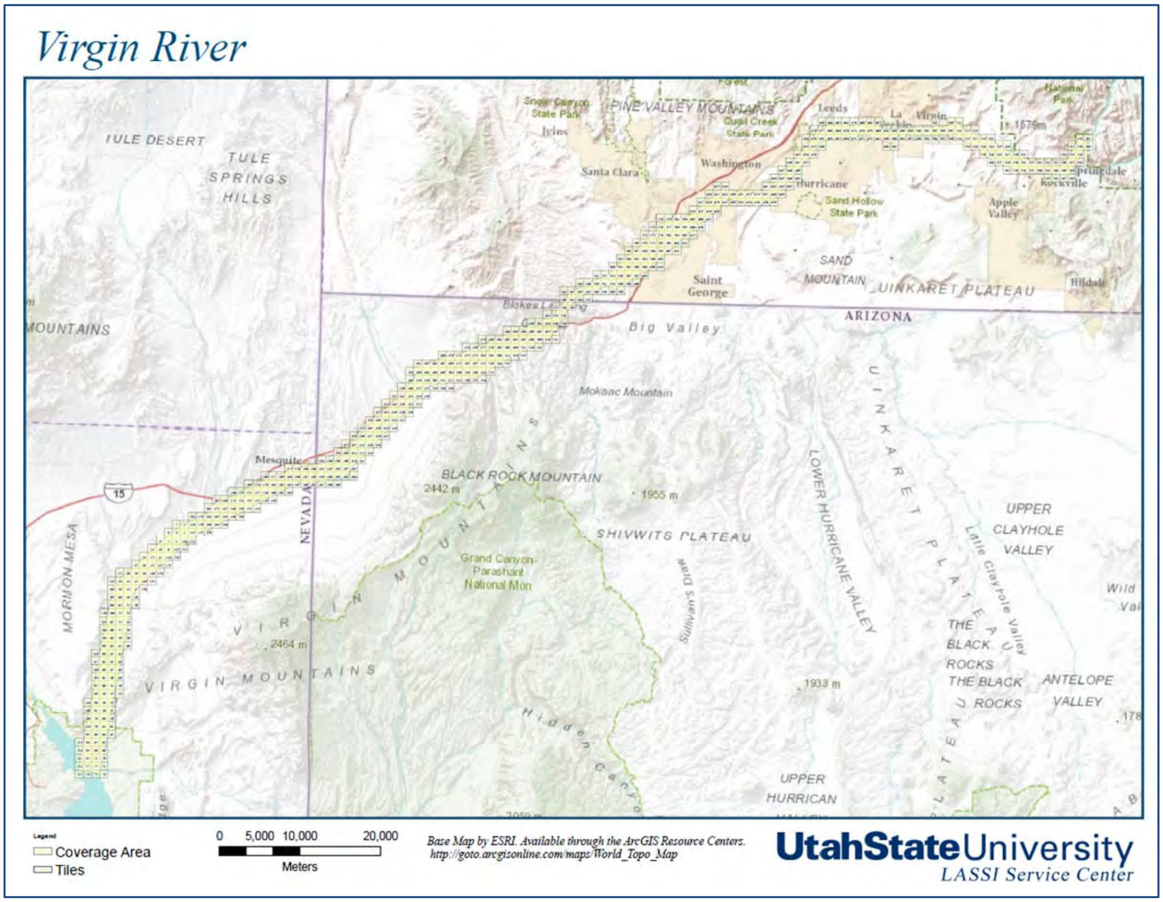


Figure 3. Tile layout and project extents.

Lidar Data Processing and Product Development

Data Storage

Data collection of the survey area resulted in a total of 84 flight lines covering the project area. After each flight, all raw navigation data, raw LiDAR data, raw image data, coverage data, and flight logs were offloaded to a computer and an additional backup storage copy created.

Navigation System

Raw GPS/IMU data from the airborne navigation system and raw GPS data from two IGS base stations are processed in Waypoint Inertial Explorer software (www.novatel.com) to produce a solution for aircraft position and attitude. GPS/IMU data is processed independently forward and backward in time, combined, and smoothed. The difference between forward and reverse solutions if used to asses solution accuracy. At export the trajectory data is transformed to the NAD83(CORS96) project datum for use in the LiDAR processing.

LiDAR System

LiDAR waveform files were analyzed using RiAnalyze software to discriminate data points. These points are output in the internal coordinate system of the LiDAR scanner. Each data point is assigned an echo value so it can be used in point classification work. RiProcess then uses the trajectory files created from the raw navigation data to generate XYZ points in a world coordinate system. A boresite calibration and strip (single scan line) adjustment was performed in RiProcess to improve data accuracy. This project's data were processed in strip form, meaning each flight line was processed independently. Processing the lines individually provides the data analyst with the ability to quality control (QC) the overlap between lines. To assess trajectory integrity, individual flight strips were then checked against adjacent strips to ensure good matching in the dataset.

Each flight line (strip) was then brought into Terrascan (by TerraSolid) in the project datum and coordinate system. These flight lines were then combined and several classification routines, customized for the given terrain and vegetation, were then run to classify the points into standard ASPRS/LAS default classifications. Final bare-earth DEMs and DSMs were derived from a Triangulated Irregular Network (TIN) of the classified LiDAR point clouds.

Following is an example LAS tile (Figure 4) which shows a 2.0 m contour interval and a black line where a cross-section is measured. The cross-section is shown below. The point clouds are tiled into 1000 m x 1000 m blocks. Typically, blocks of 1 million points or less are convenient, so they can be viewed with software such as ArcGIS.

The bare-earth DEM was used with the points classified as vegetation to create a canopy height map. This was done in a grid data structure using ESRI ArcGIS and a series of grid modeling steps. The grid cell size was 1 meter square, the same grid size as the DEM's.

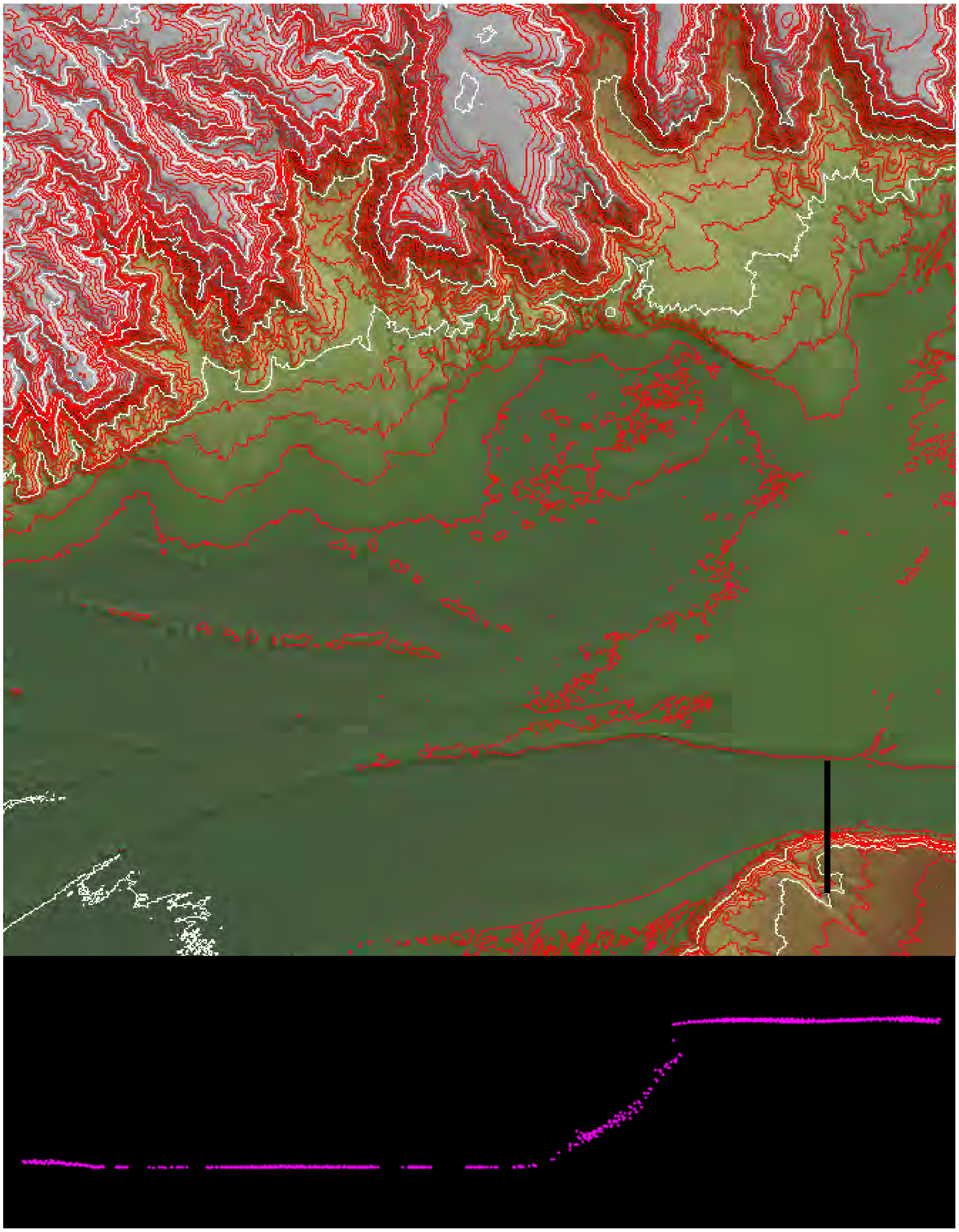


Figure 4 Classified bare-earth Lidar data tile with 2 meter contour lines and sample cross section in black.

Color Imagery

Color Images were then processed by TerraPhoto (by TerraSolid). During collection, raw images were stored with a unique timestamp which, used in relation to the flight trajectory and time, provided an initial projected rectification location for each raw image. Mission specific camera calibration parameters were adjusted, and image location was refined to align with neighboring images. Images were projected onto the collected LiDAR points, overlapping portions of the images were cut at automatically generated seam lines. Feathering was applied to the seam lines, and the orthorectified mosaic images were output as .tiff images with associated .tfw files organized in a tiling system; each tile representing an area of 1000 m x 1000 m GSD. Pixel size for color ortho-mosaics was set at 0.16 m resulting in an image with 6250 x 6250 pixel resolution.

The orthoimage in Figure 5 is an example tile that matches the lidar tile given above.

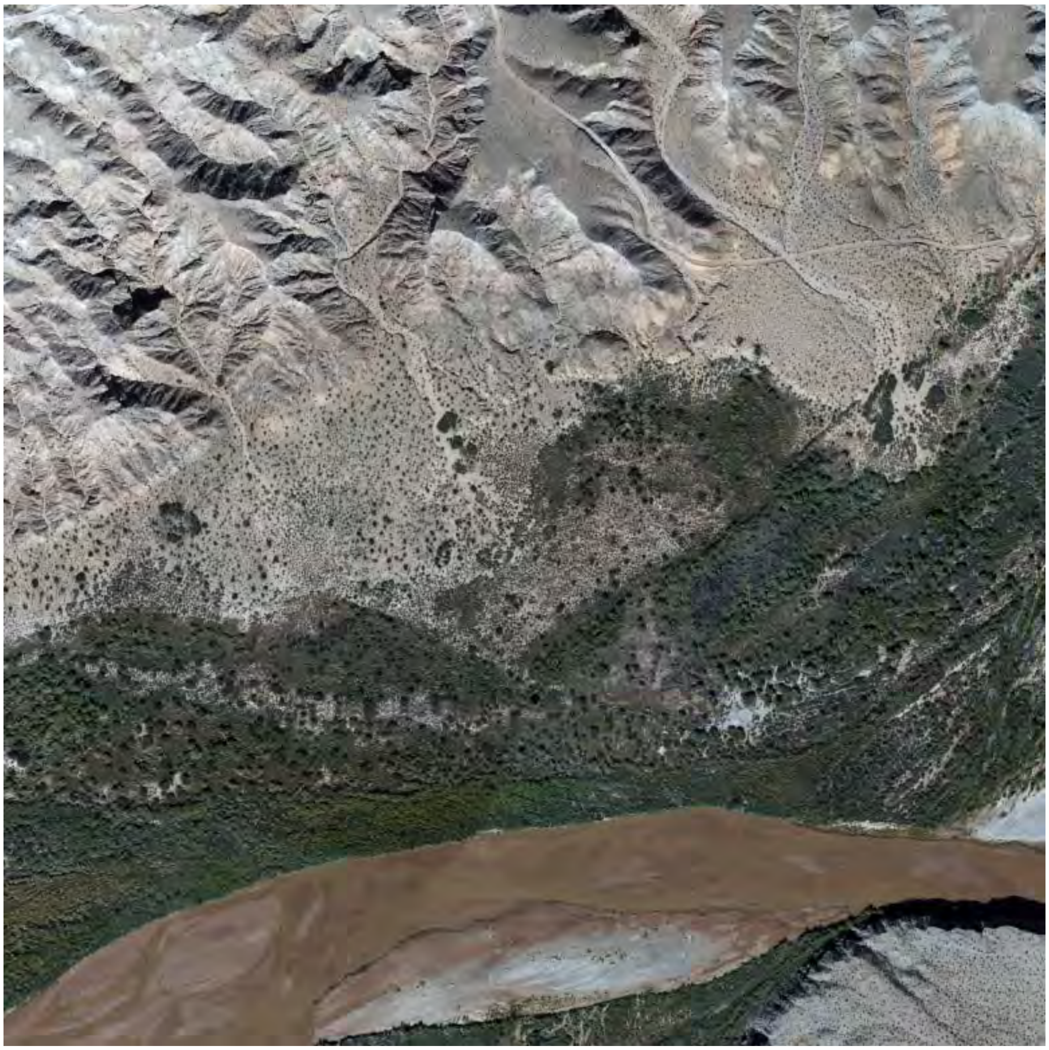


Figure 5 Sample tile of digital color orthoimage.

RESULTS

Lidar Data and Derived Products

Sample of the products are shown below. Figure 6 shows a section of the Virgin River by Saint George, Utah indicating the locations of the 1000 m x 1000 m Lidar data tiles for the section. Subsequent images show some of the data related to tile 415 identified in the figure below.

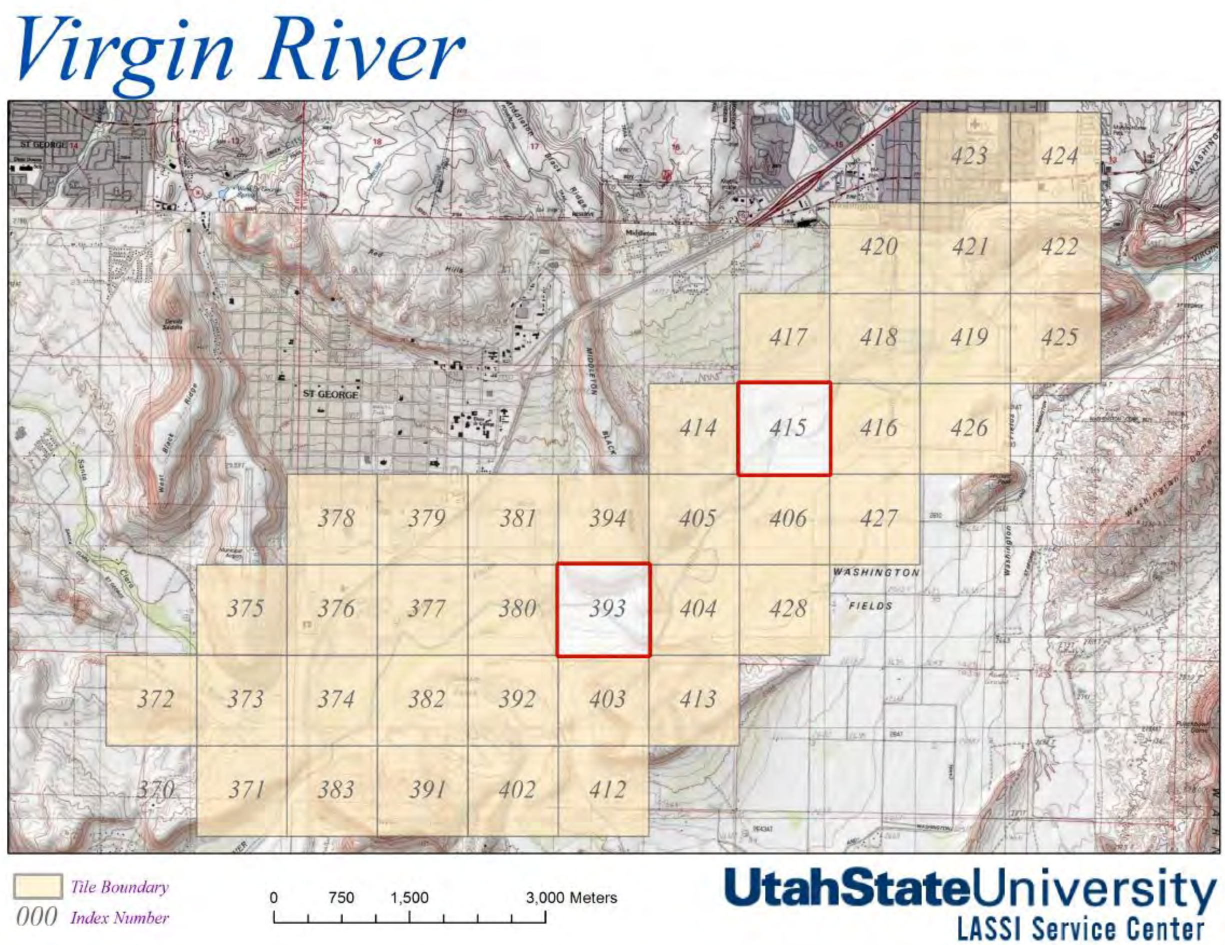


Figure 6 Lidar data tile numbering and location for a section of the Virgin River by Saint George, UT.

Block 415 –
Bird's Eye View

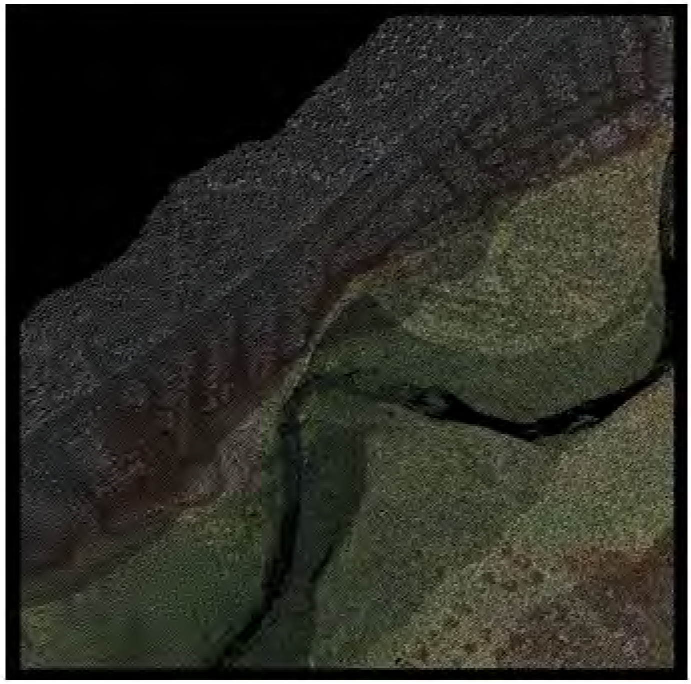


Figure 7 Colorized Lidar point cloud returns for tile 415.

Block 415 –
Zoomed Area

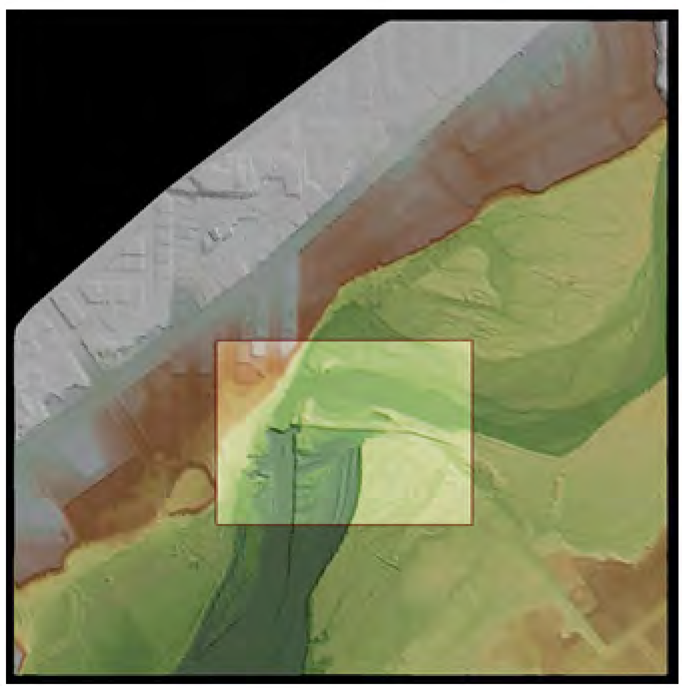


Figure 8 Triangular Irregular Network (TIN) produced from the classified Lidar surface returns.

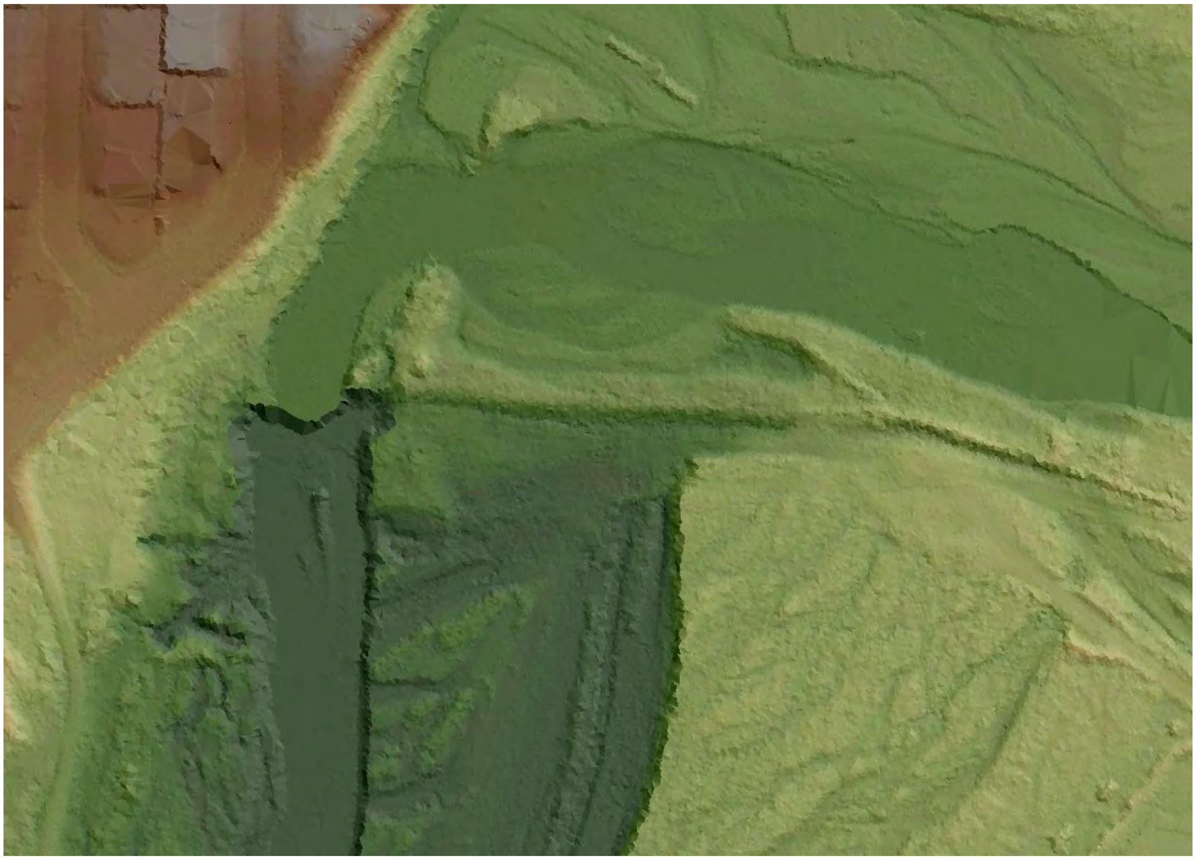


Figure 9 Detail of the TIN for tile 415

Figure 10 Contour lines (0.2 m) produced from the TIN surface

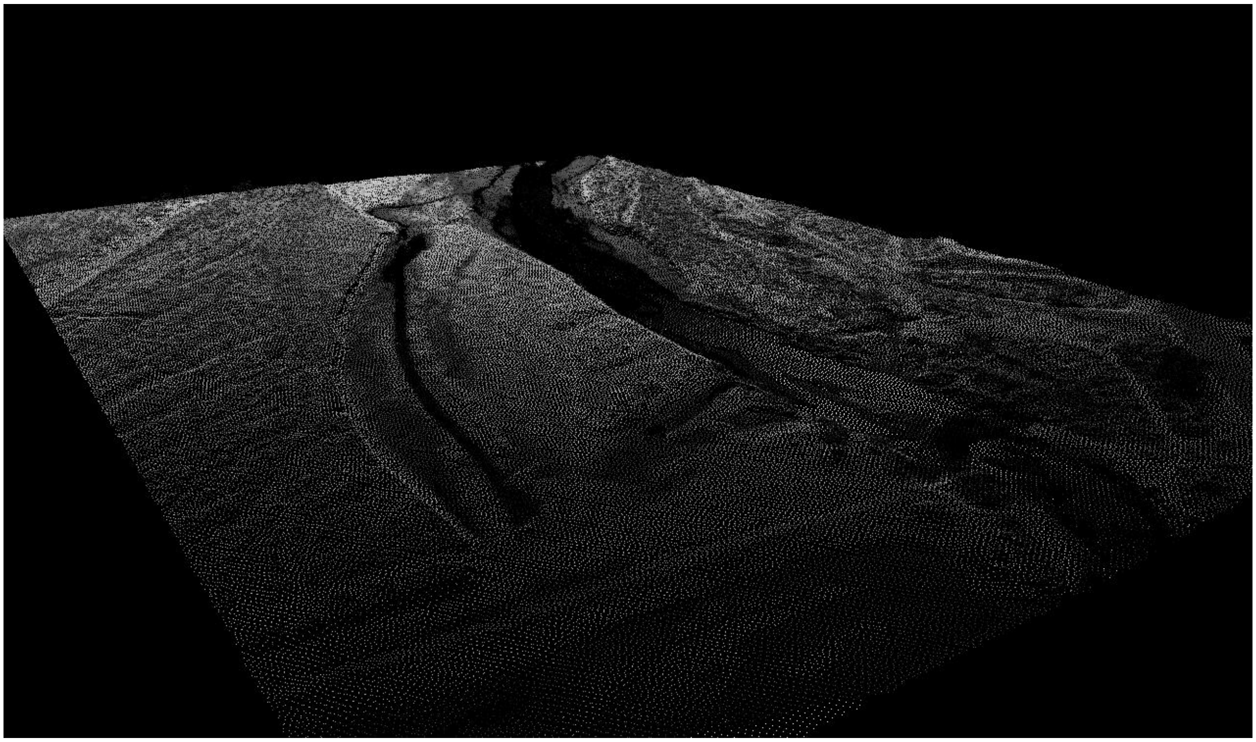


Figure 11 Point cloud intensity image of the detail area of Tile 415

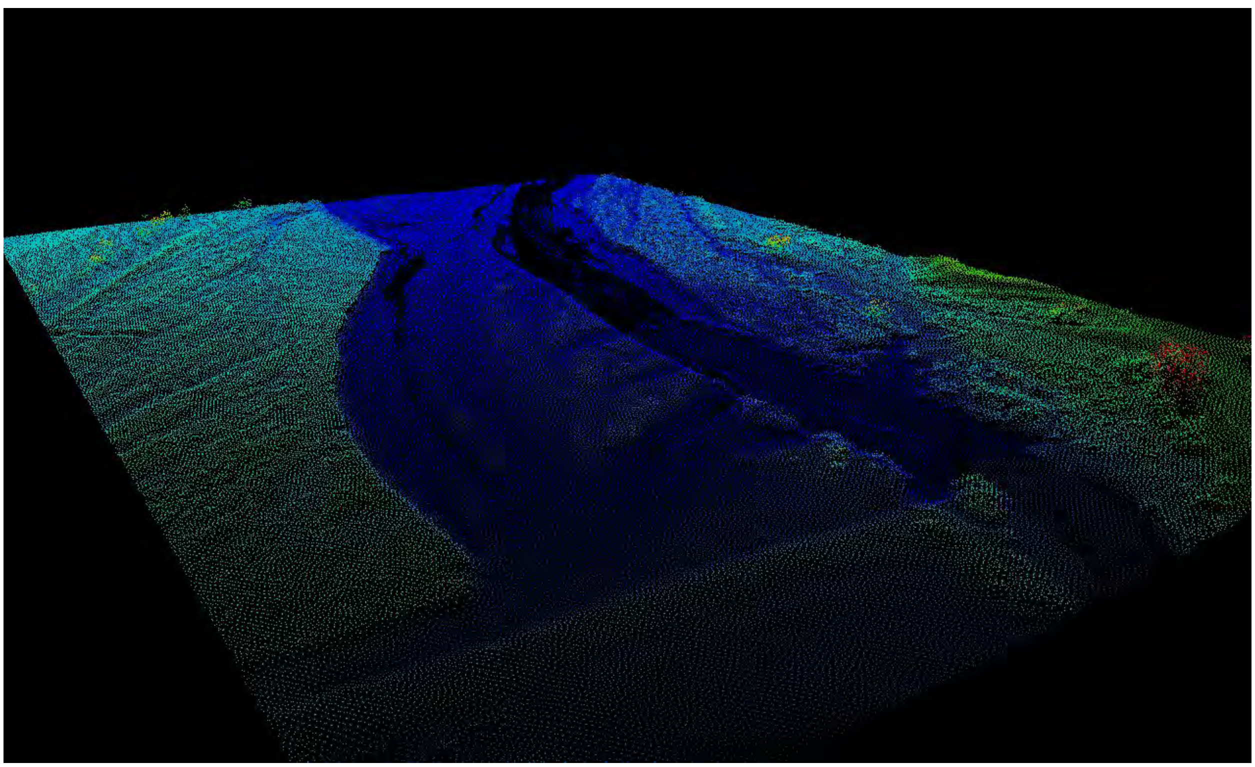


Figure 12 Point cloud colored by elevation

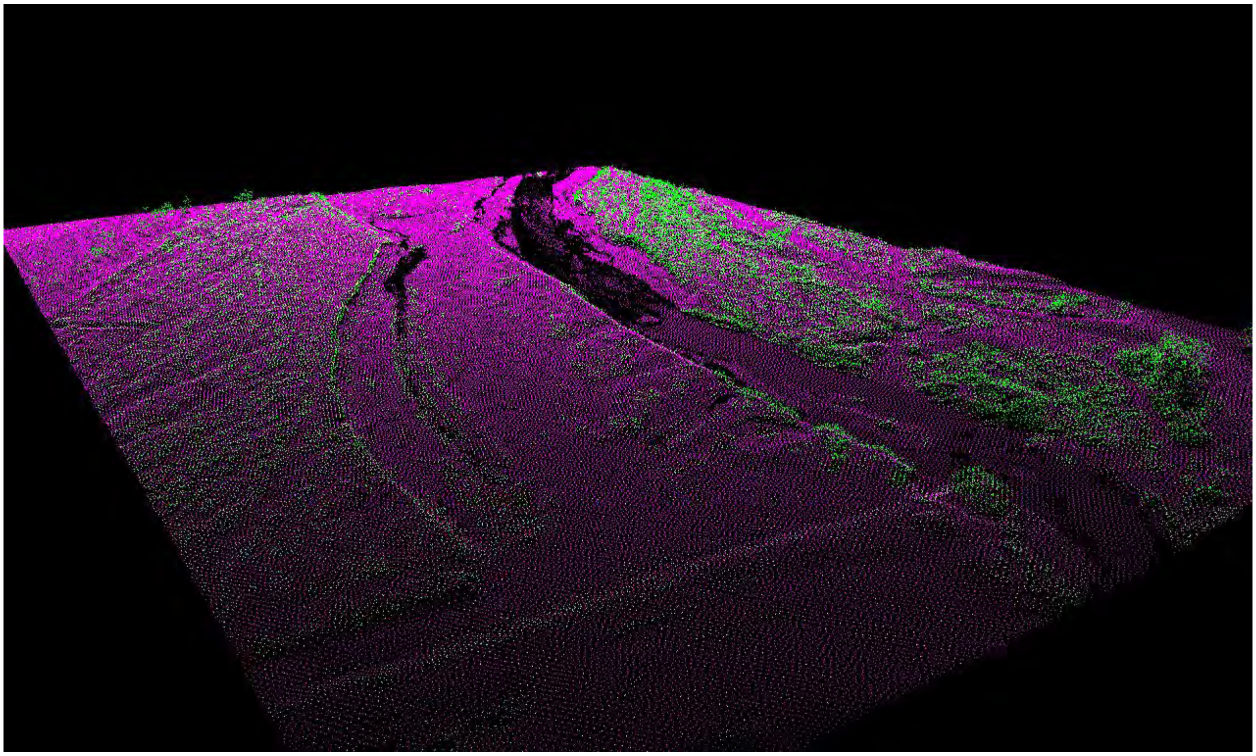


Figure 13 Classified Lidar point cloud separating vegetation and ground surfaces

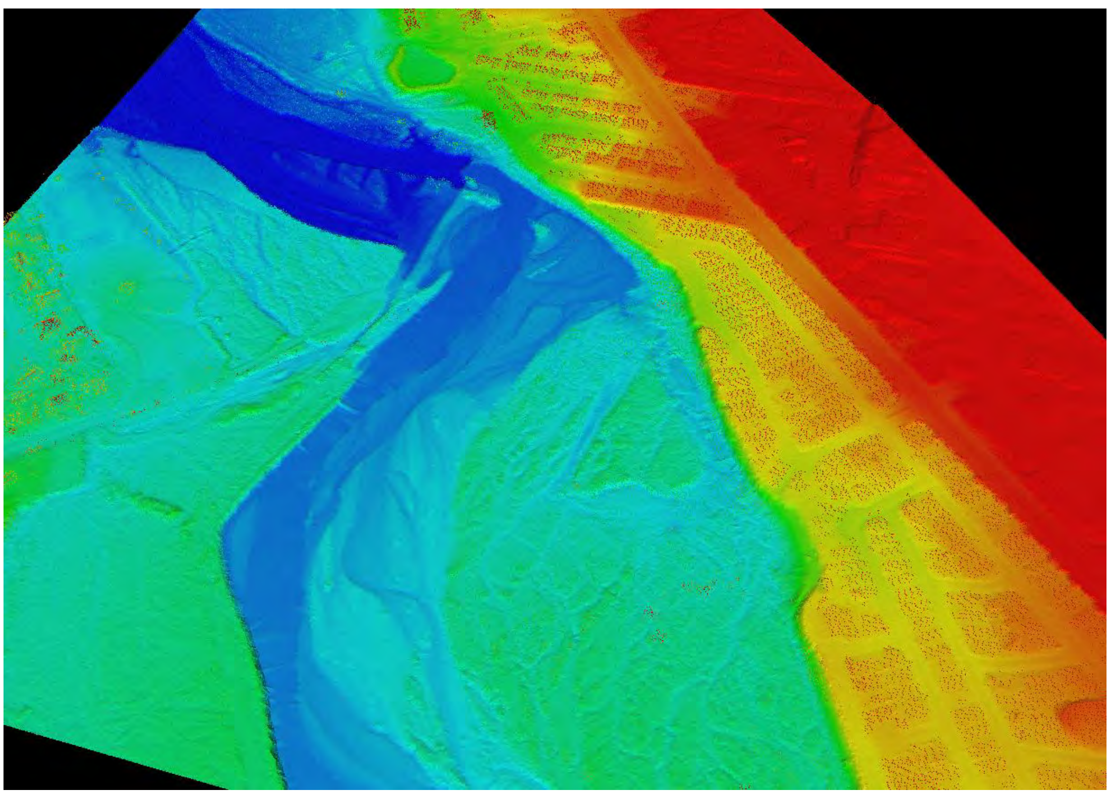


Figure 14 Colorized Tin with elevation

Color digital orthophotos

A complete set of color digital orthophotos was produced using data from the color digital camera of the LASSI system, corresponding to the Lidar tiles. An example is shown in Figure 15 below.

Figure 15 Color digital orthophoto tile of a section of the Virgin River, near Saint George, UT.

Multispectral Imagery

Multispectral digital orthophotos were produced for the Virgin River floodplain from individual 3band registered multispectral images. As the green band was missing due to camera failure, the red band was doubled up. An example of an individual image can be seen in Figure 16 below.

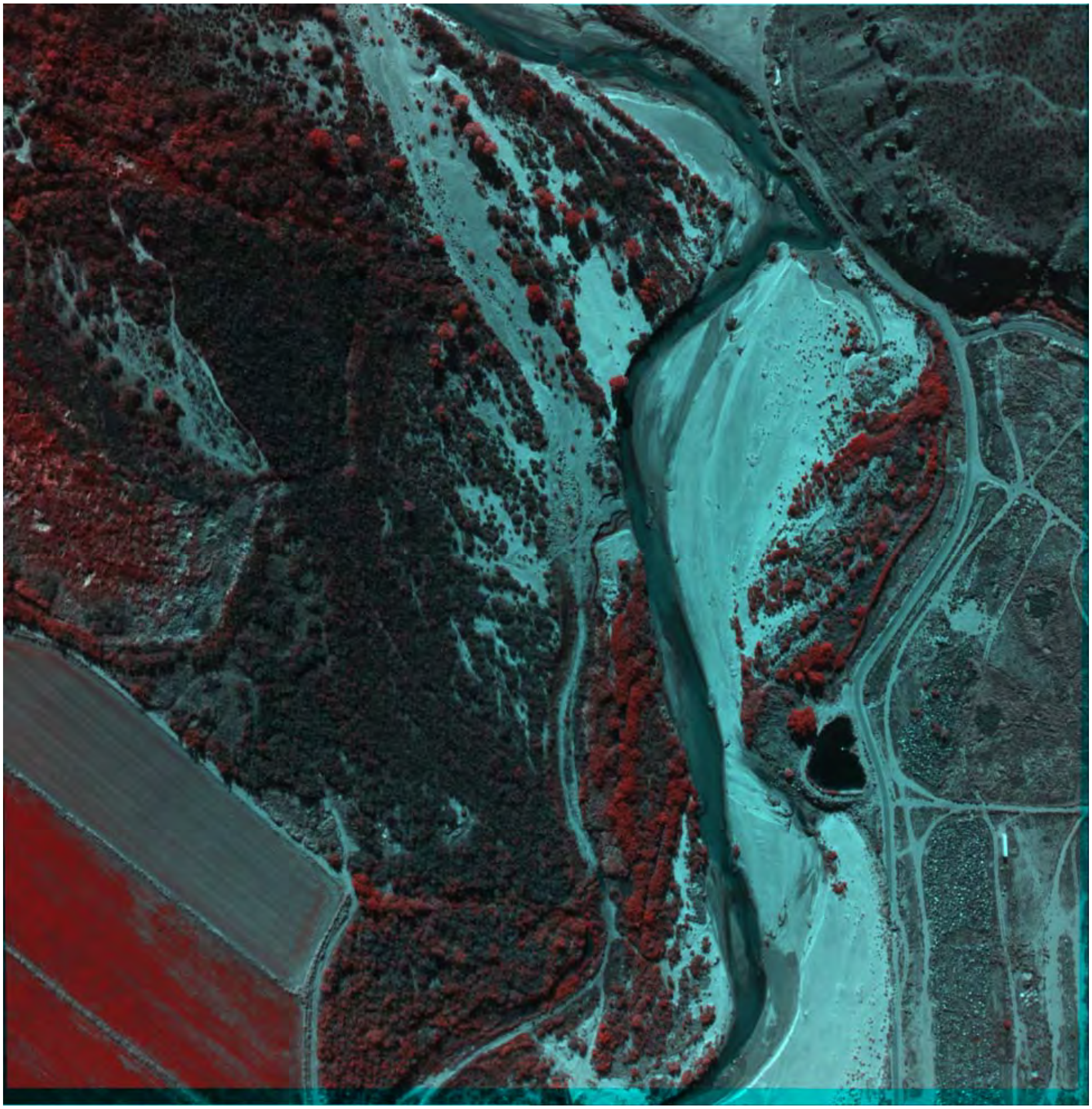


Figure 16 and individual multispectral 3band image of a section of the Virgin River close to Saint George, UT showing defoliated salt cedar (grey colors) and other riparian vegetation species and an agricultural field.

The multispectral digital orthos were produced by flight blocks which are a series of parallel flight lines covering a section of the river and that can be seen in Figure 2. An example of a multispectral mosaic for 3 blocks is shown in Figure 17 below.

Figure 17 Multispectral orthophoto mosaics for three flight blocks of the Virgin River.

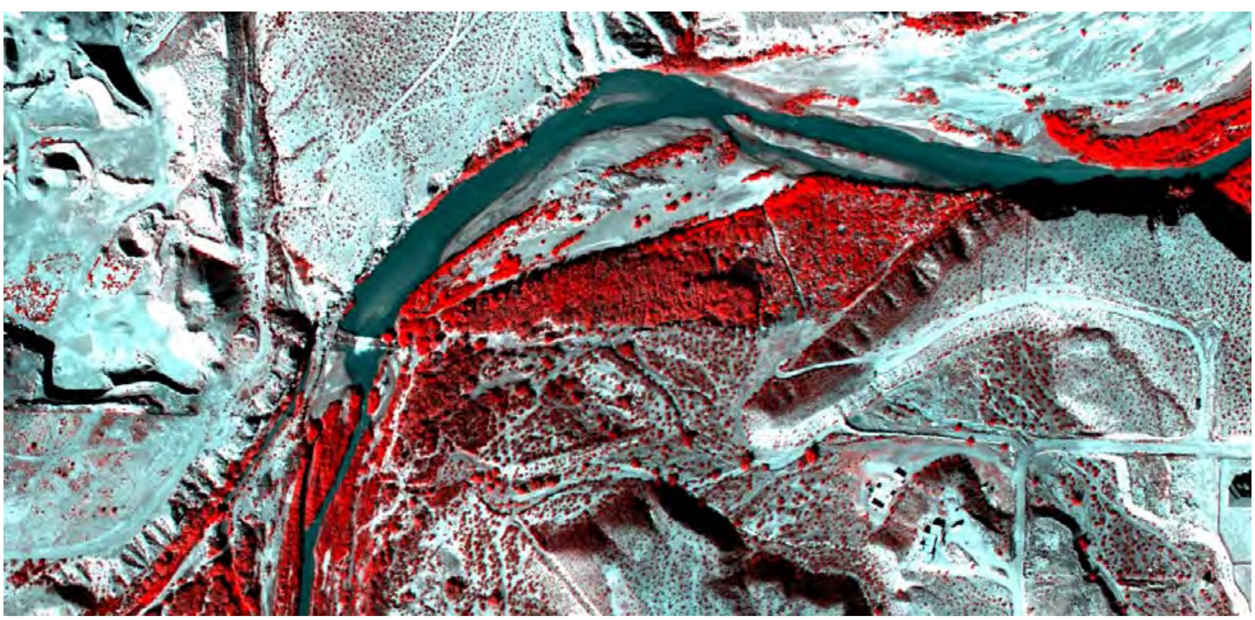


Figure 18 Detail of the digital multispectral orthophoto of Block 14.

Field Maps

Field maps of existing transects monitored by Stillwater Sciences and University of Santa Barbara were prepared and printed to be used for support in the field. A sample can be seen below in Figure 19.

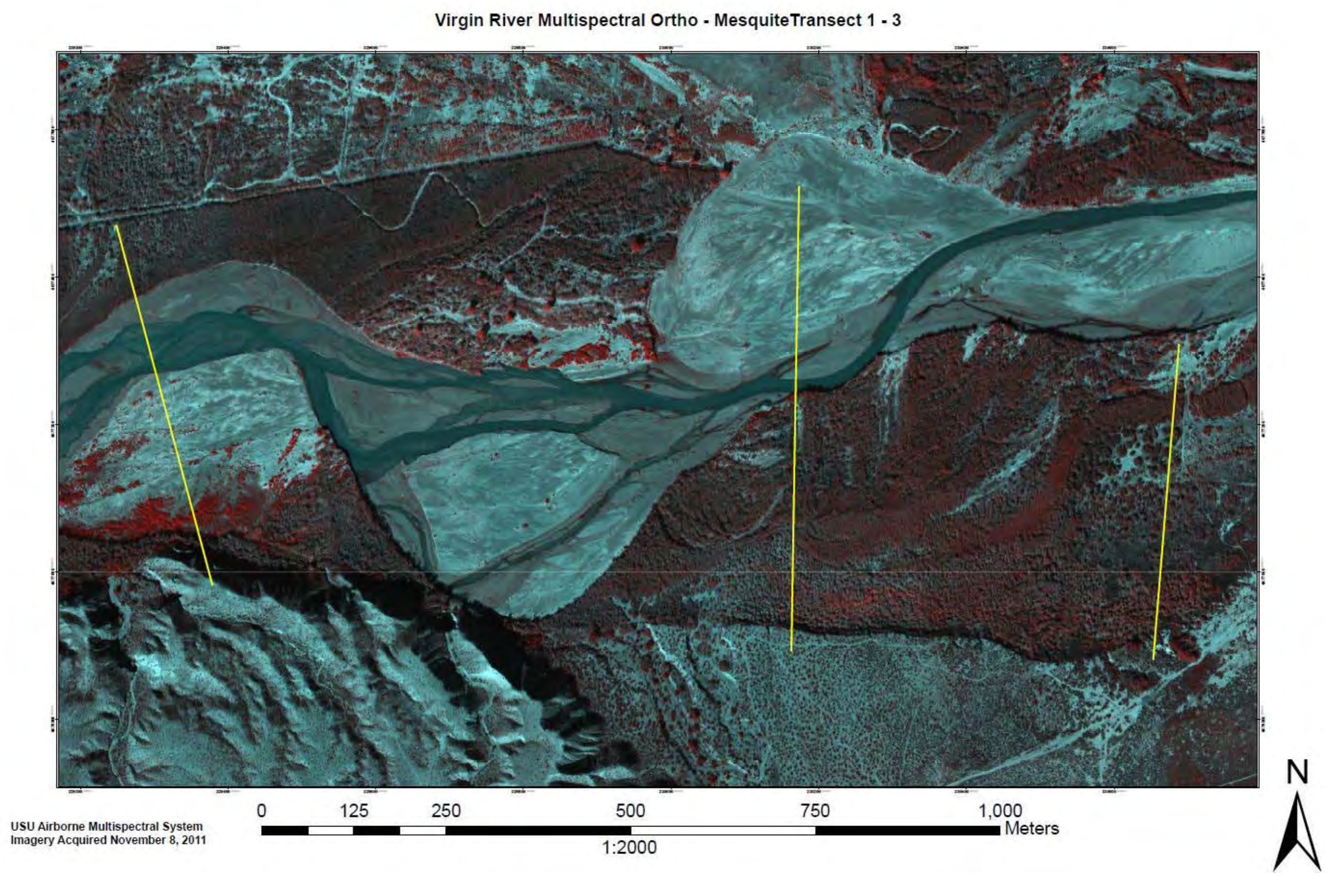


Figure 19. Example of a field map produced from the multispectral orthos covering 3 of the study transects.

Multispectral Image Classification

Due to the fact that the green band was absent in the multispectral imagery due to the failure of the green camera on the first day of image acquisition, the Soil Adjusted Vegetation Index (SAVI) (Huete, 1994) calculated from the red and near-infrared bands was estimated and used in its place. The SAVI is calculated on a pixel-by-pixel basis as:

$$SAVI = (NIR - RED)*1.5/(NIR+RED+0.5)$$

where NIR and RED and the reflectance values in those respective bands.

A model within ERDAS Imagine was programmed to estimate the SAVI, create the 3-band image as (NIR, RED, SAVI) and transform the values into integers by multiplying them by 1000. The latter is done to decrease the size of the calibrated image blocks which were very large in float format. In addition, in order to decrease the number of surface classes, an Area-of-interest (AOI) polygon was interpreted and digitized over the image to represent just the immediate floodplain of the Virgin River and the image was cut down to this size prior to classification.

The transformed and cut multispectral image blocks were classified using supervised classification techniques. Signatures were extracted using supervised seeding with the spectral Euclidean distance of the seeding growing properties set to 13. Signatures representing different depths of water, different hues of wet and dry mud and sand, bare soil, Salt Cedar (Tamarisk) trees at different densities, defoliated Salt Cedar, willows, cottonwood, ash, Russian olive and upland vegetation types were extracted using an iterative procedure. At each iteration, the signatures were evaluated for spectral separability using the Transformed Divergence method and overlapping signatures were removed. The image was then classified using the Maximum Likelihood scheme, selecting the unclassified rule as unclassified in ERDAS Imagine (Neale et al, 2011). This would leave pixels not represented by signatures in the signature set unclassified or black. Additional signatures would be extracted in these areas to represent these classes. After evaluation for spectral separability, a new classification iteration would be conducted. The procedure would be repeated until only salt-and-pepper pixels would remain unclassified. The final classification would classify all pixels resulting in a classified rendition of the image block.

Figure 20 shows image blocks 6 and 7 in the Utah section of the Virgin River with the classified floodplain overlaid. Because of the high resolution of the images and the bi-directional reflectance properties of the vegetation canopies, several signatures were required to represent the same class of vegetation. For image blocks 6 and 7, a total of 71 signatures were needed to represent the variability in the image. Once the image was classified, the classes were lumped through GIS recoding down to the following main resource classes:

1. Water
2. Sand/soil
3. Soil
4. Defoliated Salt Cedar
5. Salt Cedar
6. Cottonwood, Willow, Ash
7. Shadow
8. Wetland vegetation
9. Upland vegetation
10. Structures and roads
11. Agriculture

Figure 20 Multispectral image blocks 6 and 7 with classified floodplain overlaid.

A detail of the classified image can be seen in Figure 21. The sections the Virgin river in Utah, upstream of the canyon, has a mixed presence of salt cedar, cottonwood, willow and some ash. Large extents of salt cedar were defoliated at the time of the flight. On the lower sections of the Virgin, north of Lake Mead, larger extents of salt cedar were encountered but much of the floodplain was blown out by the flood, re-orienting and widening the main channel. The presence of Mesquite was also noted, mostly mixed in with the salt cedar within the floodplain analyzed.   A sample of a classified section (blocks 16 and 17) can be seen in Figure 22 with a detail shown in Figure 23.

CONCLUSIONS AND RECOMMENDATIONS

The final Lidar products delivered were within specifications. The late timing of the flight in early November impacted the quality of the image products due the increased amount of shadows in the imagery. The images in the canyon section of the Virgin River were particularly impacted. The quality of the color digital orthophotos were adequate. The multispectral imagery was impacted by the lack of the green band due to the failure of one of the digital cameras during the flight. In addition, some data gaps occurred in this imagery as well due to problems with the system during the flight.

The entire Virgin River project area was re-flown in August 2012 with the new USU airborne system with improved digital cameras. This imagery is available for further processing once the funding resources become available. We recommend that the canyon section in particular be analyzed with the new imagery which was acquired under better sun illumination conditions.

The lack of the green band also impacted the ability to separate Russian olives in the multispectral image classification. This shouldn't be a problem with the new imagery acquired. Data gaps will be covered with the new imagery.

An accuracy analysis of the classified products should be conducted as more ground truth information acquired in the field becomes available.

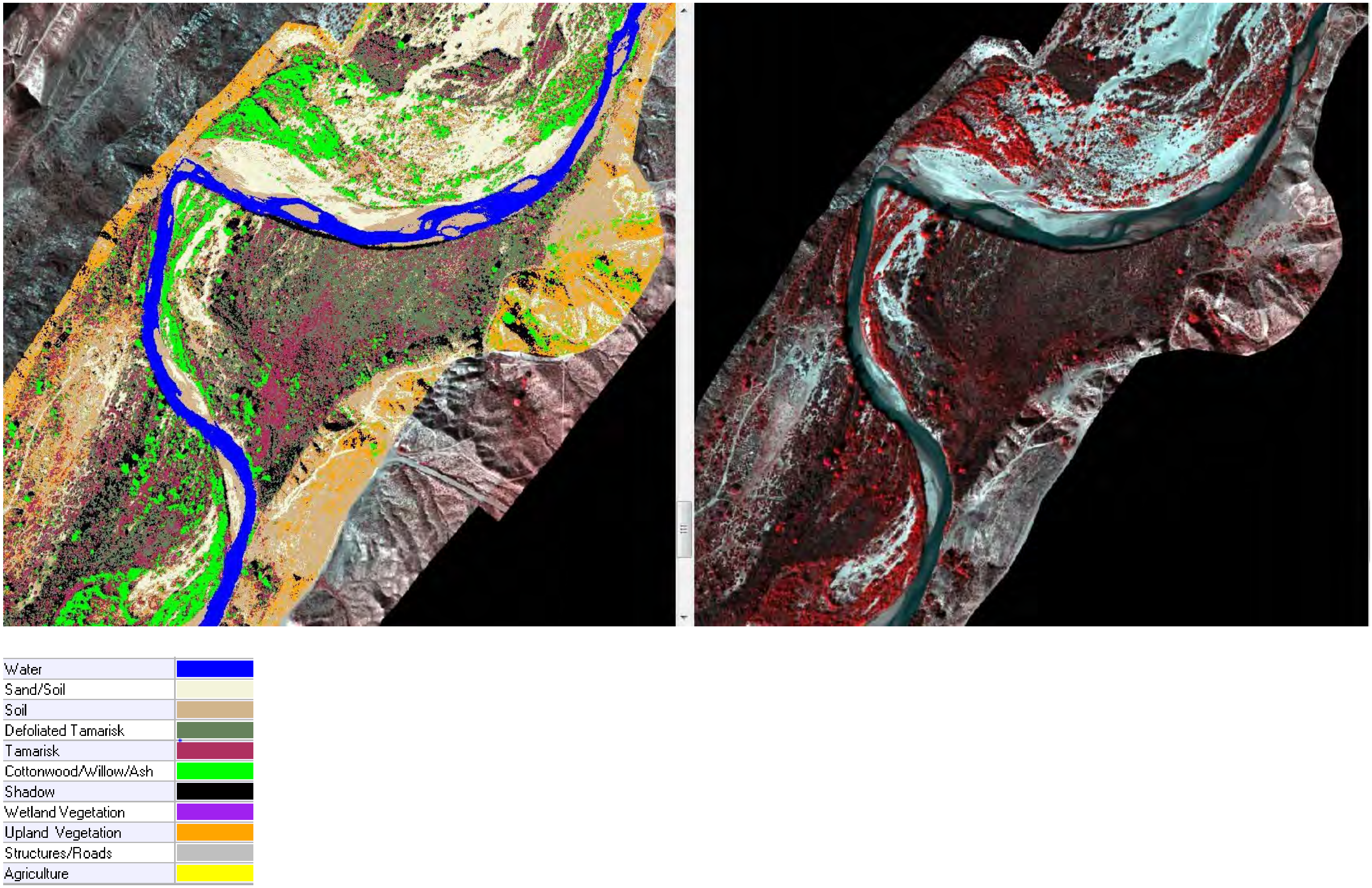


Figure 21 Detail of a classified section of Blocks 6 and 7.

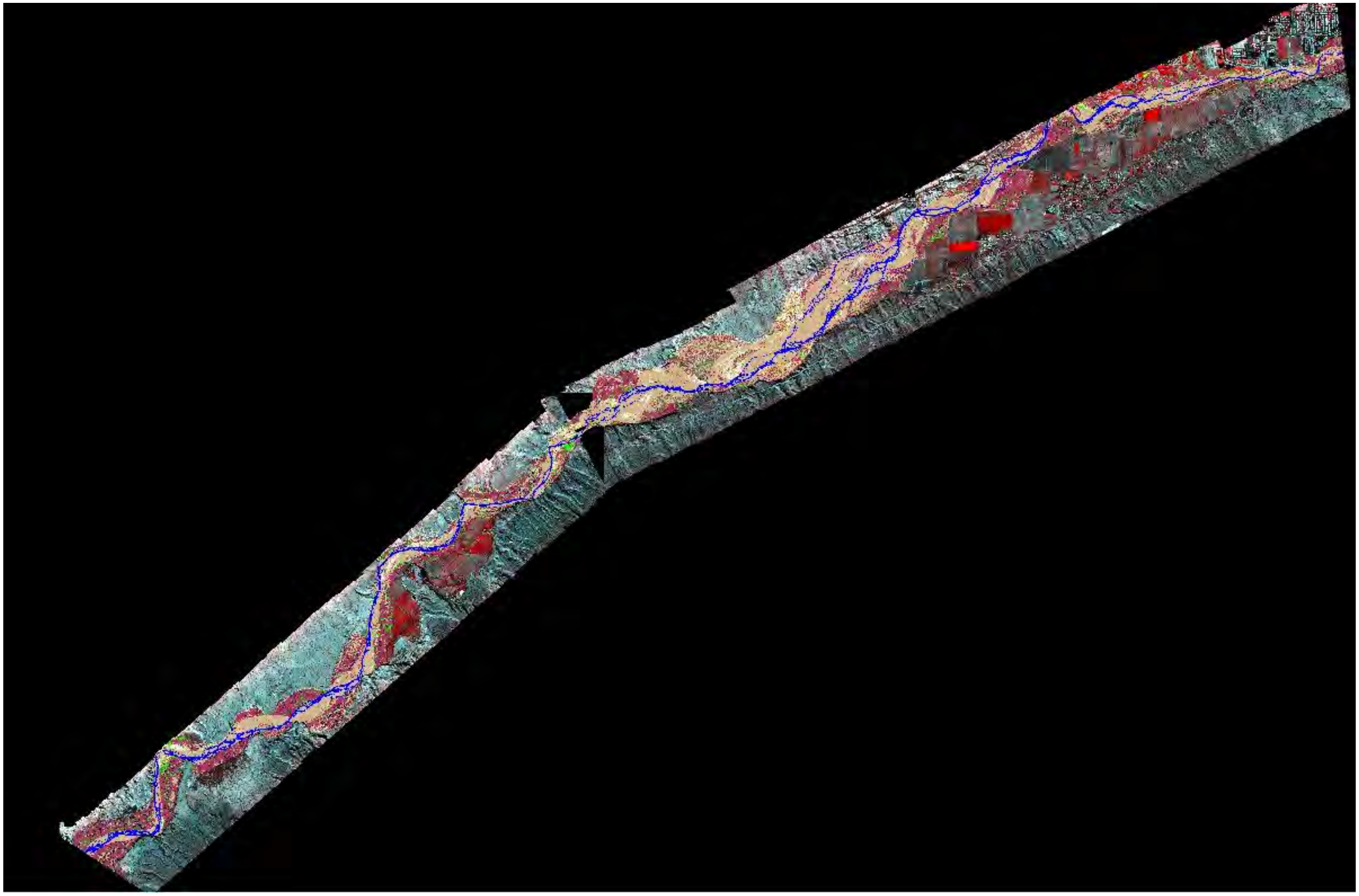


Figure 22. Classified floodplain over image blocks 16 and 17 of the lower Virgin River in Nevada, just upstream from Lake Mead

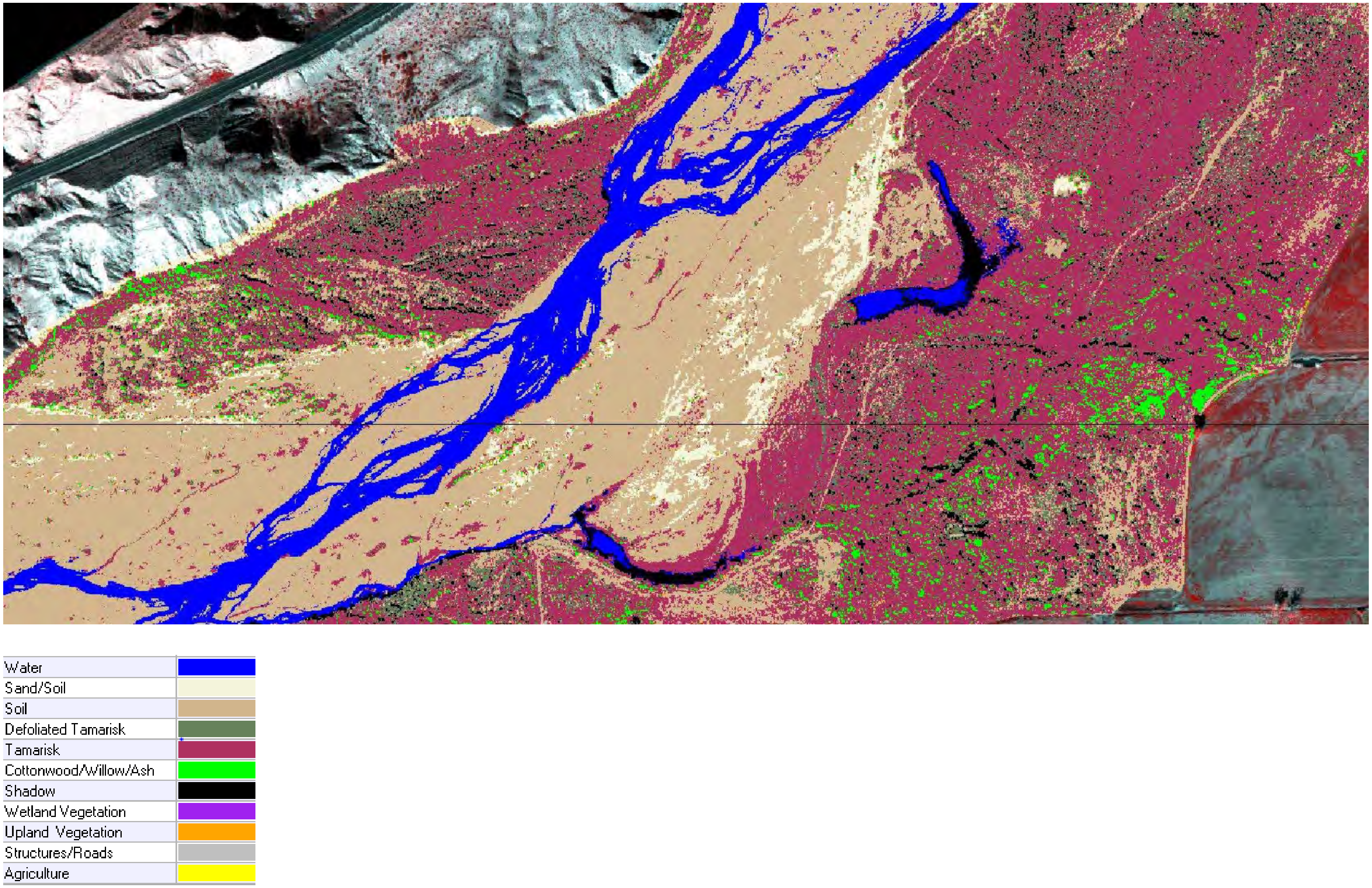


Figure 23 Detail of a classified section from Block 16

Products and Deliverables

The following products were part of the deliverables:

- Lidar classified point cloud data
- Digital elevation models (DEM) in 1000 m x 1000 m tiles
- Color digital orthophotos in 1000 m x 1000 m tiles
- Multispectral orthos of the floodplain mosaicked in flight blocks
- Field maps
- Classified multispectral imagery by blocks

The products were sent to Stillwater Sciences to be used in the floodplain analysis.

REFERENCES

Cai B., and C. M. U. Neale, 1999. A method for constructing three Dimensional Models from Airborne Imagery. 17th Biennial Workshop on Color Photography and Videography in Resource Assessment. May 5-7, 1999. Held at Peppemill Hotel and Casino. Reno – Nevada. Cosponsored by the American Society for Photogrammetry and Remote Sensing and Department of Environmental and Resource Science, University of Nevada

Neale, C.M.U, and B. Crowther. 1994. An airborne multispectral video/radiometer remote sensing system: development and calibration. *Remote Sens. Environ.*, Vol.49 (3), pp.187-194.

Farag, F. A.; C. M. U. Neale; R. K. Kjelgren; J. Endter-Wada. 2011. Quantifying Urban Landscape Water Conservation Potential Using High Resolution Remote Sensing and GIS Photogrammetric Engineering and Remote Sensing 77 11 1113-1122

APPENDIX

Lidar Data Acquisition

The LiDAR acquisition between November 08, 2011 and November 09, 2011 resulted in collection of 84 flightlines. Following is a list of files acquired during these two missions.

Navigation Files: Remote_Virgin_20111108_01LOG, Remote_Virgin_20111108_02.LOG, Remote_20111109_01.LOG, Remote_20111109_02.LOG

Raw Flightline (LiDAR Files):

111108_174427.sdf 111108_174629.sdf 111108_174905.sdf 111108_175658.sdf
111108_180531.sdf 111108_185357.sdf 111108_185817.sdf 111108_190806.sdf
111108_191612.sdf 111108_192414.sdf 111108_193215.sdf 111108_194022.sdf
111108_194840.sdf 111108_195311.sdf 111108_195742.sdf 111108_200201.sdf
111108_200837.sdf 111108_201421.sdf 111108_201958.sdf 111108_202532.sdf
111108_205018.sdf 111108_205404.sdf 111108_205846.sdf 111108_210211.sdf
111108_210541.sdf 111108_210907.sdf 111108_211245.sdf 111108_211606.sdf
111108_212142.sdf 111108_212730.sdf 111108_213310.sdf 111108_214049.sdf
111108_214239.sdf 111108_214448.sdf 111109_182849.sdf 111109_183027.sdf
111109_183229.sdf 111109_192854.sdf 111109_193614.sdf 111109_194301.sdf
111109_195021.sdf 111109_195708.sdf 111109_200435.sdf 111109_201058.sdf
111109_202100.sdf 111109_202506.sdf 111109_203052.sdf 111109_203530.sdf
111109_204236.sdf 111109_204718.sdf 111109_205149.sdf 111109_205651.sdf
111109_210205.sdf 111109_210730.sdf 111109_211401.sdf 111109_211848.sdf
111109_212327.sdf 111109_212755.sdf 111109_213121.sdf 111109_213441.sdf
111109_213814.sdf 111109_214115.sdf 111109_214504.sdf 111109_214934.sdf
111109_215359.sdf 111109_220349.sdf 111109_220712.sdf 111109_221040.sdf
111109_221452.sdf 111109_221812.sdf 111109_222052.sdf 111109_222345.sdf
111109_222626.sdf 111109_222952.sdf 111109_223451.sdf 111109_223931.sdf
111109_224353.sdf 111109_225009.sdf 111109_225416.sdf 111109_225639.sdf
111109_225919.sdf 111109_232305.sdf 111109_232446.sdf 111109_232647.sdf

Specifications for Deliverables

The required accuracy and file formats for each delivery was as follows:

<u>LiDAR Deliverables</u>

Grid Projection:	UTM Zone 12N
Horizontal Datum:	NAD83(CORS96)
Vertical Datum:	NAVD88 using GEOID09
Tile Size:	1000 m X 1000 M
File Formats:	*.las (v. 1.2)
Classified Datasets:	ASPRS/LAS Default Classes

<u>Grid Model Deliverables</u>

File Format:	ArcINFO ACII(.asc)
Grid Projection:	UTM Zone 12N
Horizontal Datum:	NAV83(CORS96)
Vertical Datum:	NAVD88 using GEOID09
Tile Size:	1000 m X 1000 m
Cell Size:	1.00m

<u>Color Imagery Deliverables</u>

File Format:	Tagged Image File Format (.tiff) & Georeference File (.tfw)
Grid Projection:	UTM Zone 12N
Horizontal Datum:	NAD83(CORS96)
Vertical Datum:	NAVD88 using GEOID09
Tile Width:	1000 X 1000 m
Pixel Size:	0.16 m
Image Size:	6250 x 6250 pixels

<u>Miscellaneous Deliverables</u>

Metadata Files:	FGDC compliant XML file. (.xml)
Project Tile Index:	Portable Document Format (.pdf)
Completion Report:	Portable Document Format (.pdf)

LiDAR data acquisition was performed using a Riegl LMS Q560 airborne laser sensor system capable of up to a maximum 200 kHz pulse repetition rate and collection of full waveform returns.

Color photos were collected by a Cannon EOS 5D Mark II camera at 21.1 megapixels generating .jpg images with a resolution of 5616 (width) x 3744 (height) pixels.

A single ground basestation collecting GNSS data on one-second epochs was occupied during the flight.

Appendix B

Flood-Scour Analysis Supporting Information and Maps

1 INTRODUCTION

This appendix presents supplemental information on the methods and results of the flood-scour analysis performed for the ecohydrological assessment described in the main report (see Section 2.1: Flood-Scour Analysis).

1.1 Remote-sensing Analysis Methods

Historical aerial imagery was utilized in a geographic information system (GIS) to delineate areas of flood disturbance for selected historical floods along the mainstem Virgin River. For the entire length of river, three of the most recent, large flood events were selected: 1989, 2005, and 2010. As discussed above, the 1989 flood was not a natural hydrological event, but was still considered here because of its lasting effect on the river corridor. Two additional flood events in 1955 and 1966/69 were selected for the TNC reaches in Utah: Reaches 4c, 4d, 5b, 5c, 6a, 8a, 8b, and 8c. Many aspects of this analysis were modeled on similar work done by Graf (2000), Tiegs et al. (2005), and Tiegs and Pohl (2005).

1.1.1 Photo acquisition

Historical imagery was acquired from the U.S. Department of Agriculture, while the post-2010 flood conditions were captured through imagery taken in November 2011 by Utah State University's Remote Sensing/Geographical Information Systems Laboratory (USU RS/GIS) (Table B-1). Aerial photography was acquired in one of two different formats, depending upon availability and age: non-georeferenced digital images or orthorectified imagery[4]. The non-georeferenced photography was typically scanned by the supplier at resolutions ranging from 600 dots per square inch (dpi) to 1200 dpi. For both analyses, photo sets were chosen to represent the effects of several major floods of interest (see Table B-1 below and Figure 3 in the main report).

[4] Georeferencing refers to the process of "rubber-sheeting" or matching features in an image to a "real-world" coordinate system. Georeferencing typically only considers horizontal referencing, whereas an orthorectified image will be referenced using both horizontal and vertical components, resulting in a more accurate representation of earth's surface.

Table B-1. Aerial imagery sets used in the mainstem Virgin River ecohydrological flood-scour analyses.

Flood date	Peak discharge (cfs), upstream to downstream: at Virgin, UT	at Hurricane, UT	near Bloomington, UT	near St. George, UT	at Littlefield, AZ	Closest imagery year(s)	Coverage extent for analysis		Imagery type [A]	Resolution/ scale	Photo source [B]
Aug 25, 1955	10,600	NA	NA	13,800	19,800	1960	Utah		B&W non-rectified	1:20,000	USDA FSA
Dec 6, 1966	22,800	20,100	NA	NA	35,200	1973	Utah		B&W non-rectified	1:38,000	USDA FSA
Jan 25–26, 1969	13,660	12,800	NA	NA	21,400						
Jan 1, 1989 (Quail Creek Dam failure)	NA	66,000	60,000	55,000	61,000	1992	Entire river	Nevada	B&W DOQs	1 meter	USDA NAIP
						1993		Utah			
						1994		Arizona			
Jan 11, 2005	9,840	21,000	19,600	19,600	37,000	2006	Entire river	Nevada, Utah	Color DOQs and CIR	1 meter	USDA NAIP
						2007		Arizona			
Dec 21, 2010	9,540	17,700	25,100	25,100	31,000	2011	Entire river		Color DOQs, MS, and LiDAR	0.25 meter	USU RS/GIS

[A] B&W = black and white image; DOQs = Digital Orthophoto Quadrangle image; CIR = color-infrared image; MS = multi-spectral image; LiDAR = Light Detection and Ranging topographic digital elevation model
[B] USDA FSA = U.S. Dept. of Agriculture Farm Service Agency; USDA NAIP = U.S. Dept. of Agriculture National Agriculture Imagery Program; USU RS/GIS = Utah State University's Remote Sensing/Geographic Information Systems Laboratory

1.1.2 Georeferencing

In order to extract and accurately compare river planform data from the acquired aerial photography, a common spatial context was necessary. Using a GIS, the 1960 and 1973 imagery were georeferenced to a single spatial projection (UTM Zone 11S, 12S; NAD 83). Aerial photographs taken following significant flood events were obtained for several years (Table B-1). The ESRI® ArcGIS georeferencing toolset was utilized to georeference the scanned hardcopy contact prints and digital imagery to the high-resolution 2006 and 2011 orthophotography, the latter of which was rectified by USU RS/GIS with the high-resolution LiDAR topography, thus providing a highly accurate standard control point source for the entire photographic record. Control points were typically located using old buildings, bridges, intersections, and other features that appeared unchanged between photos sets. Georeferencing methods utilized at least 10 control points per photograph; thin plate splines were used to produce a smooth (continuous and differentiable) surface. Orthorectified imagery was acquired at pixel resolutions ranging from about 0.25 to 1 m.

Spatial error in certain portions of photo sets due to imagery registration errors were occasionally significant, as high as 60 ft (~20 m). These errors were typically associated with image distortion at the outer edges of older photos, due to sub-standard aerial photography techniques, standard lens distortion, or oblique camera angles. However, spatial errors between most photo sets generally ranged between 10 and 50 ft (3 and 15 m), and sometimes were as low as 3 ft (1 m).

1.1.3 Flood-scour digitizing

Each set of spatially referenced photography (each representing a particular flood) was used in a GIS to interpret two levels of flood-caused disturbance in the channel and floodplain areas. In addition, areas of low-disturbance or areas apparently retaining natural riparian vegetation coverage[5] within the floodplain after the flood were also mapped. Continuous examination of the high-resolution LiDAR topographic surface alongside the aerial imagery in a GIS provided an excellent means to delineate the static floodplain boundaries.

For purposes of photographic interpretation, the flood-scour areas were defined as follows:

High disturbance: These areas are characterized by distinct channel and floodplain areas severely disturbed by flow (i.e., scoured to bare substrate), typically with 10% or less apparent remaining riparian vegetative cover. This category may include agricultural or developed lands with a high level of apparent disturbance by flood flows, thus identification of this type is not always based upon vegetative cover, sometimes relying on patterns of obvious scour or deposition. Additionally, certain channel-adjacent areas surrounded by scour were classified as high disturbance, despite having high coverage of herbaceous or nascent vegetation; this characterization was assigned when vegetation appeared to have grown post-flood and prior to the aerial photograph date.

Medium disturbance: This class is characterized by distinct areas of low to moderate apparent disturbance by flow, typically defined as areas with more than 10% but less than 80% apparent

[5] In the context of the floodplain vegetation communities of the Virgin River, "riparian vegetation" includes all visible plant species, which may include a mixture of native and non-native species. It may also include vegetation types more typical of upland communities, such as creosote bush scrub. Agricultural lands within the river's floodplain were also included as Low Disturbance, but were excluded from the active channel area in the absence of recent flood-scour.

riparian vegetative cover. This type includes agricultural or developed lands with low to moderate apparent disturbance by flood flows, thus, as with the high disturbance class, identification of this type is not always based upon vegetative cover.

Low disturbance (riparian vegetation): These areas were characterized by distinct zones of apparently natural riparian vegetation with little to no apparent disturbance by flood, typically containing more than 80% riparian vegetation. Areas in this class may have been inundated by floodwaters, but did not show significant signs of scouring or other disturbance that removed vegetation.

In addition to flood disturbance level, all polygons were classified as being either within or outside of the "active channel." Polygons within the active channel were those that appeared to have been directly affected by the river during the prior flood event and/or subsequent flows—areas of medium to high disturbance. Areas of riparian or non-riparian vegetation with no apparent disturbance were excluded. Areas of medium to high disturbance affected by flows from tributaries at their confluence with the Virgin River

To record these areas, polygons were delineated around features within each flood year photo set using heads-up digitizing at a scale of 1:3000 in the GIS; in certain canyon areas, shadow or dense vegetation made it necessary to sometimes digitize at scales of 1:2000 or, in cases of extremely low visibility, 1:1000. For the 2011 dataset, orthophotographs and associated 2011 LiDAR data were used to delineate the active channel and classify areas of disturbance. While methods for digitizing generally followed those described by Tiegs and Pohl (2005), the data generated in this study were not converted to a raster format for analysis, but rather kept as polygons in an ESRI shapefile format (.shp), as originally digitized. All subsequent analyses were conducted using the polygon representation, which allowed for a finer scale of resolution in analysis output.

In addition to spatial error related to georeferencing, polygon delineation likely resulted in unknown spatial errors due to difficulties in interpreting features of interest. These types of error are most likely to occur with older images (e.g., 1960 and 1973) used in this study. Older photographic film typically had a coarser grain than more modern films resulting in lower feature resolution once the image was scanned and georeferenced, making interpretation of riparian vegetation and other floodplain features more difficult.

1.1.4 Quality control

Each flood-year polygon dataset was checked extensively for spatial and interpretive accuracy by a GIS supervisor and a senior geomorphologist who were not associated with the digitization process. This process ensured that the datasets were consistent and accurate within and across years. Assessments of spatial error were conducted by a GIS analyst who was not directly involved in the georeferencing or digitization processes.

1.1.5 GIS analyses

The planform data digitized from the aerial photography sets were used to conduct two distinct spatial analyses to support understanding of fluvial dynamics in the mainstem Virgin River. These analyses included display of active channel widths per flood event and calculation of historical flood disturbance probability.

1.1.5.1 Width of active channel bed in successive floods

Knowledge of the last known flood disturbance for any particular area of the floodplain is critical to understanding the age of geomorphic surfaces and thus the approximate age of riparian vegetation growing there. All active channel layers were thus overlain in order of oldest to most recent event to produce a map displaying the active channel width (or extent) per event (see Figures B2.1–B2.23 below). Additionally, the Low Disturbance areas from each flood-year layer were merged to represent the cumulative floodplain extent, an equally valuable component of the active channel maps for restoration planners seeking to identify potential sites safely outside the flood-disturbance areas but within the floodplain boundaries.

1.1.5.2 Locational probability model

The methods and nomenclature discussed below have been generally based on those of Graf (2000) and Tiegs et al. (2005). For this analysis, we define a locational probability model as a graphical representation of the historical probability that any particular area within the floodplain and channel of the river was scoured (i.e., the High Disturbance and Medium Disturbance categories described above) by a major flood. As discussed above, aerial photographs chosen for use in this study were taken after major floods (see Table B-1) and thus represent the post-flood channel configuration for a particular flood.

Because the Virgin River is a flood-event dominated system and each set of photography was taken shortly after a major flood event, it can be assumed that each photo set represents the dominant planform configuration of the channel until the next large flood documented by aerial photography. This approach differs from that of Graf (2000), Tiegs et al. (2005), and Tiegs and Pohl (2005), who assume that each photo set is representative of general channel conditions for a period of time from one photo set to the previous photo set. Thus, their approach does not appear to explicitly consider whether the photo is representative of the effects of particular floods, but rather describes general channel conditions over time.

There are numerous caveats to our assumption discussed above, the most important being that smaller floods occur between the photograph sets and likely result in at least some reworking of the channel; however, it remains that major changes to the channel and floodplain of the river are accomplished by large floods. Another significant caveat for the analysis is the non-inclusion of aerial photographic coverage for two major floods in 1978 and 1995 for the entire river, in addition to non-inclusion of coverage for floods of 1955 and 1966/69 in the non-TNC reaches; although at least partial imagery exists to document these floods, funding limited the number of photographic sets that could be processed at this time.

To derive a disturbance probability model, we sub-divided the mainstem river into 26 hydrogeomorphically distinct sub-reaches (see Figure 5 and Table 2 in the main report). A separate disturbance probability model was calculated for each sub-reach. In order to build the disturbance probability model, the photo sets needed to be weighted based on the amount of time each represented in the overall study period[6] (i.e., TNC reaches in Utah: 1960–2011; non-TNC reaches: 1993–2011), on a sub-reach basis. The weighting values were calculated for each flood year and reach using the following equation:

[6] Photography was acquired for selected floods between 1960 and 2011 for the TNC reaches and between 1993 and 2011 for the non-TNC reaches, thus these periods represent the photographic records for each analysis. For the purposes of calculating probability of disturbance, the “study periods” were 1960–2012 and 1993–2012 for the TNC and non-TNC reaches, respectively, since no major floods have occurred since the December 2010 event.

$$Weighting\ value\ (W_n) = \frac{years\ represented\ by\ given\ photograph\ (t_n)}{total\ number\ of\ years\ in\ photographic\ record\ (m)}$$

The value of t_n is the number of years between the documented flood of interest and the next photo documented flood. The value of m is the total number of years documented by aerial photography for a particular sub-reach, from earliest photography set to most recent. Working through the equation for each flood year and reach gave the results displayed in Tables B-2 and B-3.

Weighting values were assigned to flood year and reach polygon layers in the GIS. All of the flood year layers for each analysis were then combined in the GIS (using the "union" function), resulting in numerous smaller polygons, all of which retained their original assigned probability for each year and reach. For each individual polygon, all the years weighting values were summed, resulting in a probability of scour for each. The probability field was then used to illustrate locational probability in a map (see Figures B2.1–B2.23 below) for each sub-reach.

Table B-2. Years represented by individual flood photography and total number of years in the photographic record, by sub-reach of the Virgin River.

Reach	Years of photography	Number of years represented by given flood photography (t_n)					Number of years in photographic record since 2012 (m)
		1960	1973	1992/ 1993/ 1994	2006/ 2007	2011	
1a	1994, 2006, 2011	--	--	12	5	1	18
1b	1994, 2006, 2011	--	--	12	5	1	18
2a	1994, 2006, 2011	--	--	12	5	1	18
2b	1994, 2006, 2011	--	--	12	5	1	18
2c	1994, 2006, 2011	--	--	12	5	1	18
2d	1994, 2006, 2011	--	--	12	5	1	18
2e	1994, 2006, 2011 1992, 2006, 2011 1992, 2007, 2011	--	--	12 14 15	5 5 4	1 1 1	18 20 20
2f	1992, 2007, 2011	--	--	15	4	1	20
3a	1992, 2007, 2011 1992, 2006, 2011	--	--	15 14	4 5	1 1	20 20
3b	1992, 2006, 2011	--	--	14	5	1	20
3c	1992, 2006, 2011	--	--	14	5	1	20
3d	1992, 2006, 2011	--	--	14	5	1	20
4a	1993, 2006, 2011	--	--	13	5	1	19
4b	1993, 2006, 2011	--	--	13	5	1	19
4c	1960, 1973, 1993, 2006, 2011	13	20	13	5	1	52
4d	1960, 1973, 1993, 2006, 2011	13	20	13	5	1	52
5a	1993, 2006, 2011	--	--	13	5	1	19
5b	1960, 1973, 1993, 2006, 2011	13	20	13	5	1	52
5c	1960, 1973, 1993, 2006, 2011	13	20	13	5	1	52
6a	1960, 1973, 1993, 2006, 2011	13	20	13	5	1	52
6b	1960, 1973, 1993, 2006, 2011	13	20	13	5	1	52
7a	1993, 2006, 2011	--	--	13	5	1	19
7b	1993, 2006, 2011	--	--	13	5	1	19
8a	1960, 1973, 1993, 2006, 2011	13	20	13	5	1	52
8b	1960, 1973, 1993, 2006, 2011	13	20	13	5	1	52
8c	1960, 1973, 1993, 2006, 2011	13	20	13	5	1	52

Table B-3. Weighting values for individual floods photography and reaches of the Virgin River.

Reach	Years of photography	Weighting value (W_n)				
		1960	1973	1992/ 1993/ 1994	2006/ 2007	2011
1a	1994, 2006, 2011	-	-	0.67	0.28	0.06
1b	1994, 2006, 2011	-	-	0.67	0.28	0.06
2a	1994, 2006, 2011	-	-	0.67	0.28	0.06
2b	1994, 2006, 2011	-	-	0.67	0.28	0.06
2c	1994, 2006, 2011	-	-	0.67	0.28	0.06
2d	1994, 2006, 2011	-	-	0.67	0.28	0.06
2e	1994, 2006, 2011 1992, 2006, 2011 1992, 2007, 2011	-	-	0.67 0.70 0.75	0.28 0.25 0.20	0.06 0.05 0.05
2f	1992, 2007, 2011	-	-	0.75	0.20	0.05
3a	1992, 2007, 2011 1992, 2006, 2011	-	-	0.75 0.70	0.20 0.25	0.05 0.05
3b	1992, 2006, 2011	-	-	0.70	0.25	0.05
3c	1992, 2006, 2011	-	-	0.70	0.25	0.05
3d	1992, 2006, 2011	-	-	0.70	0.25	0.05
4a	1993, 2006, 2011	-	-	0.68	0.26	0.05
4b	1993, 2006, 2011	-	-	0.68	0.26	0.05
4c	1960, 1973, 1993, 2006, 2011	0.25	0.38	0.25	0.10	0.02
4d	1960, 1973, 1993, 2006, 2011	0.25	0.38	0.25	0.10	0.02
5a	1993, 2006, 2011	-	-	0.68	0.26	0.05
5b	1960, 1973, 1993, 2006, 2011	0.25	0.38	0.25	0.10	0.02
5c	1960, 1973, 1993, 2006, 2011	0.25	0.38	0.25	0.10	0.02
6a	1960, 1973, 1993, 2006, 2011	0.25	0.38	0.25	0.10	0.02
6b	1960, 1973, 1993, 2006, 2011	0.25	0.38	0.25	0.10	0.02
7a	1993, 2006, 2011	-	-	0.68	0.26	0.05
7b	1993, 2006, 2011	-	-	0.68	0.26	0.05
8a	1960, 1973, 1993, 2006, 2011	0.25	0.38	0.25	0.10	0.02
8b	1960, 1973, 1993, 2006, 2011	0.25	0.38	0.25	0.10	0.02
8c	1960, 1973, 1993, 2006, 2011	0.25	0.38	0.25	0.10	0.02

1.2 Results of Flood-Scour Analysis

As a predominantly braided but dryland river, the mainstem channel of the Virgin River largely comprises a primary low-flow channel and various short-lived secondary channels. The flood-scour analysis performed here reveals that the low-flow channel boundary changes rapidly and completely during flood events according to the magnitude of the event and other factors, whereas the boundary of the larger mainstem channel changes less frequently.

The results of our flood-scour analysis are presented graphically in two sets of maps: "Width of active channel bed in successive floods" and "Historical active channel position." As described above, the former category presents the active-channel areas per mapped flood event. The latter category maps highlight those channel areas most frequently disturbed by repeat flood events. The Flood Reset Zone therefore depends on those more active areas, and are considered henceforth to include those areas found to have >33% flood-scour frequency (i.e., scoured in 2 out of the 3 mapped events [1989, 2005, and 2010]) *and* "high" flood-disturbance activity—areas severely disturbed by flow, typically scoured to bar substrate retaining <10% apparent riparian vegetation cover—during the most recent flood of 2010. The apparent trajectory of the active channel's position was also considered (i.e., lateral-migration direction).

Figure B-1 presents an index map to the numerous flood-scour maps that are presented in Figure B-2. The individual flood-scour maps are grouped by location, and presented in downstream to upstream order beginning in Reach 1 near Lake Mead. Polygons depicting the historical active channel position are absent in Reach 1a because high reservoir levels in 1992–1994 prevented incorporation of that third aerial photographic period into the analysis.

These maps are meant to guide restoration planning and implementation at multiple scales, ranging from restoration strategy development at the full river corridor and reach levels to site-specific restoration design and implementation. However, the maps are only one tool and need to be combined with a variety of other information to develop the most effective and efficient strategies and designs for riparian restoration, such as riparian vegetation classification (see Section 3: Vegetation Characterization in the main report). In particular, more detailed field-based information and geomorphic interpretation may be warranted to refine the fine-scale delineation of the Flood Reset Zone and predictions of likely future flood paths when designing and implementing site-specific plans for invasive species removal and revegetation of native riparian species.

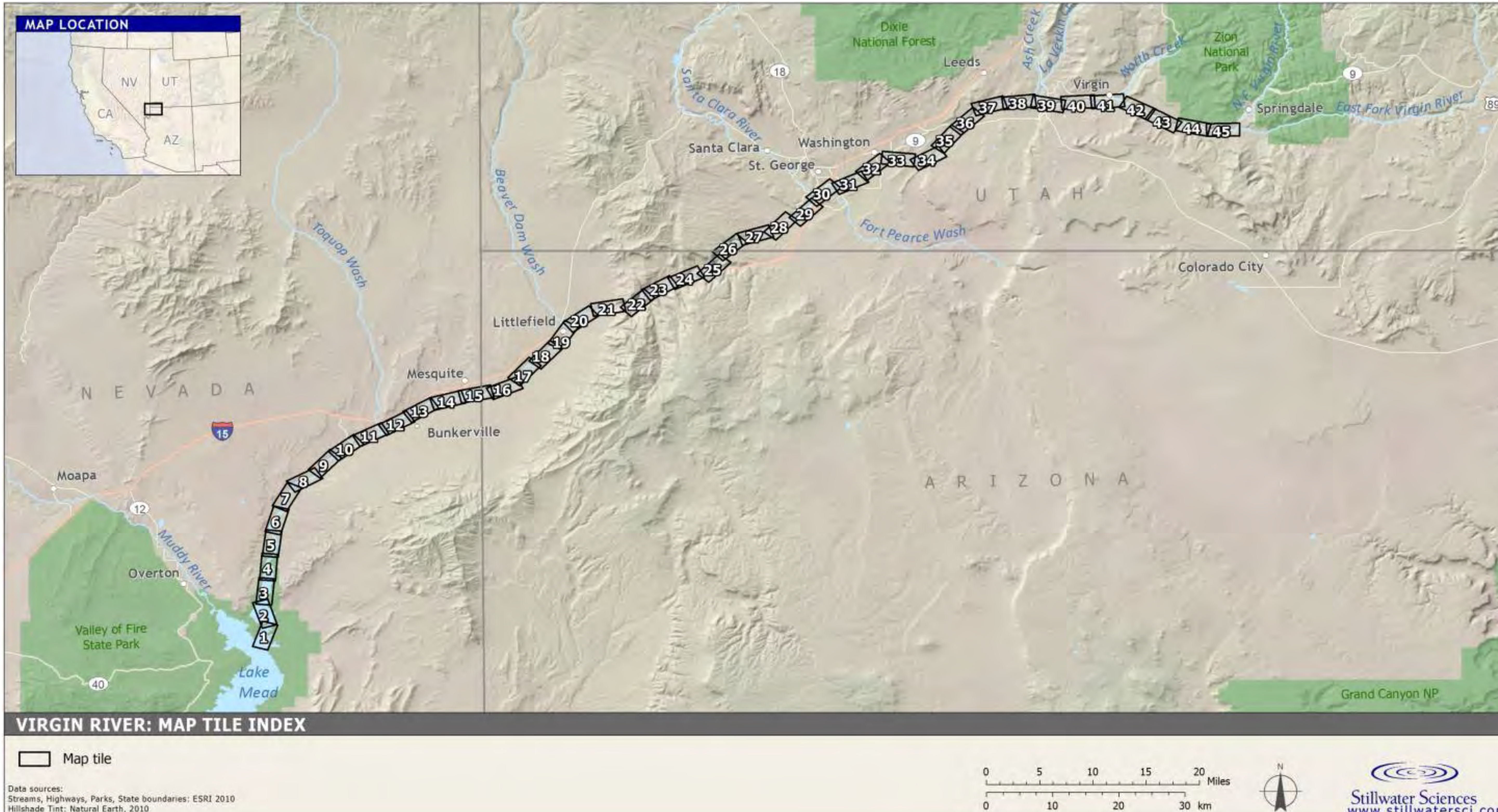


Figure B-1. Index map for flood-scour map tiles along the mainstem Virgin River. See Figures B2.1 through B2.23 for individual map tiles.

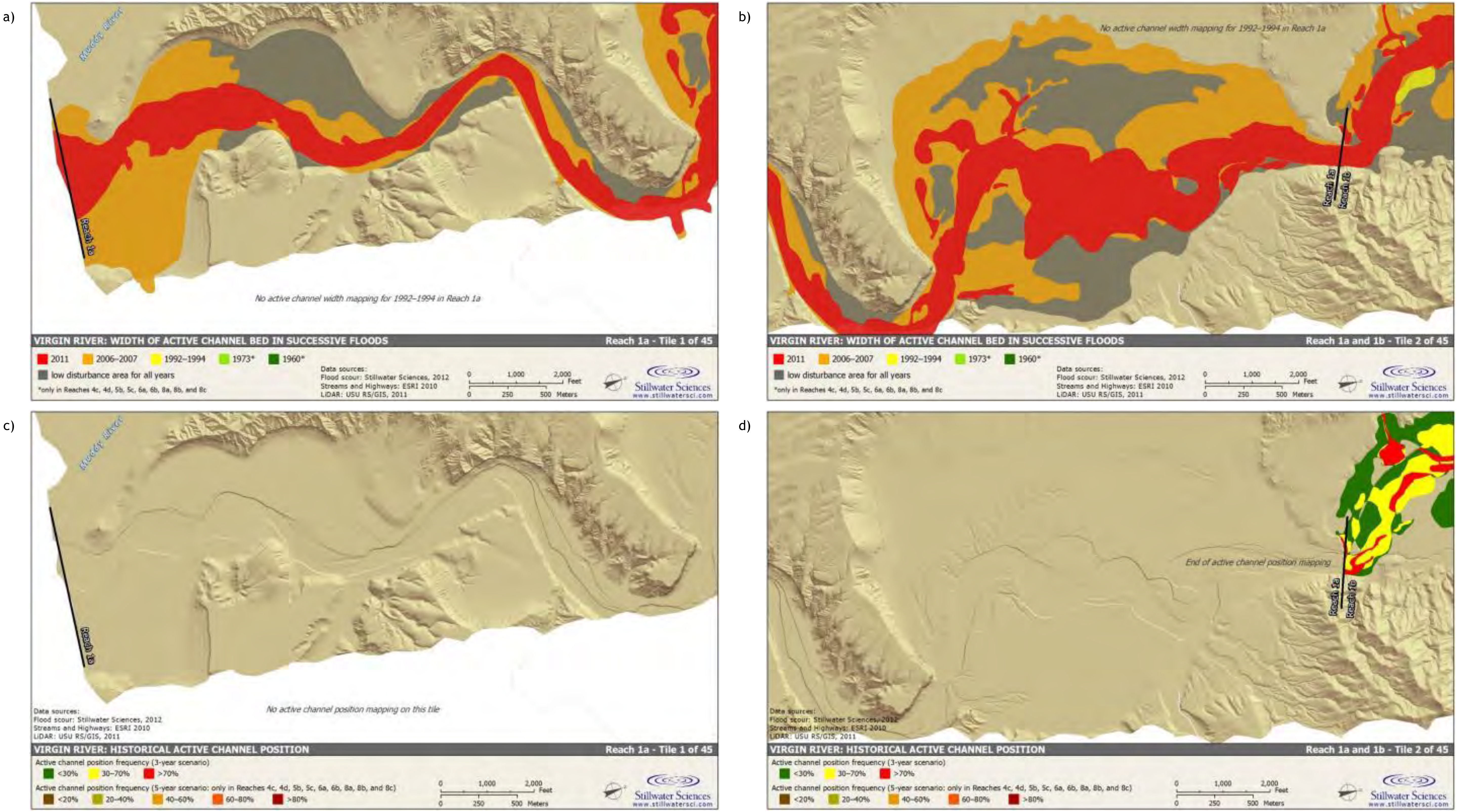


Figure B2.1. Virgin River flood-scour analysis results for Reach 1a: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

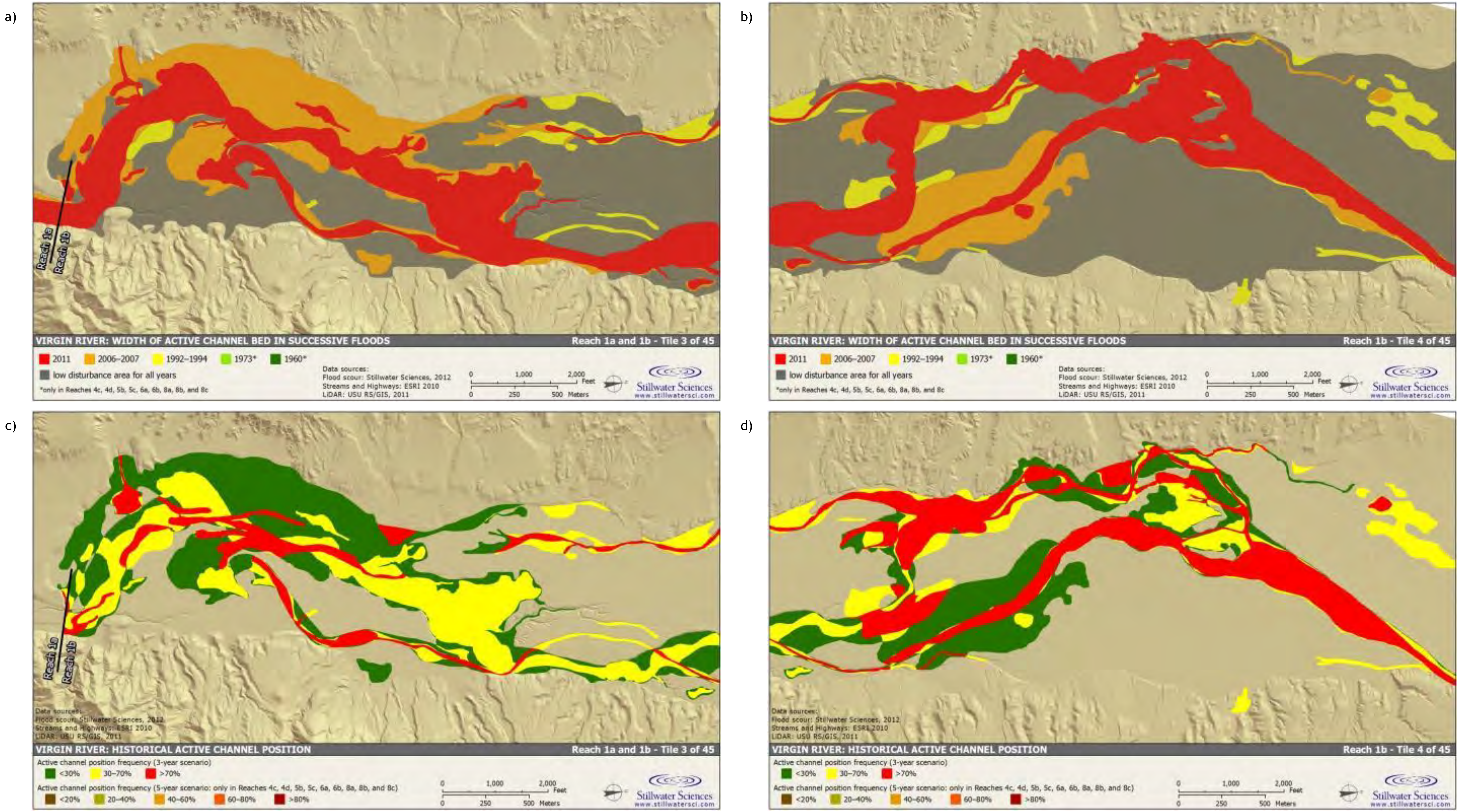


Figure B2.2. Virgin River flood-scour analysis results for Reach 1b (lower): active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

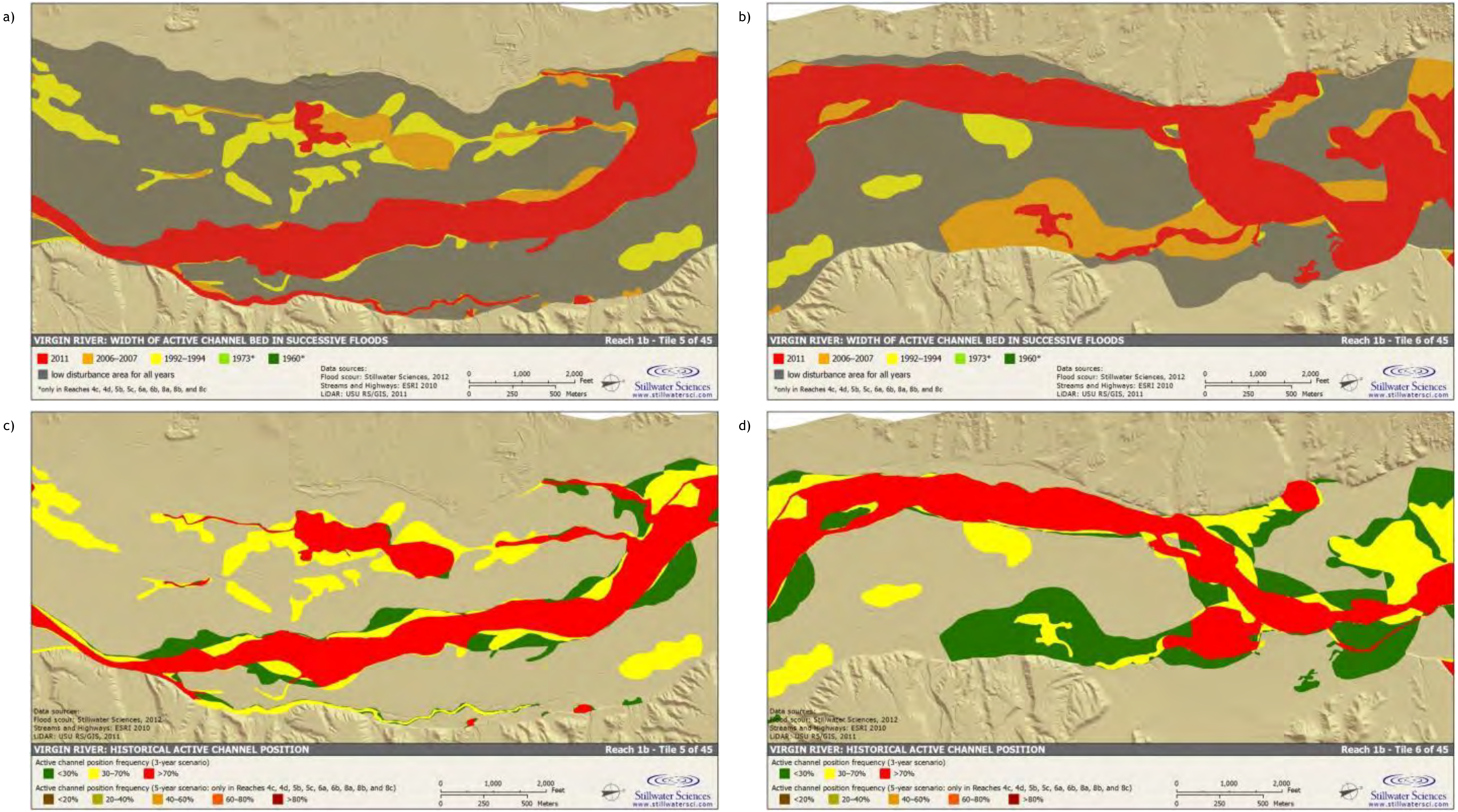


Figure B2.3. Virgin River flood-scour analysis results for Reach 1b (upper): active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

a) b) c) d)

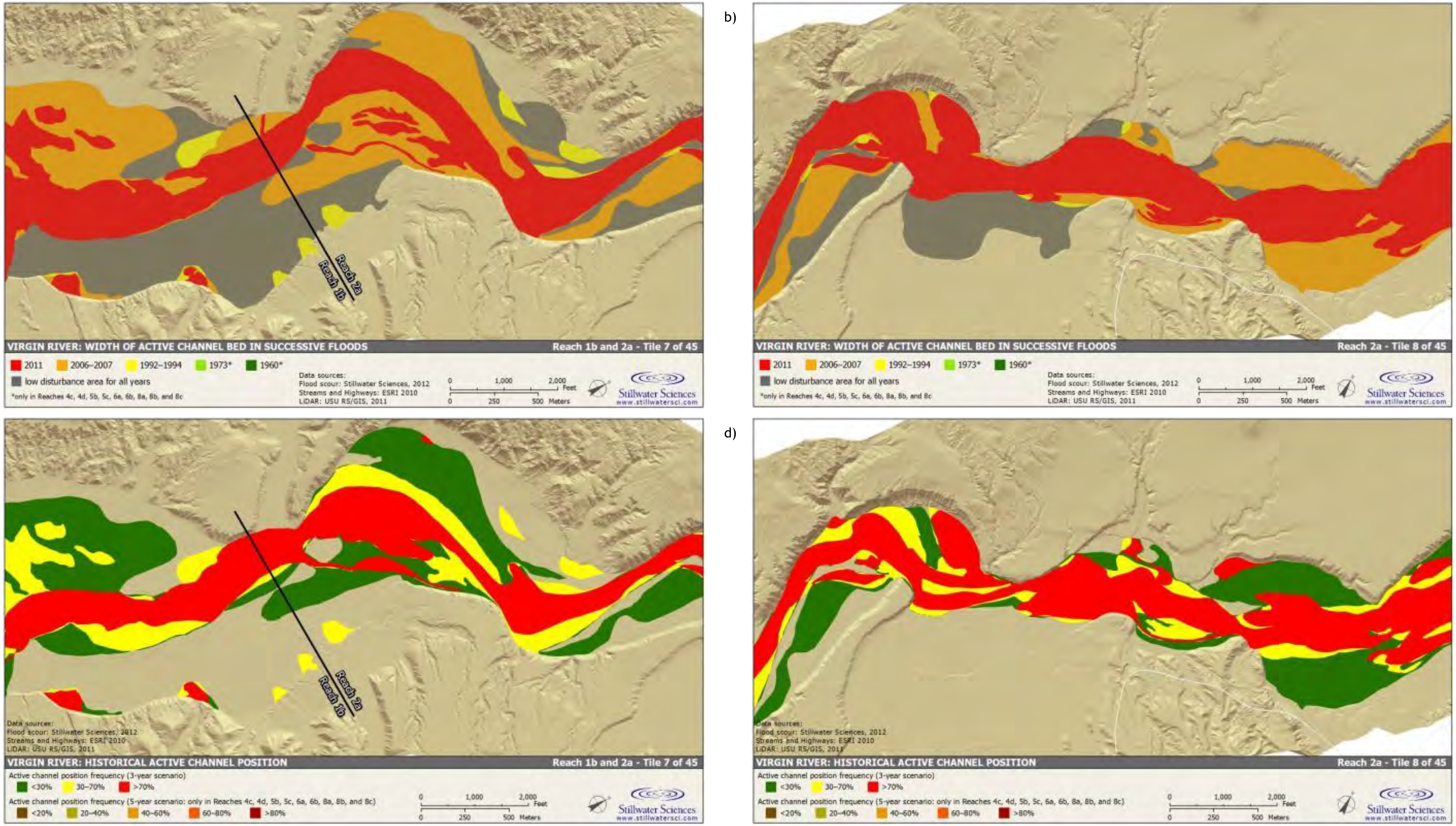


Figure B2.4. Virgin River flood-scour analysis results for Reaches 1b and 2a: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

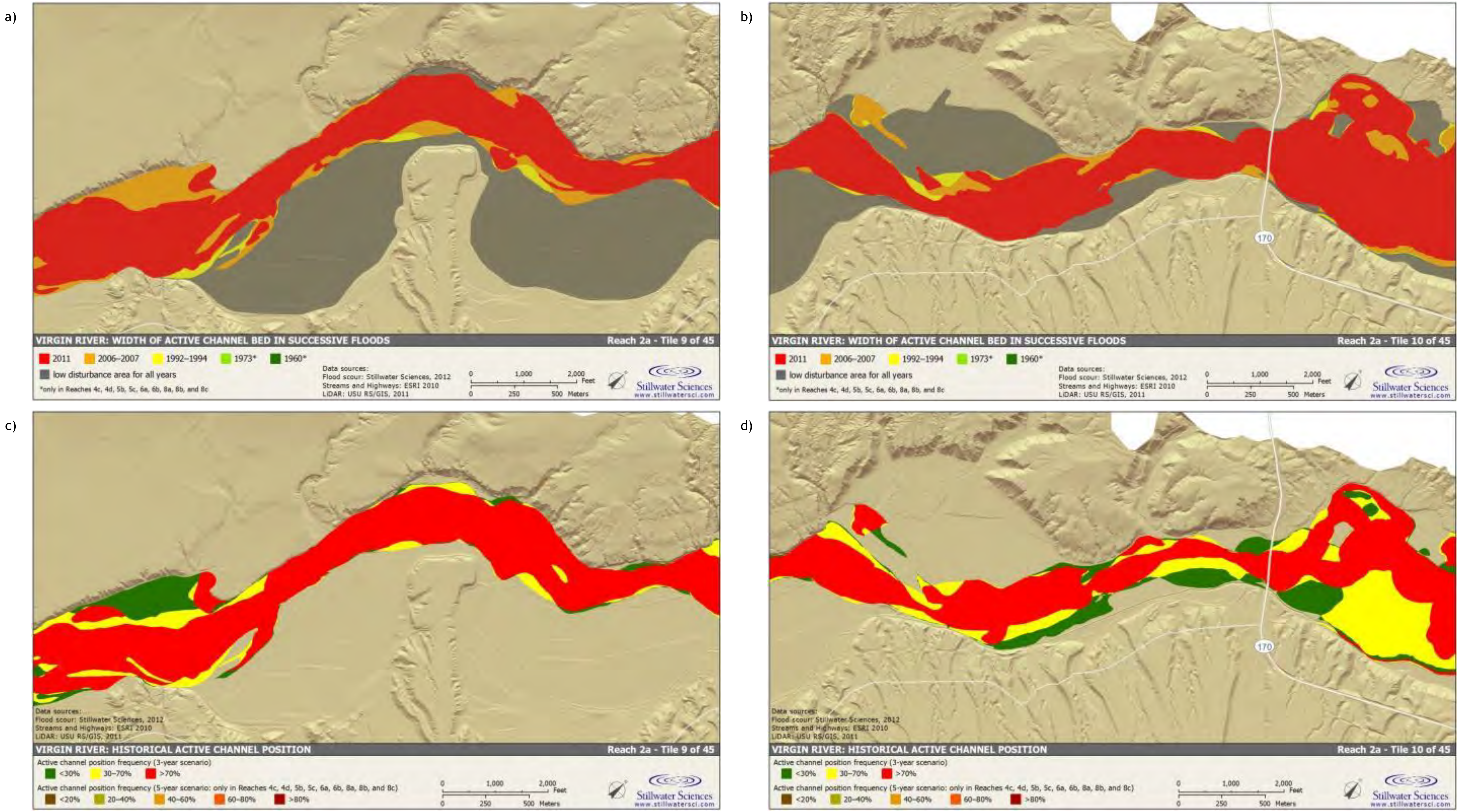


Figure B2.5. Virgin River flood-scour analysis results for Reach 2a: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

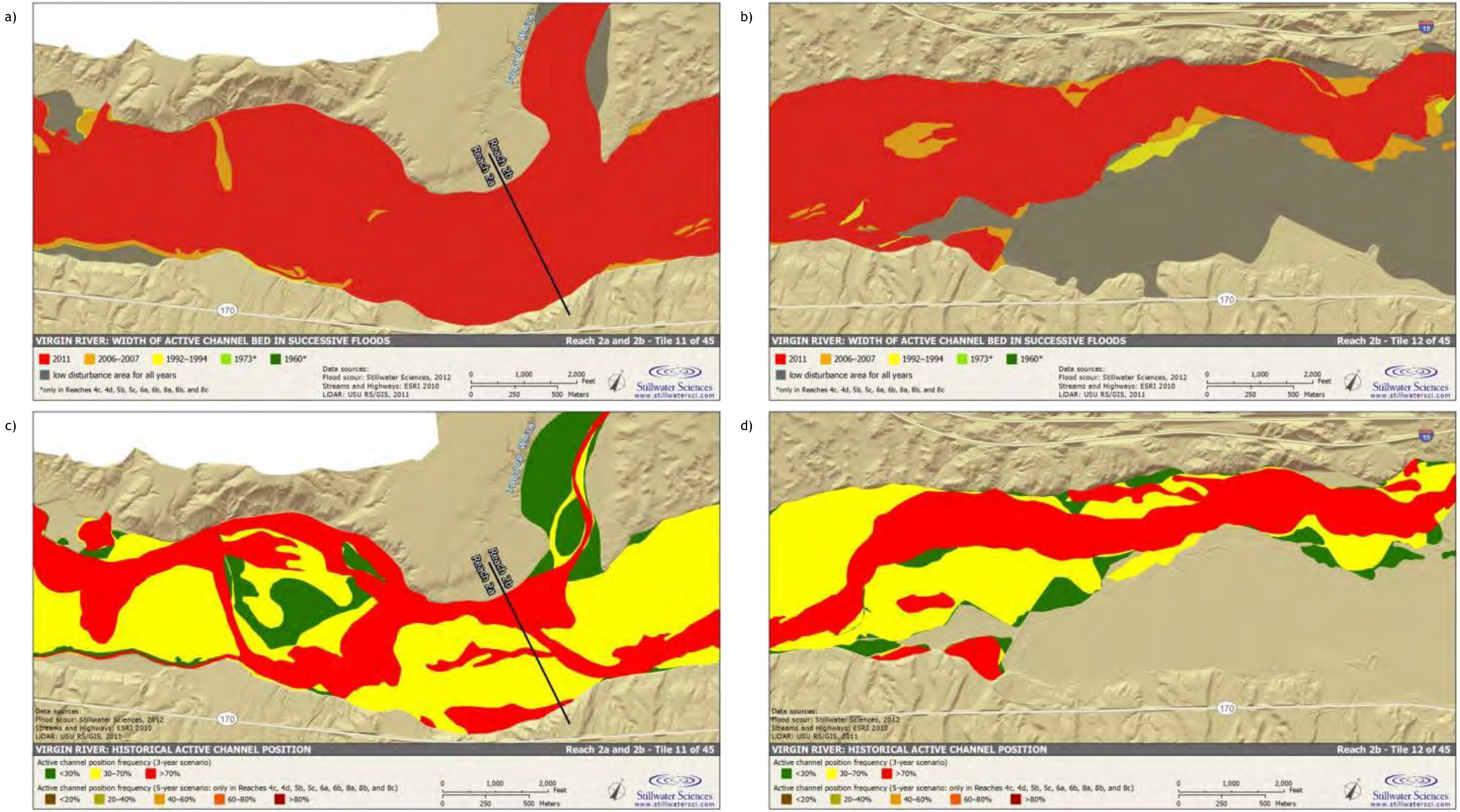


Figure B2.6. Virgin River flood-scour analysis results for Reaches 2a and 2b: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

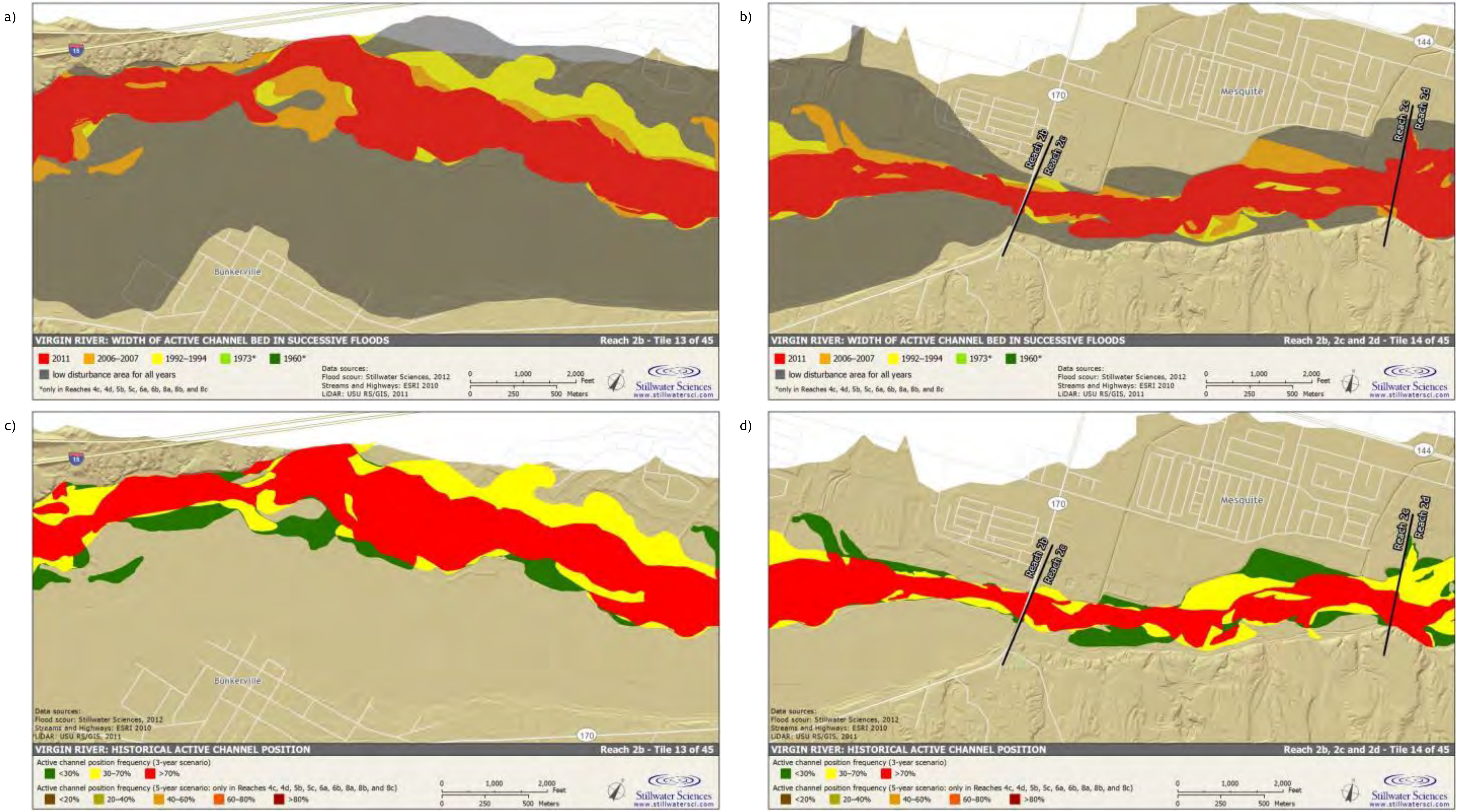


Figure B2.7. Virgin River flood-scour analysis results for Reaches 2b and 2c: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

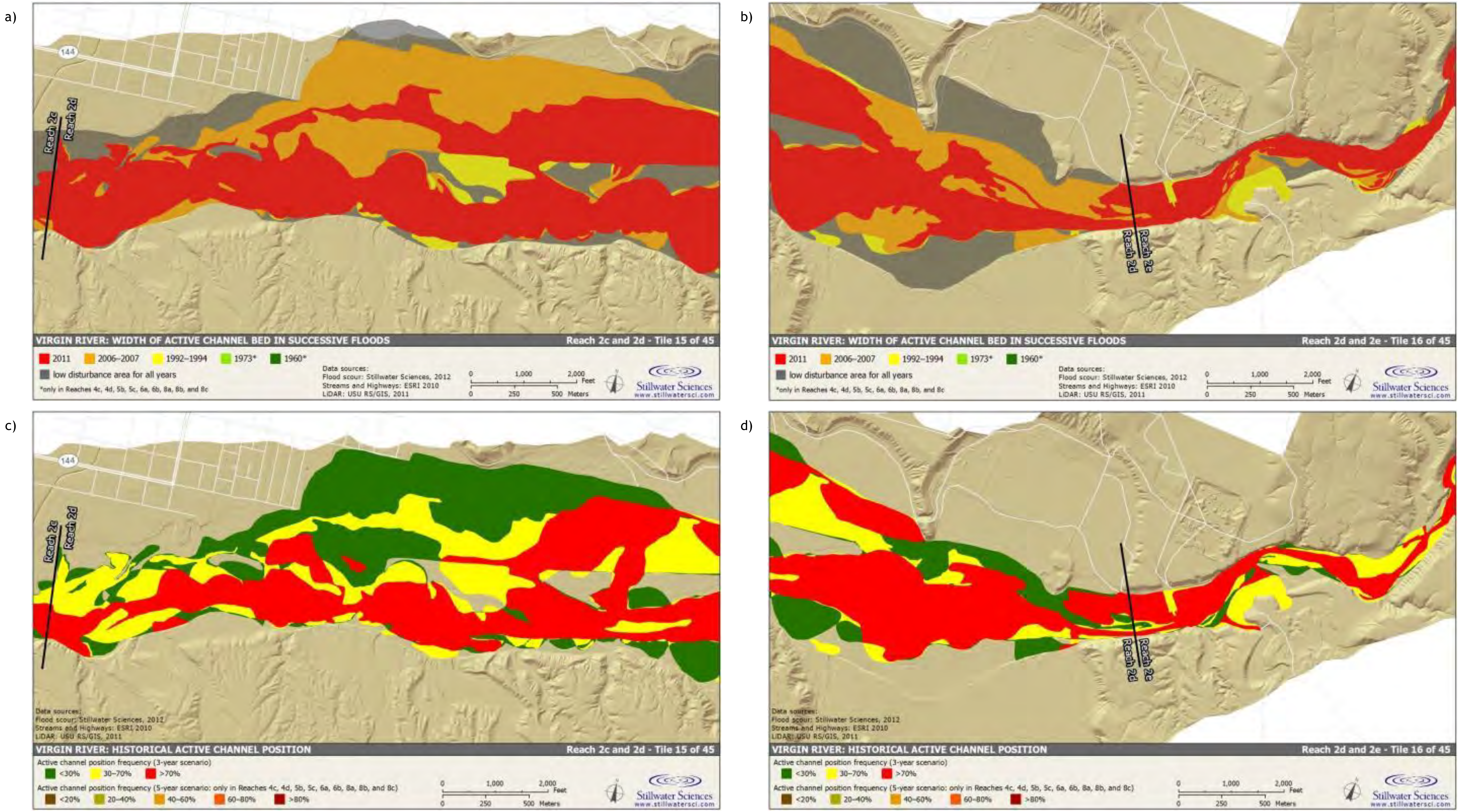


Figure B2.8. Virgin River flood-scour analysis results for Reaches 2d and 2e: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

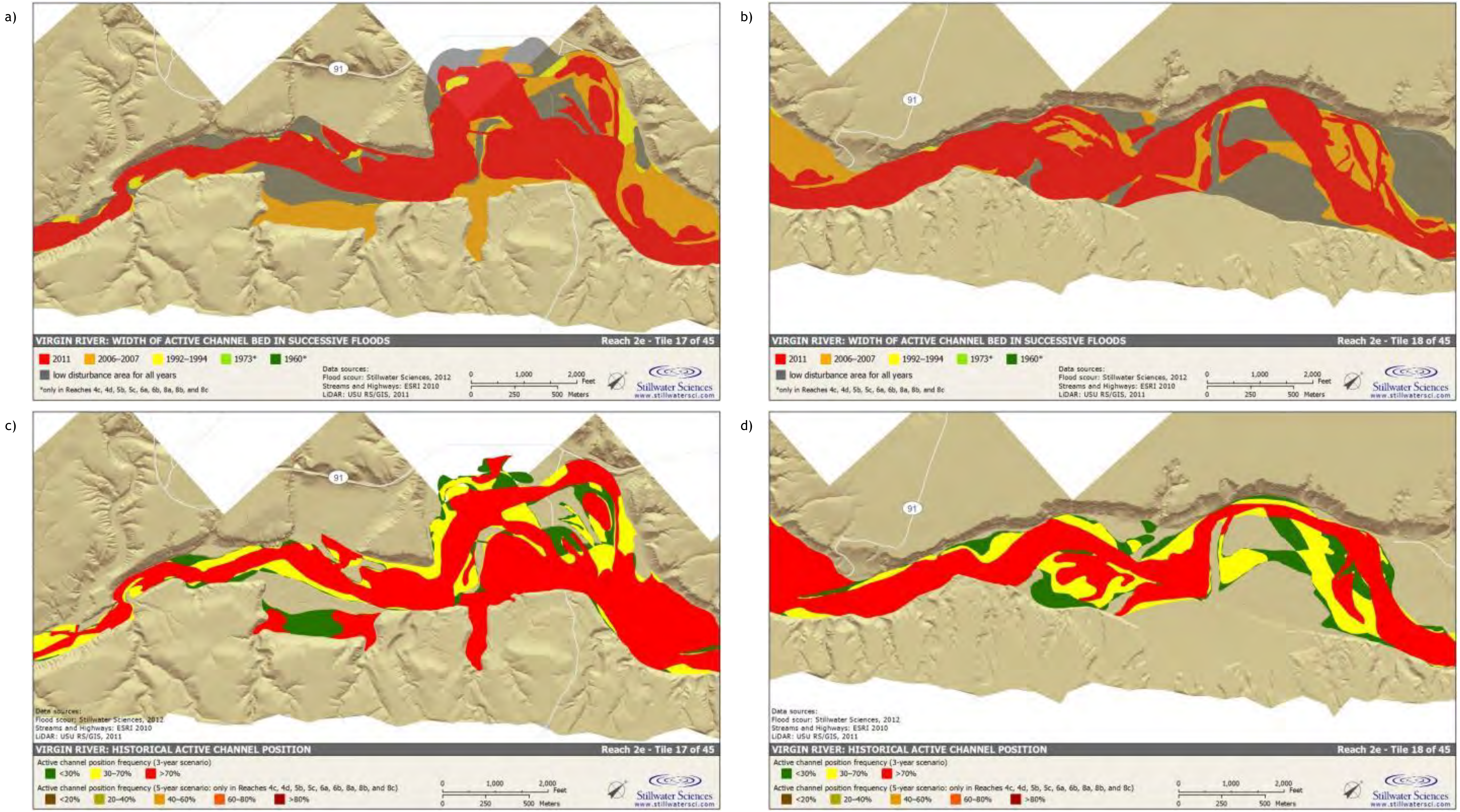


Figure B2.9. Virgin River flood-scour analysis results for Reach 2e: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

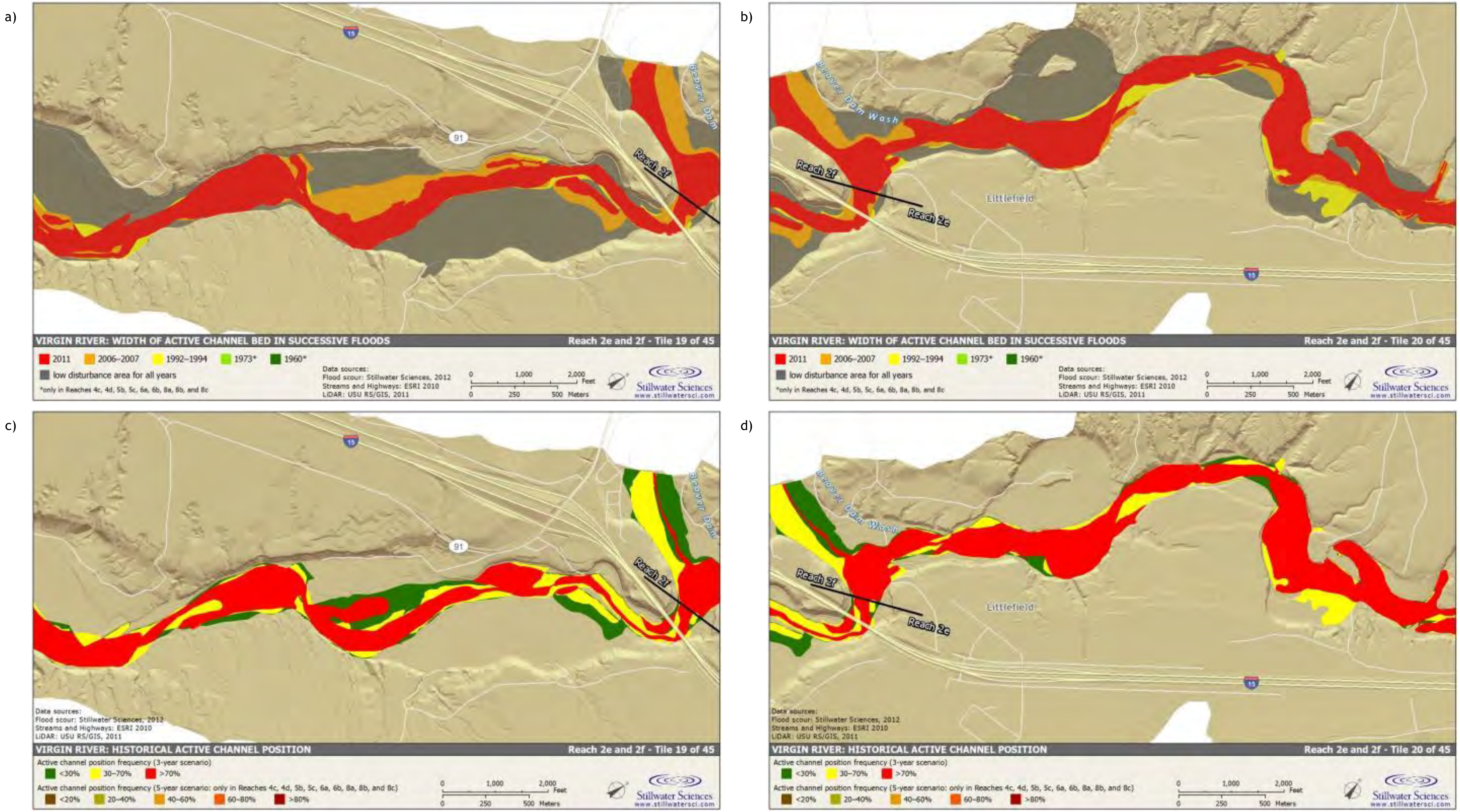


Figure B2.10. Virgin River flood-scour analysis results for Reaches 2e and 2f: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

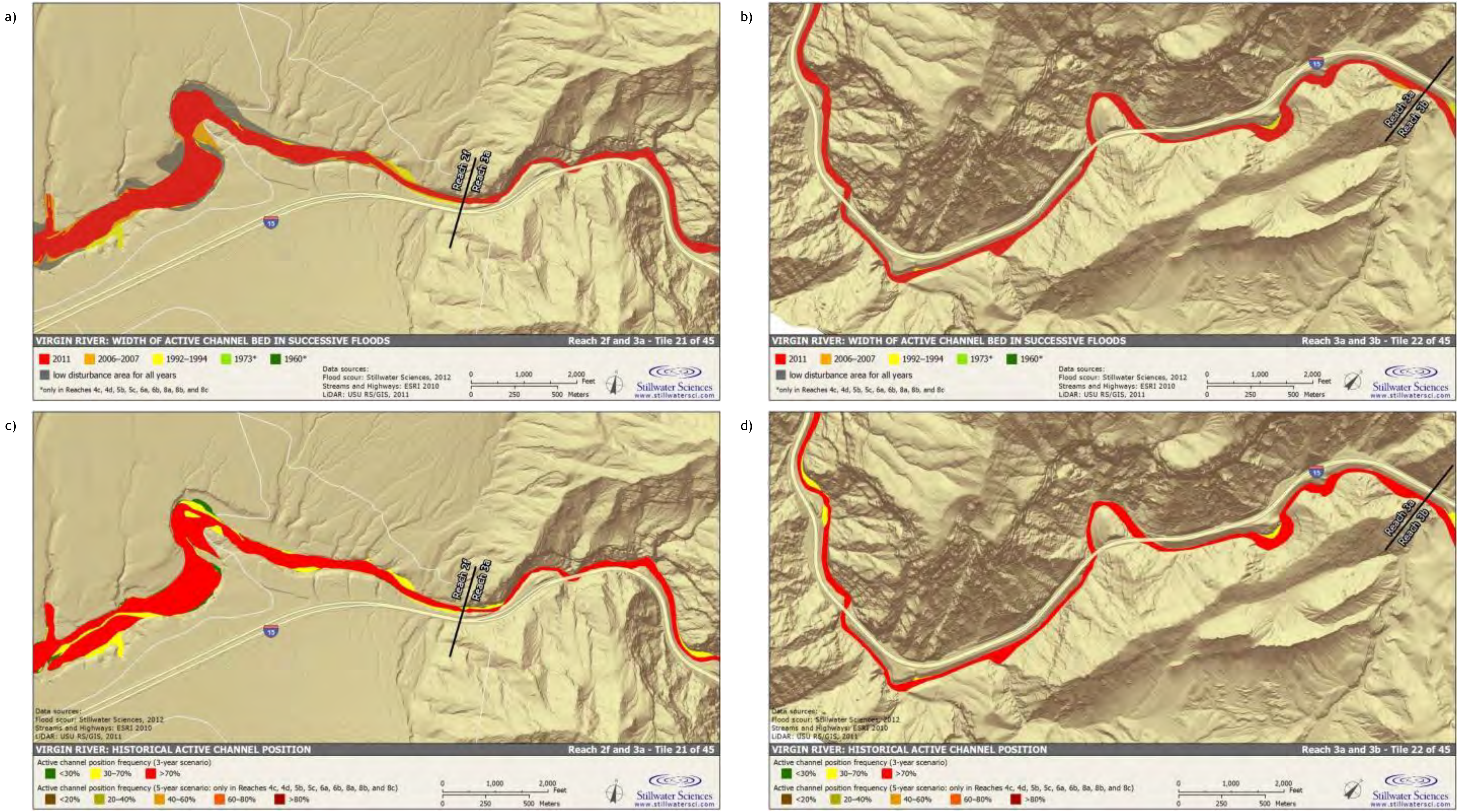


Figure B2.11. Virgin River flood-scour analysis results for Reaches 2f and 3a: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

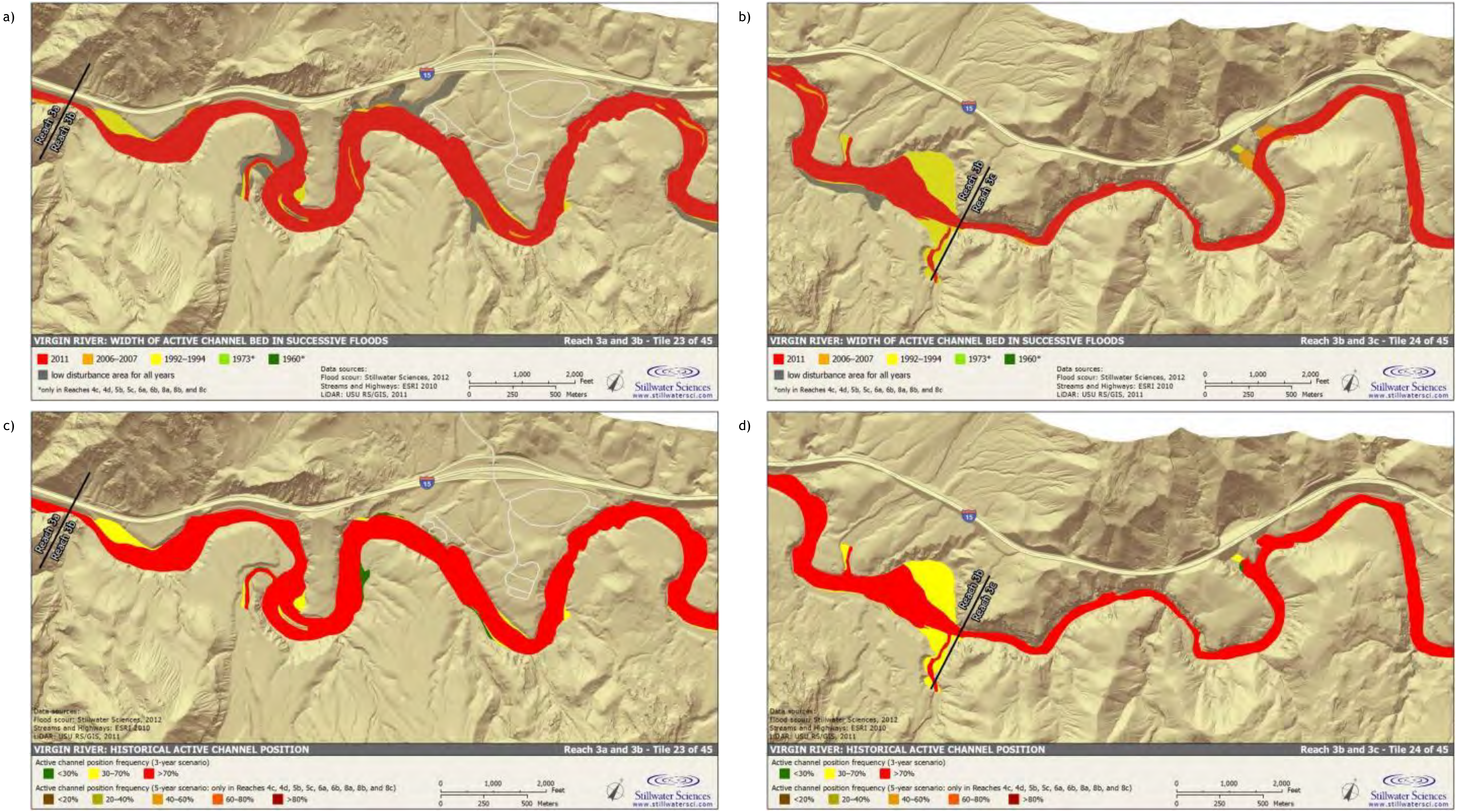


Figure B2.12. Virgin River flood-scour analysis results for Reaches 3b and 3c: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

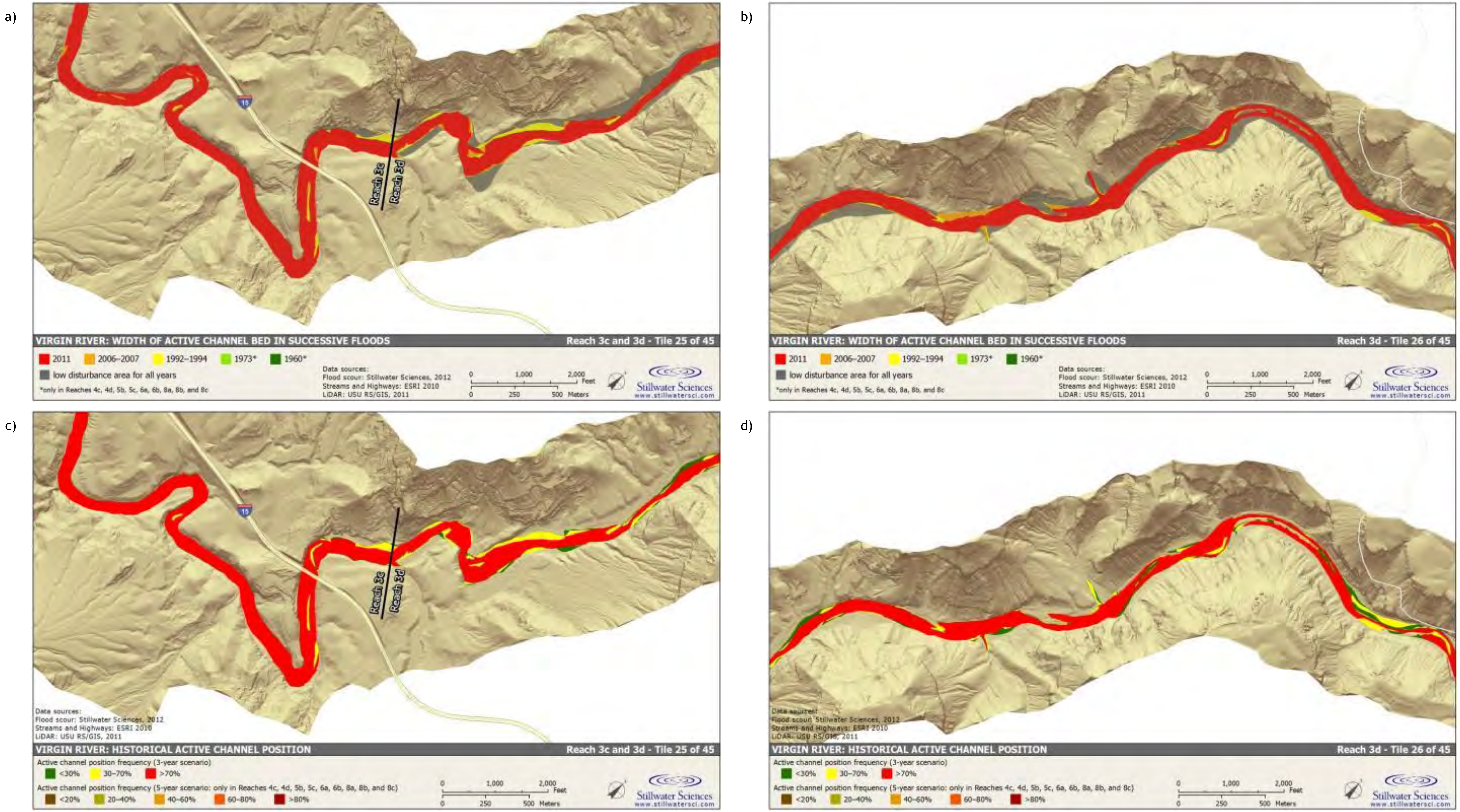


Figure B2.13. Virgin River flood-scour analysis results for Reaches 3c and 3d: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

a) b) c) d)

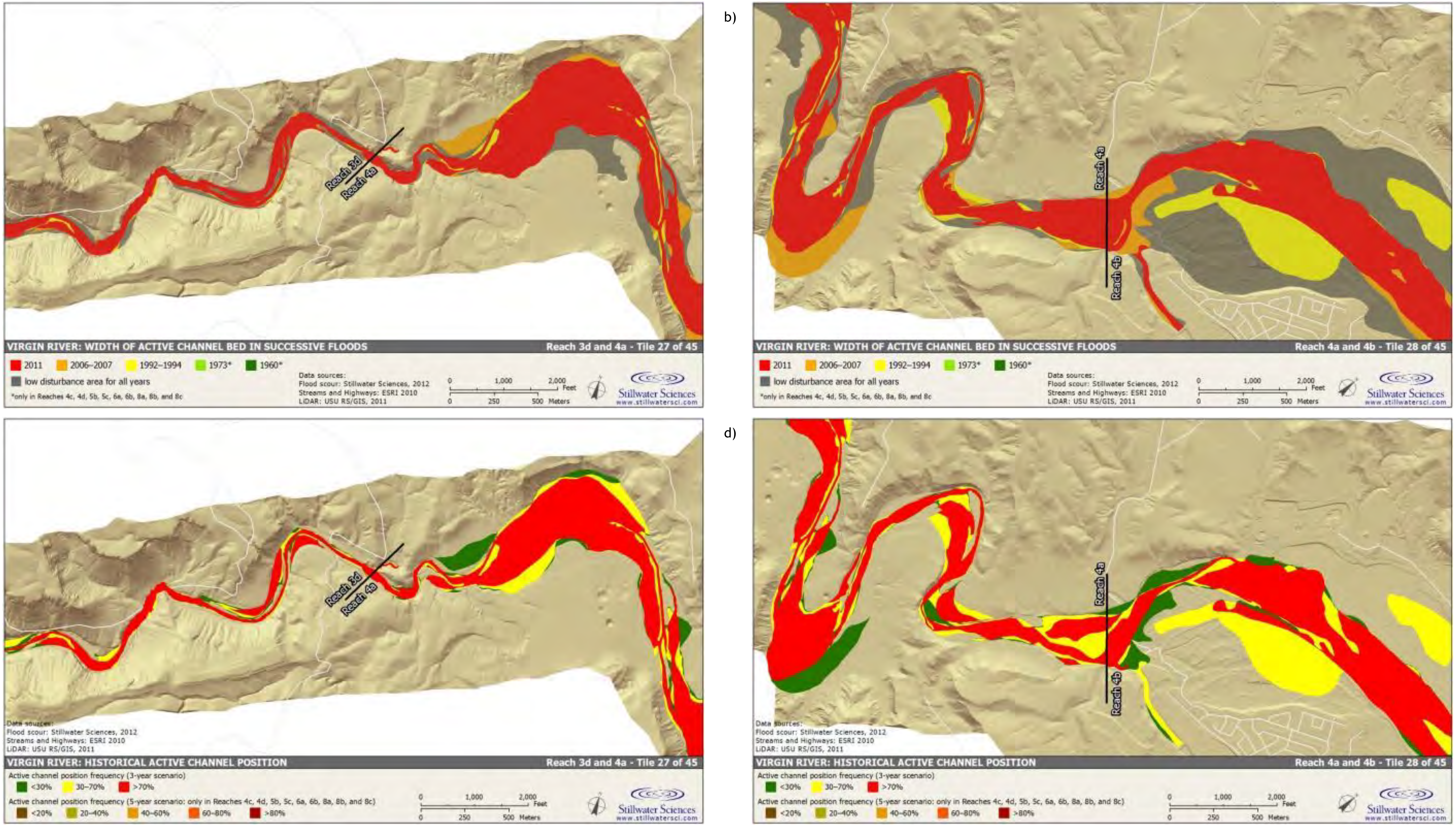


Figure B2.14. Virgin River flood-scour analysis results for Reaches 3d, 4a, and 4b: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

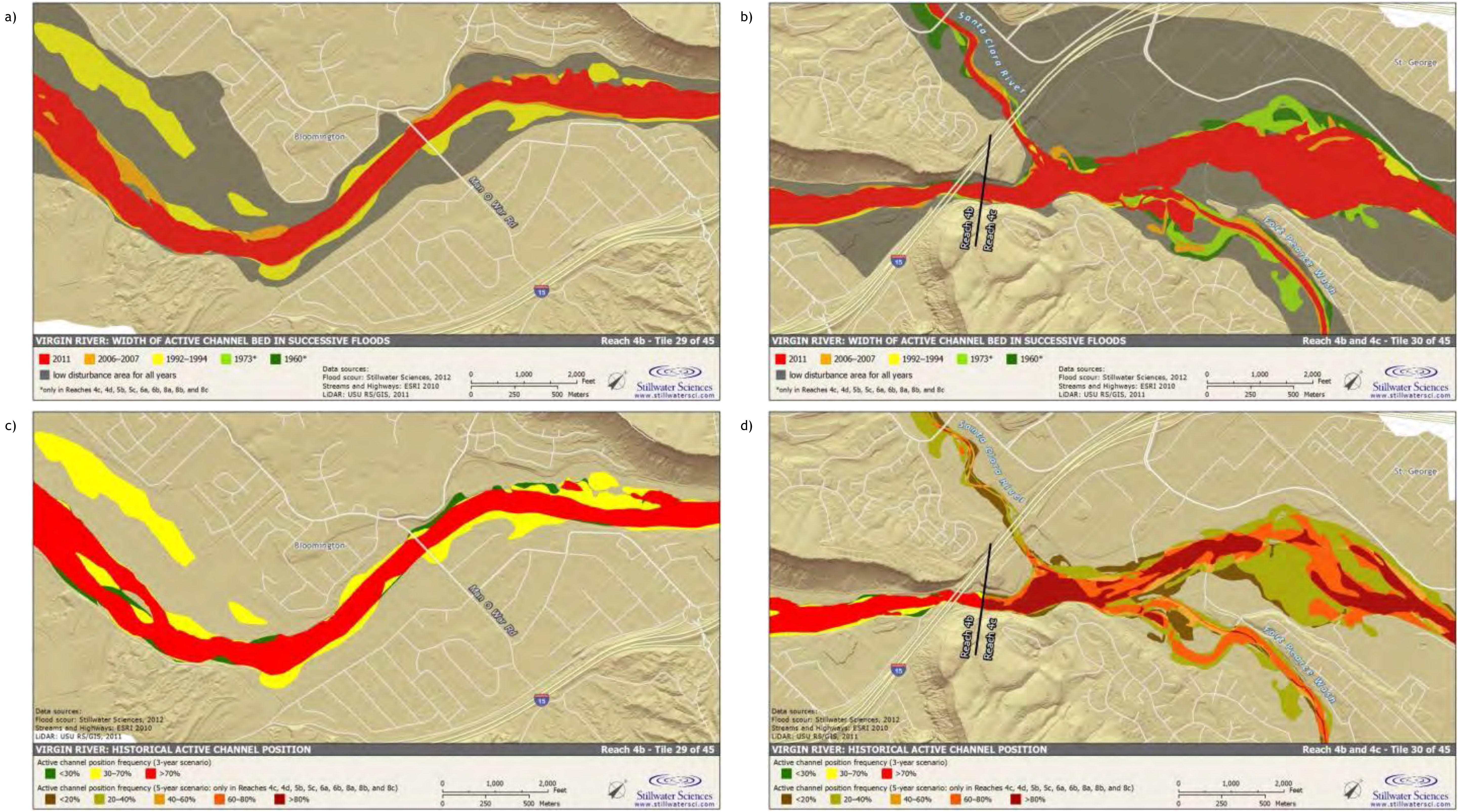


Figure B2.15. Virgin River flood-scour analysis results for Reaches 4b and 4c: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

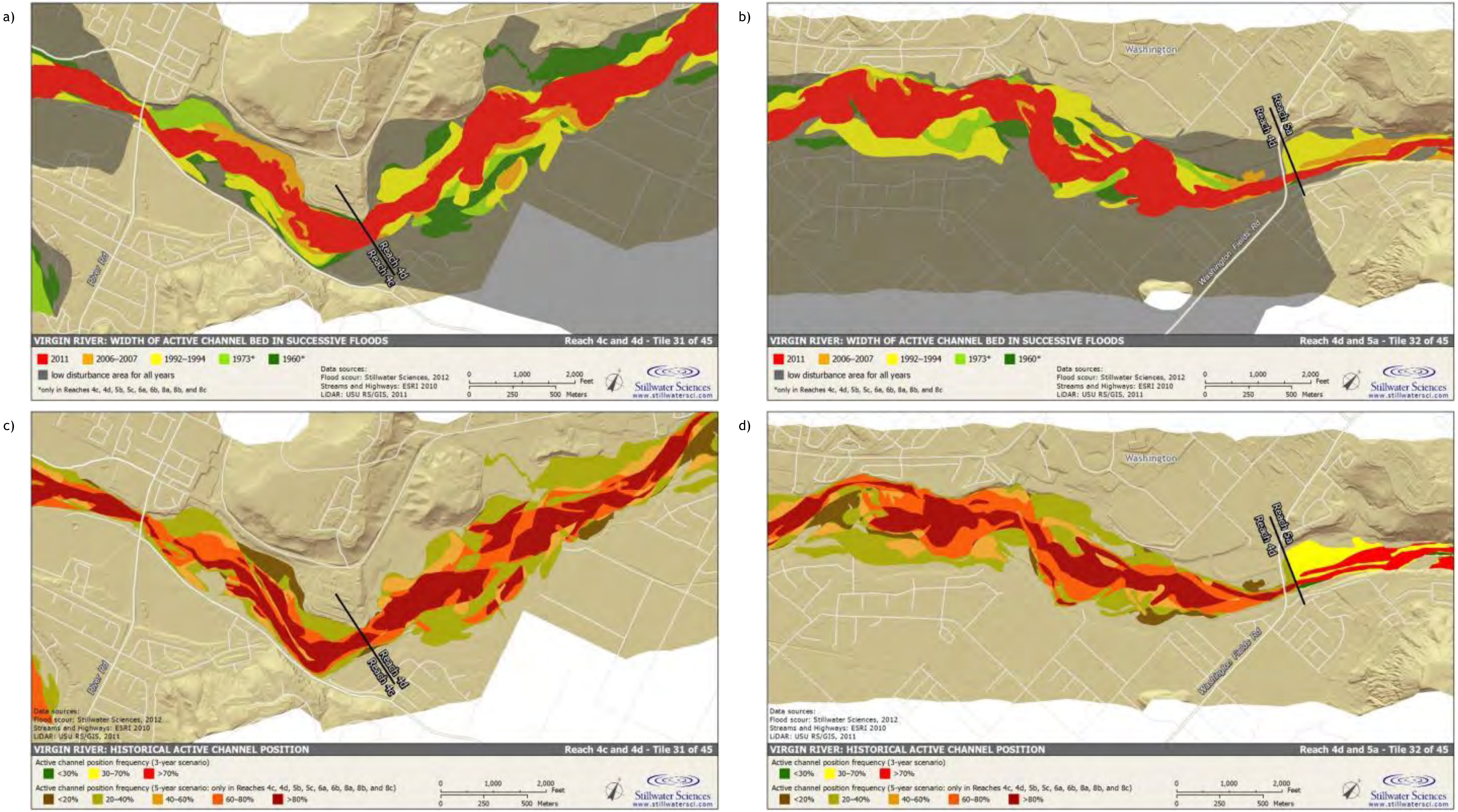


Figure B2.16. Virgin River flood-scour analysis results for Reaches 4c, 4d, and 5a: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

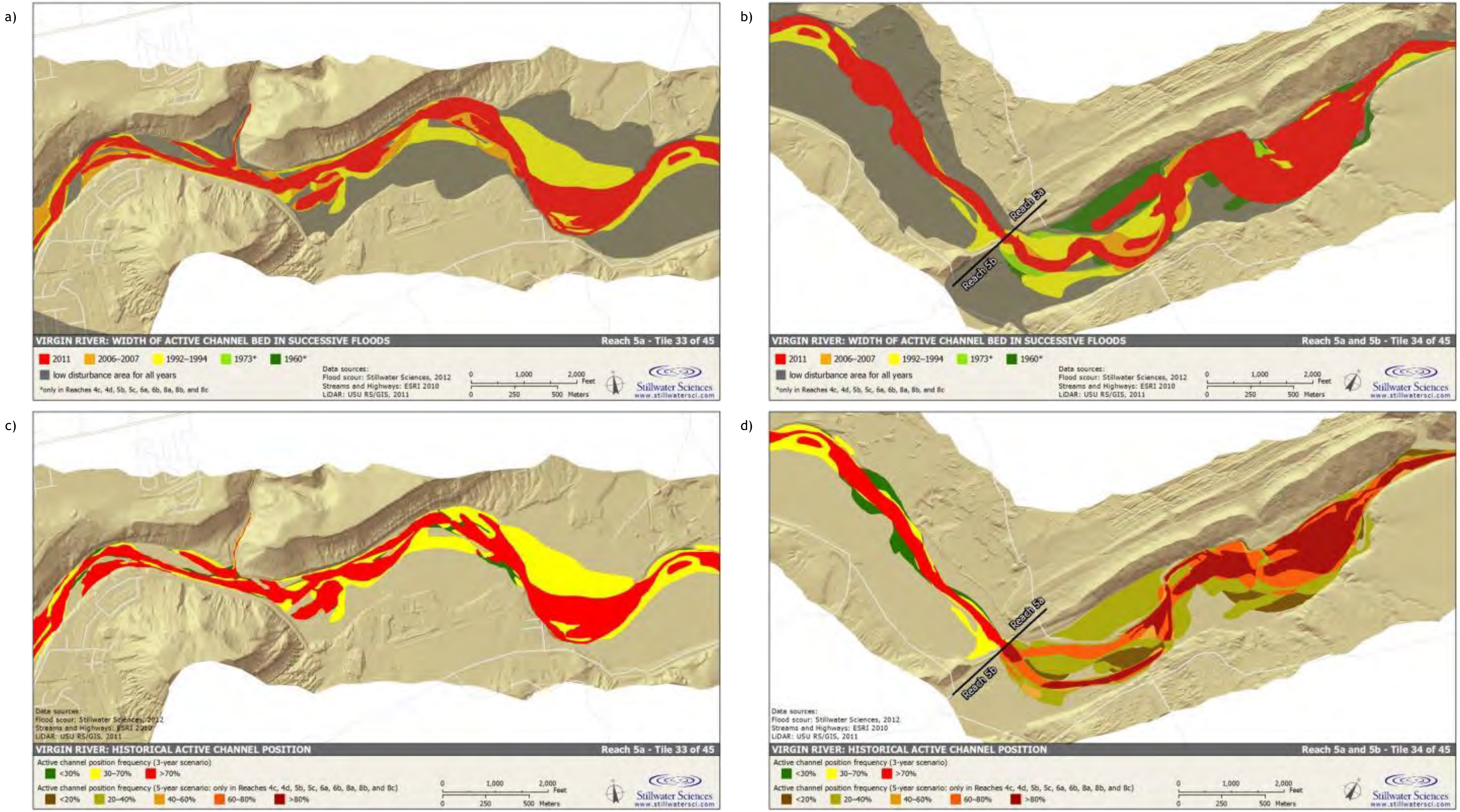


Figure B2.17. Virgin River flood-scour analysis results for Reaches 5a and 5b: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

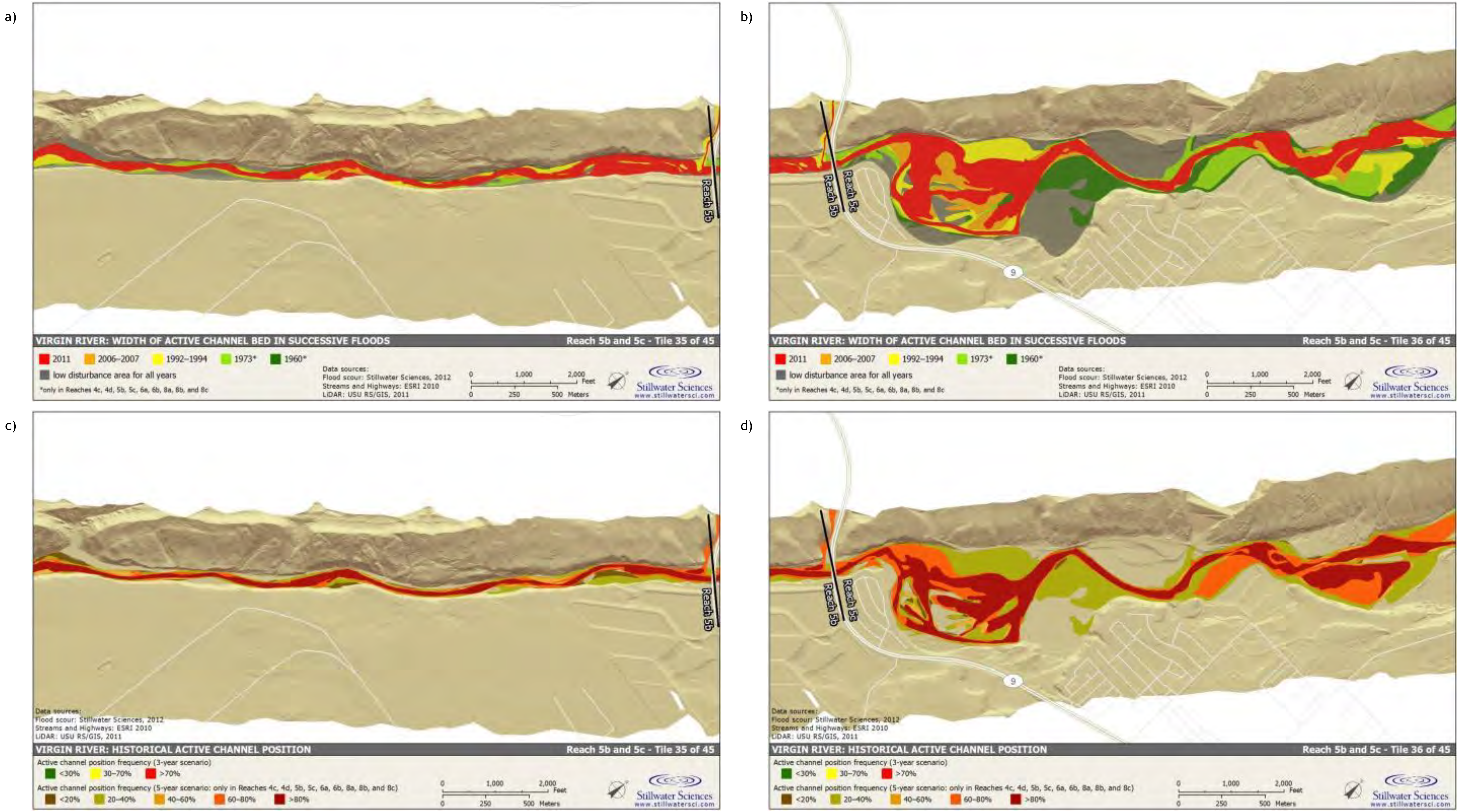


Figure B2.18. Virgin River flood-scour analysis results for Reaches 5b and 5c: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

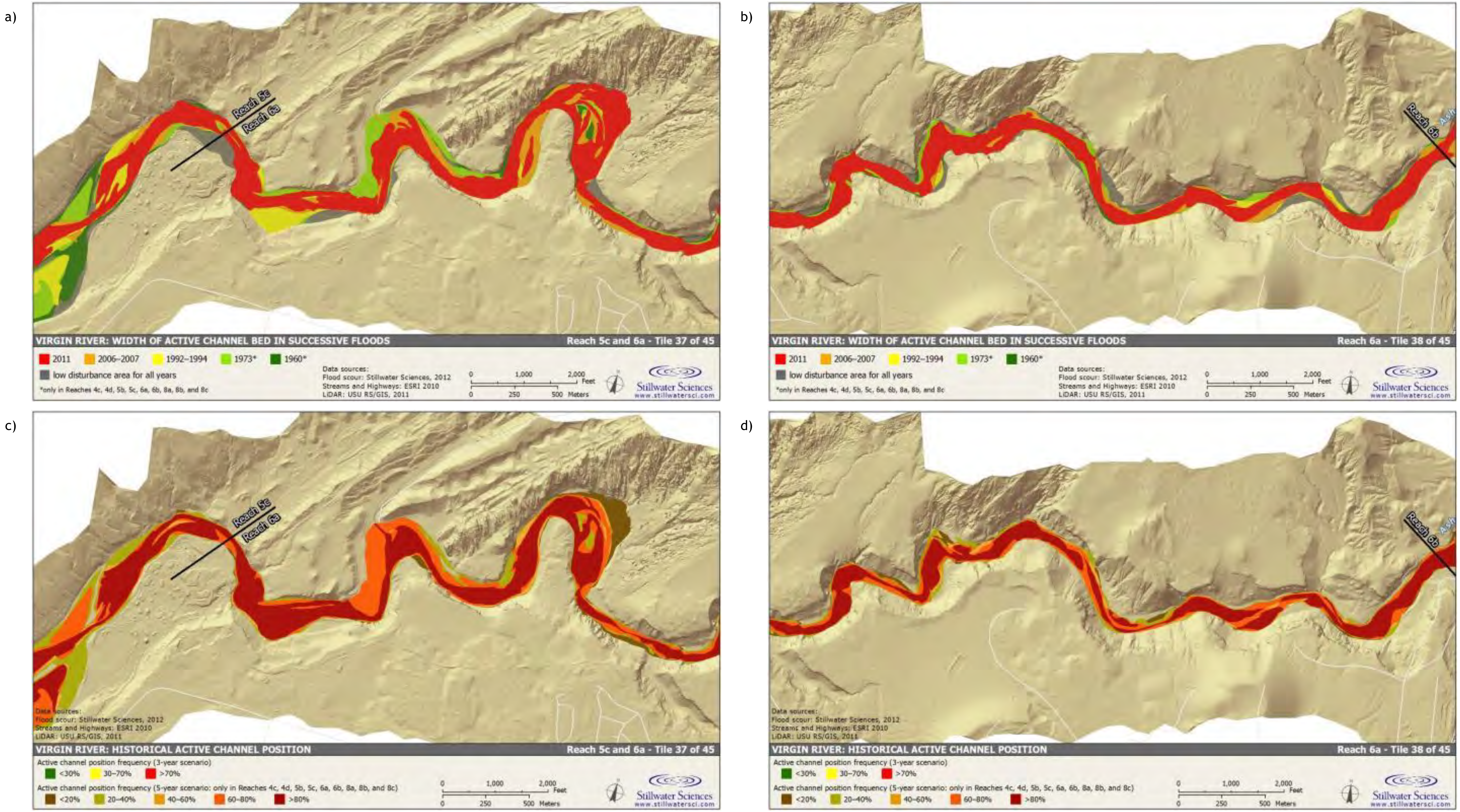


Figure B2.19. Virgin River flood-scour analysis results for Reaches 5c and 6b: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

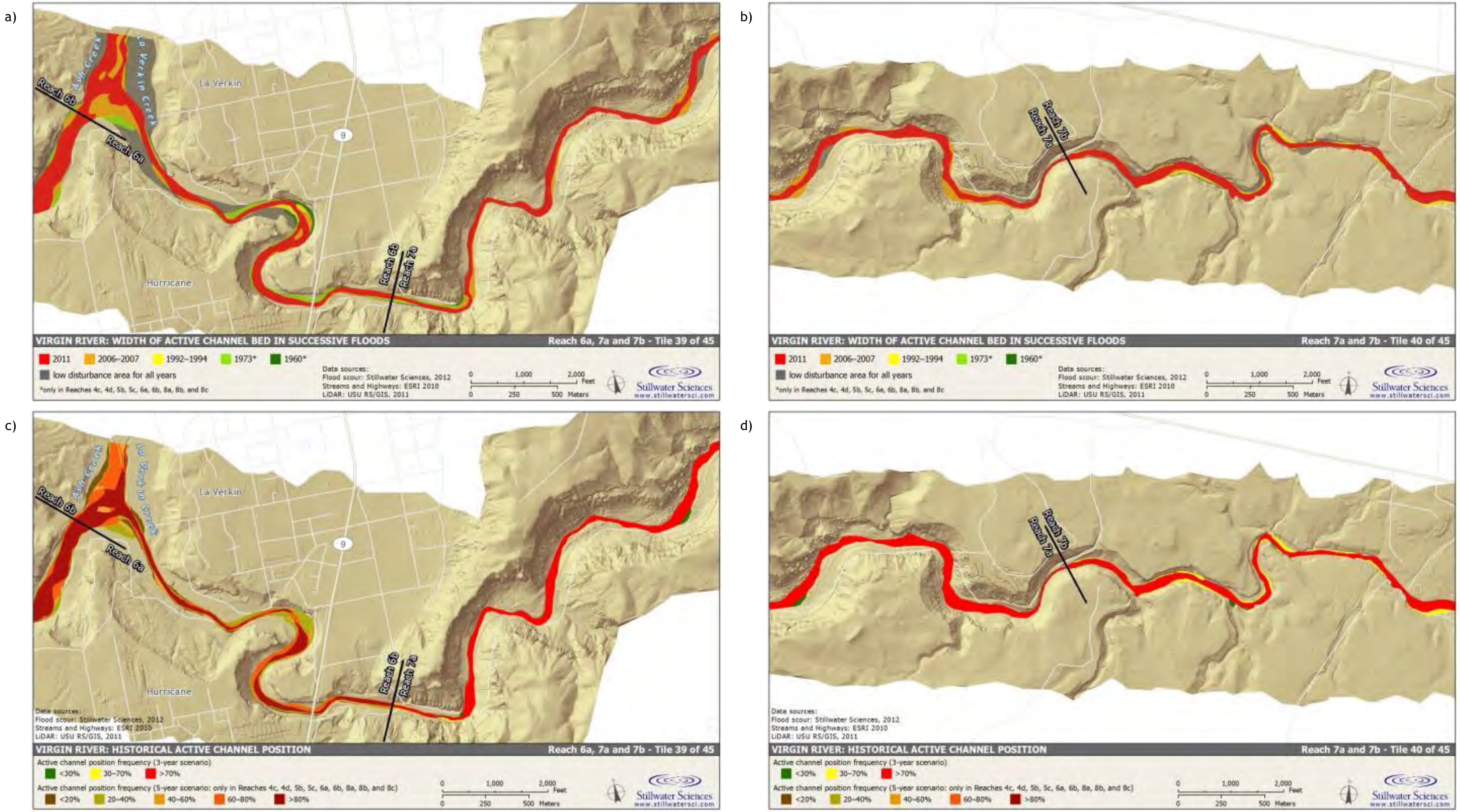


Figure B2.20. Virgin River flood-scour analysis results for Reaches 6b, 7a, and 7b: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

a) b) c) d)

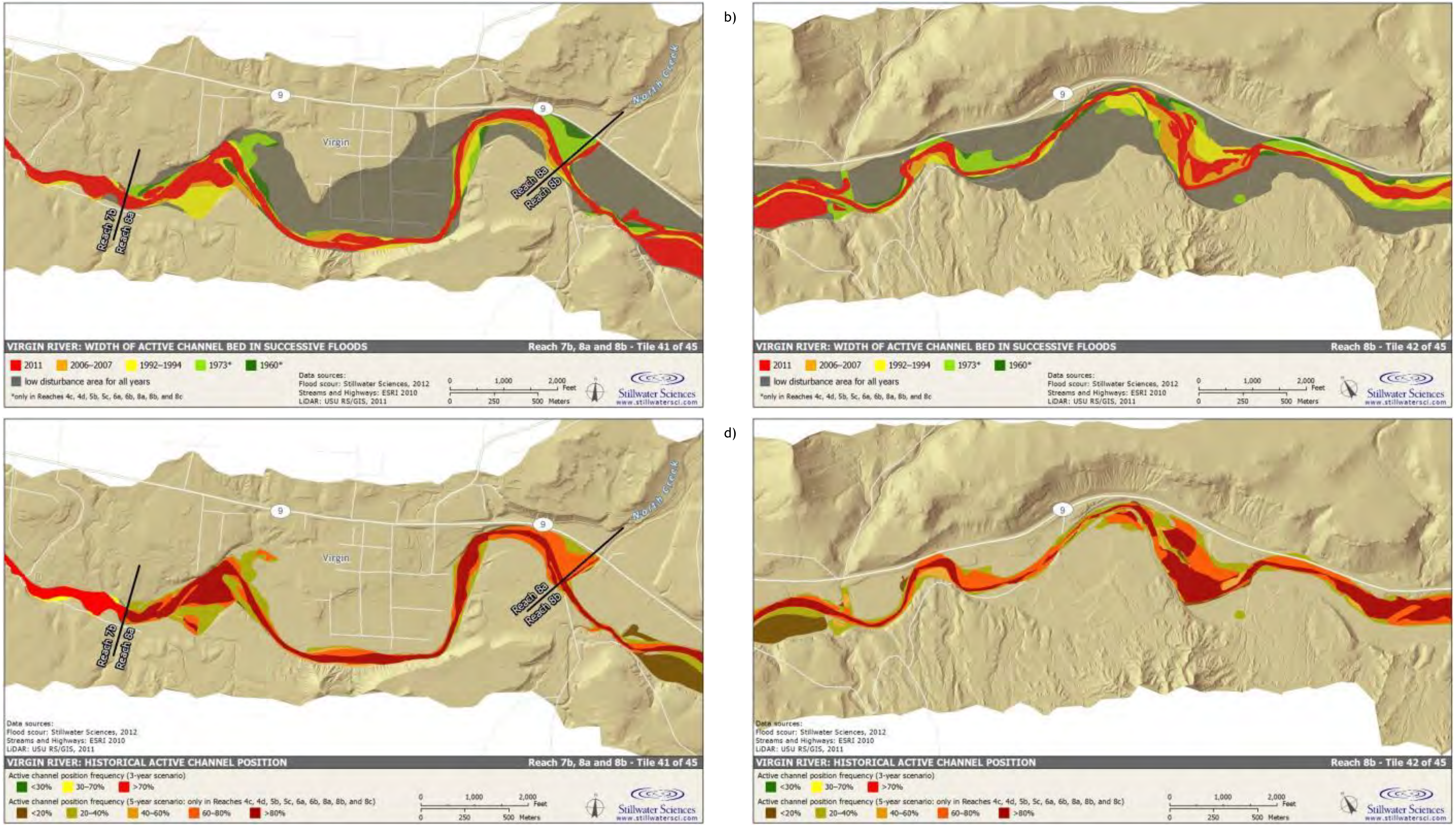


Figure B2.21. Virgin River flood-scour analysis results for Reaches 7b, 8a, and 8b: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

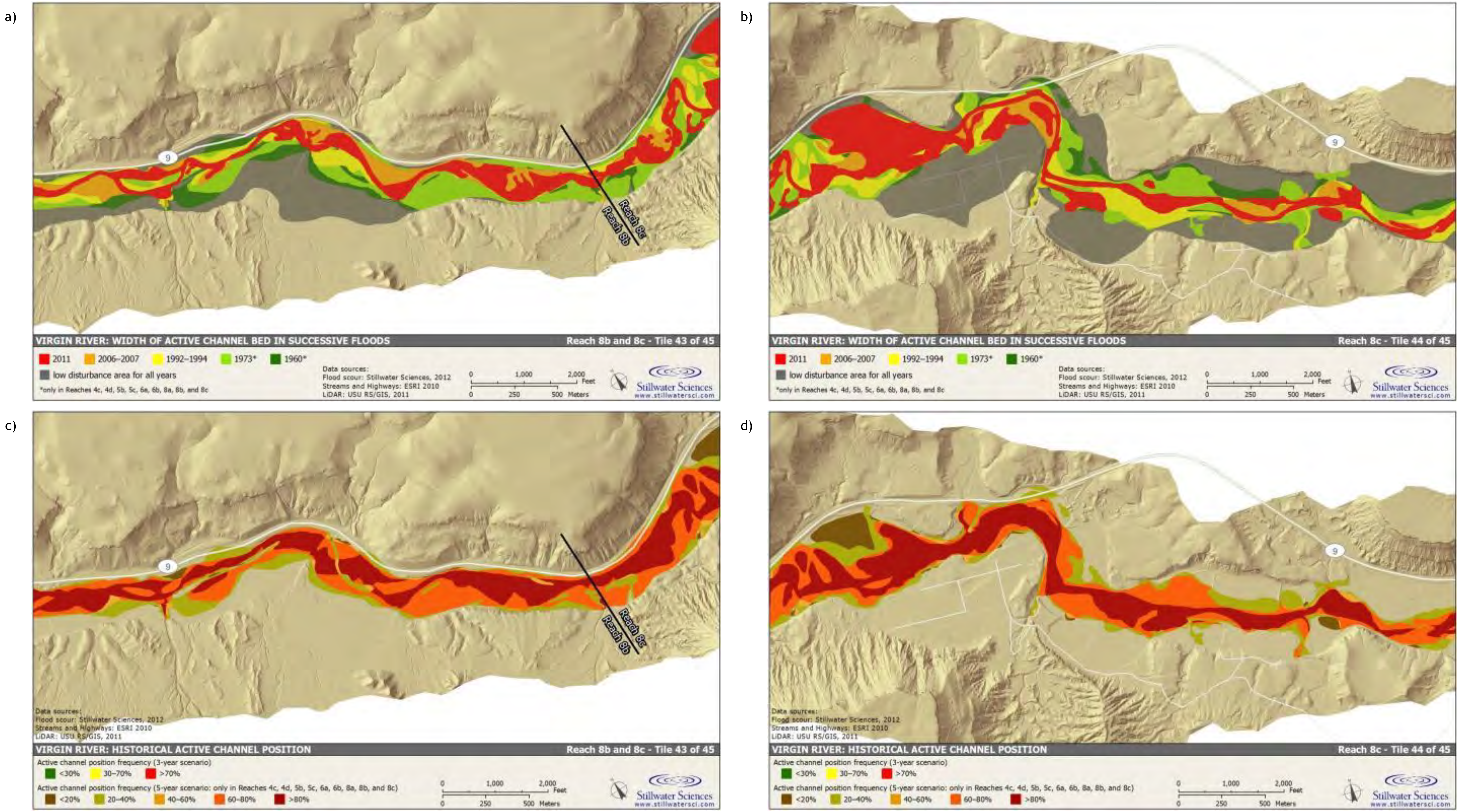
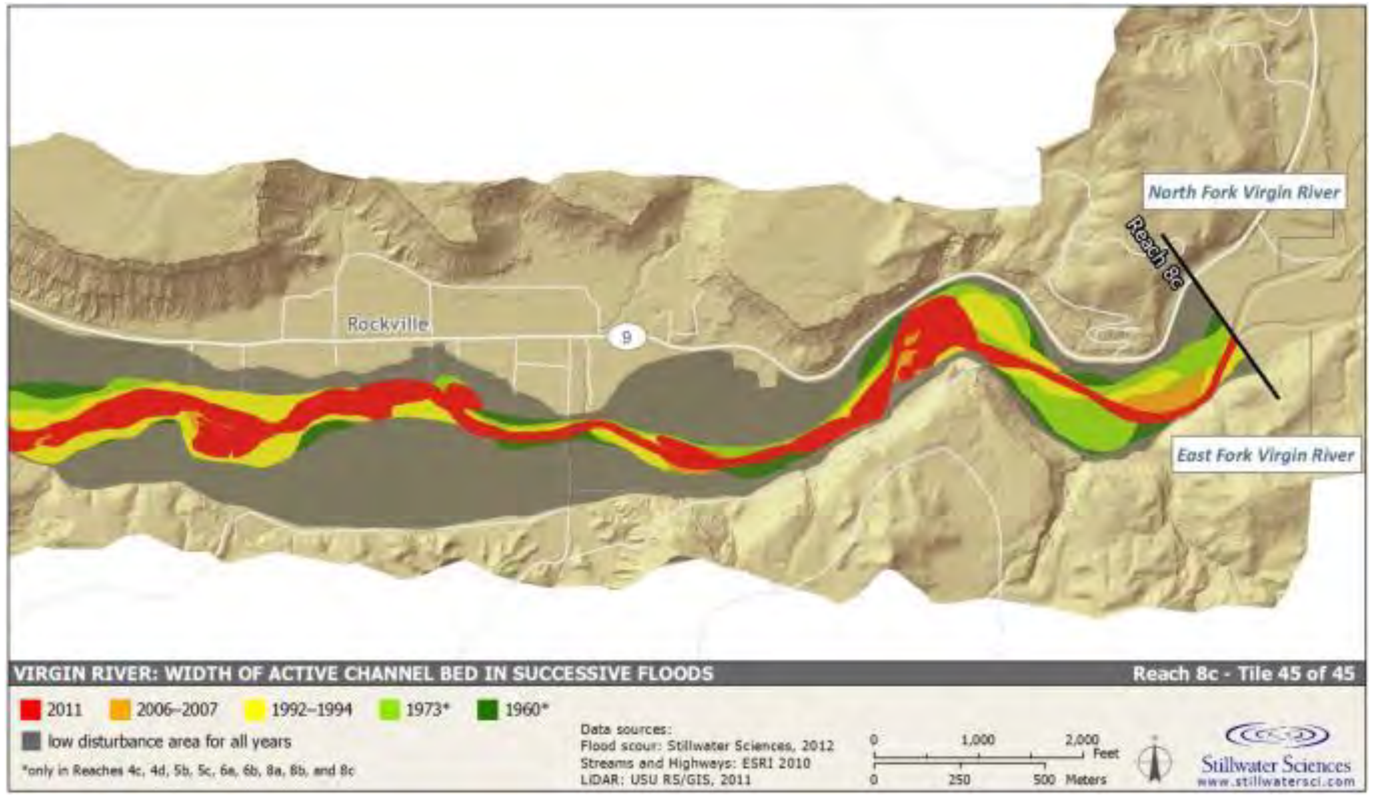


Figure B2.22. Virgin River flood-scour analysis results for Reaches 8b and 8c: active width of channel bed in successive floods (a, b), with more recent floods on top; and historical channel position (c, d) showing proportion of time that the active channel bed has occupied a given location.

a)



b)

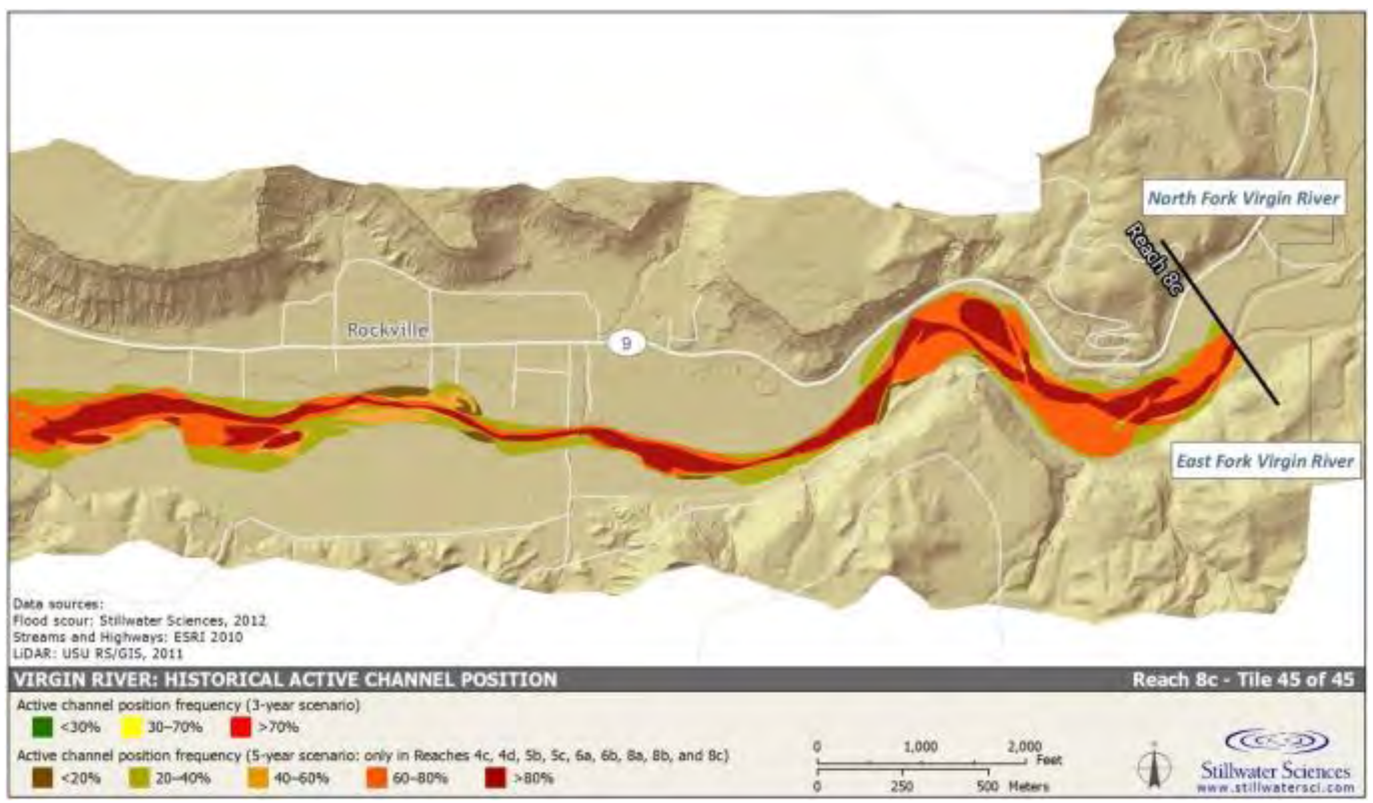


Figure B2.23. Virgin River flood-scour analysis results for Reach 8c (upper): active width of channel bed in successive floods (a), with more recent floods on top; and historical channel position (b) showing proportion of time that the active channel bed has occupied a given location.

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Tiegs, S. D. and M. Pohl. 2005. Planform channel dynamics of the lower Colorado River: 1976-2000. Geomorphology 69: 14–27.

Tiegs, S. D., J. F. O'Leary, M. M. Pohl, and C. L. Munill. 2005. Flood disturbance and riparian diversity on the Colorado River Delta. Biodiversity and Conservation 14: 1,175–1,194.

Appendix C

Field-Based Vegetation Maps for the Three TNC-Utah Conservation Reaches

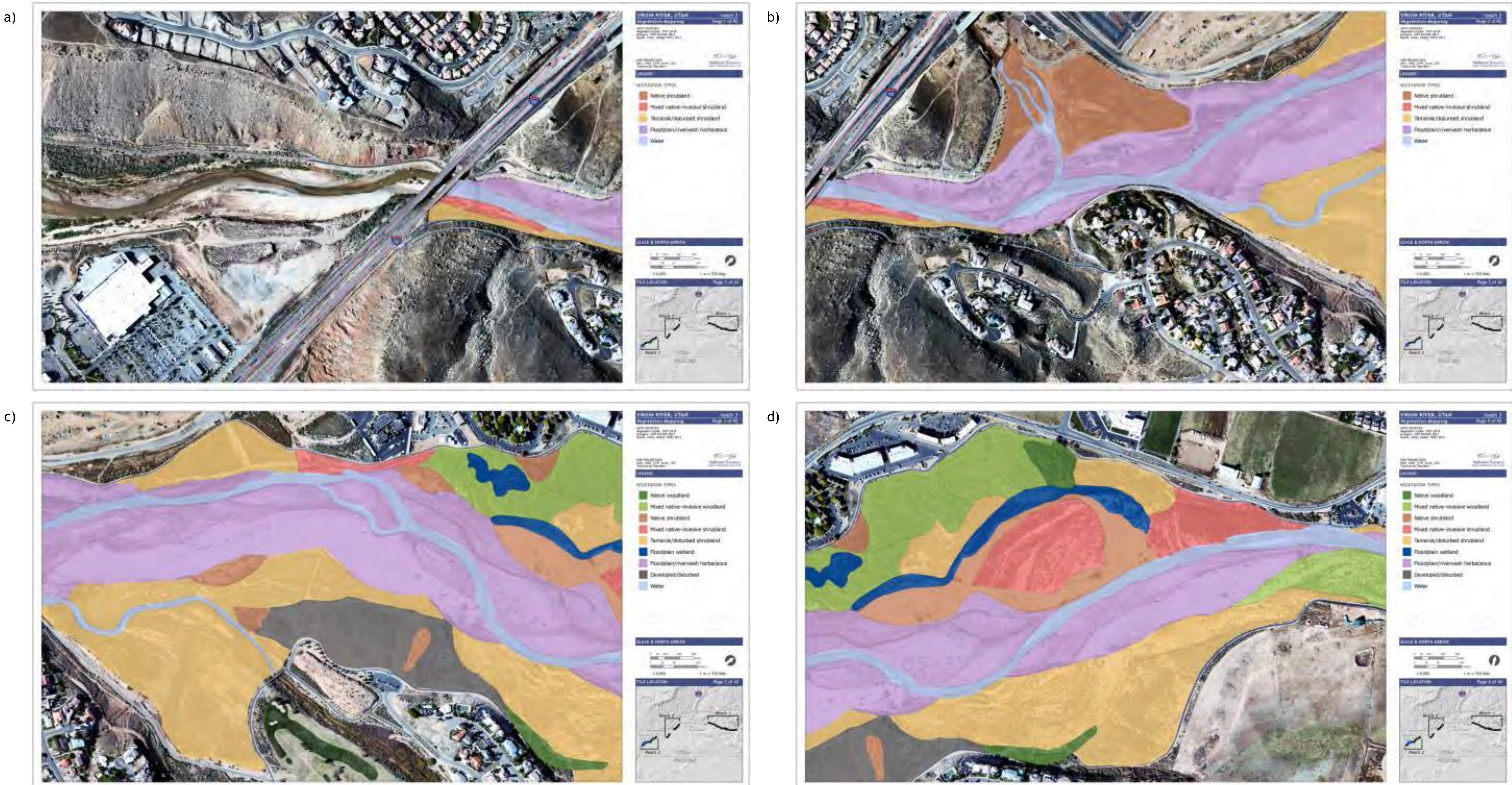


Figure C1.1. Upper Virgin River field-based vegetation mapping for TNC-Utah's Lower Reach near St. George, Utah.

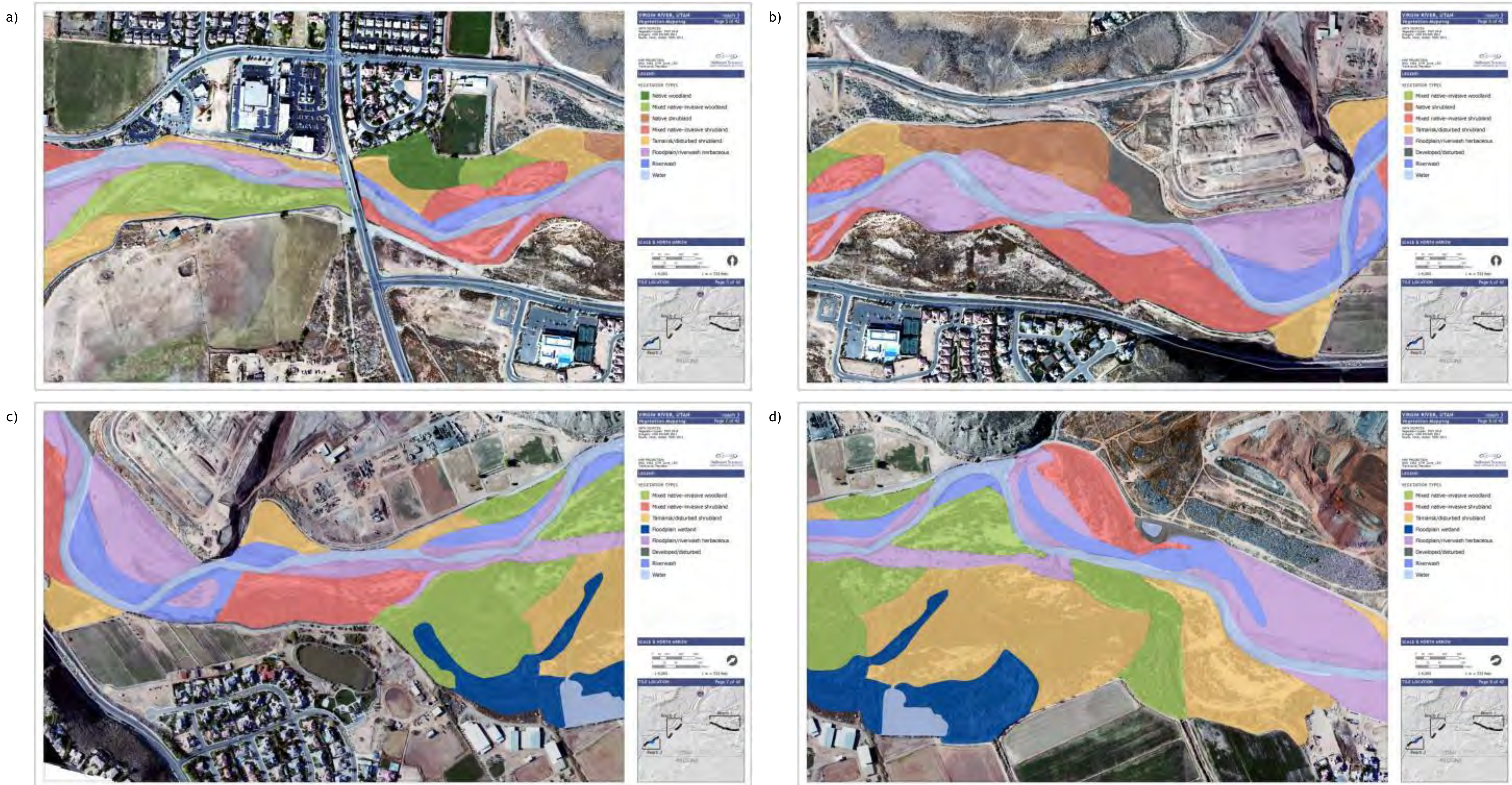


Figure C1.2. Upper Virgin River field-based vegetation mapping for TNC-Utah's Lower Reach near Washington, Utah.

Figure C1.3. Upper Virgin River field-based vegetation mapping for TNC-Utah's Lower Reach near Washington, Utah.

a) b) c) d)

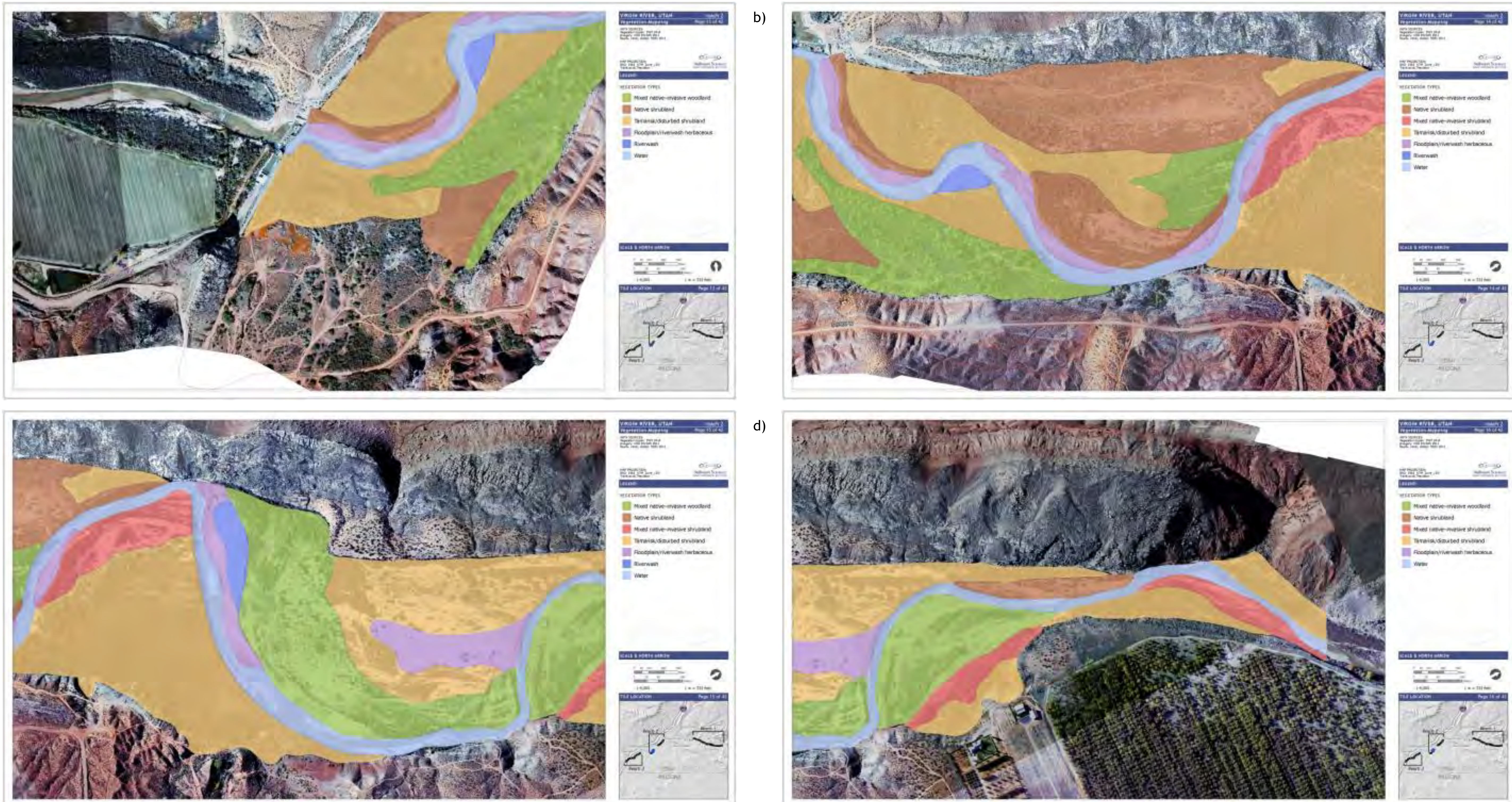


Figure C2.1. Upper Virgin River field-based vegetation mapping for TNC-Utah's Middle Reach near Washington Field Diversion.

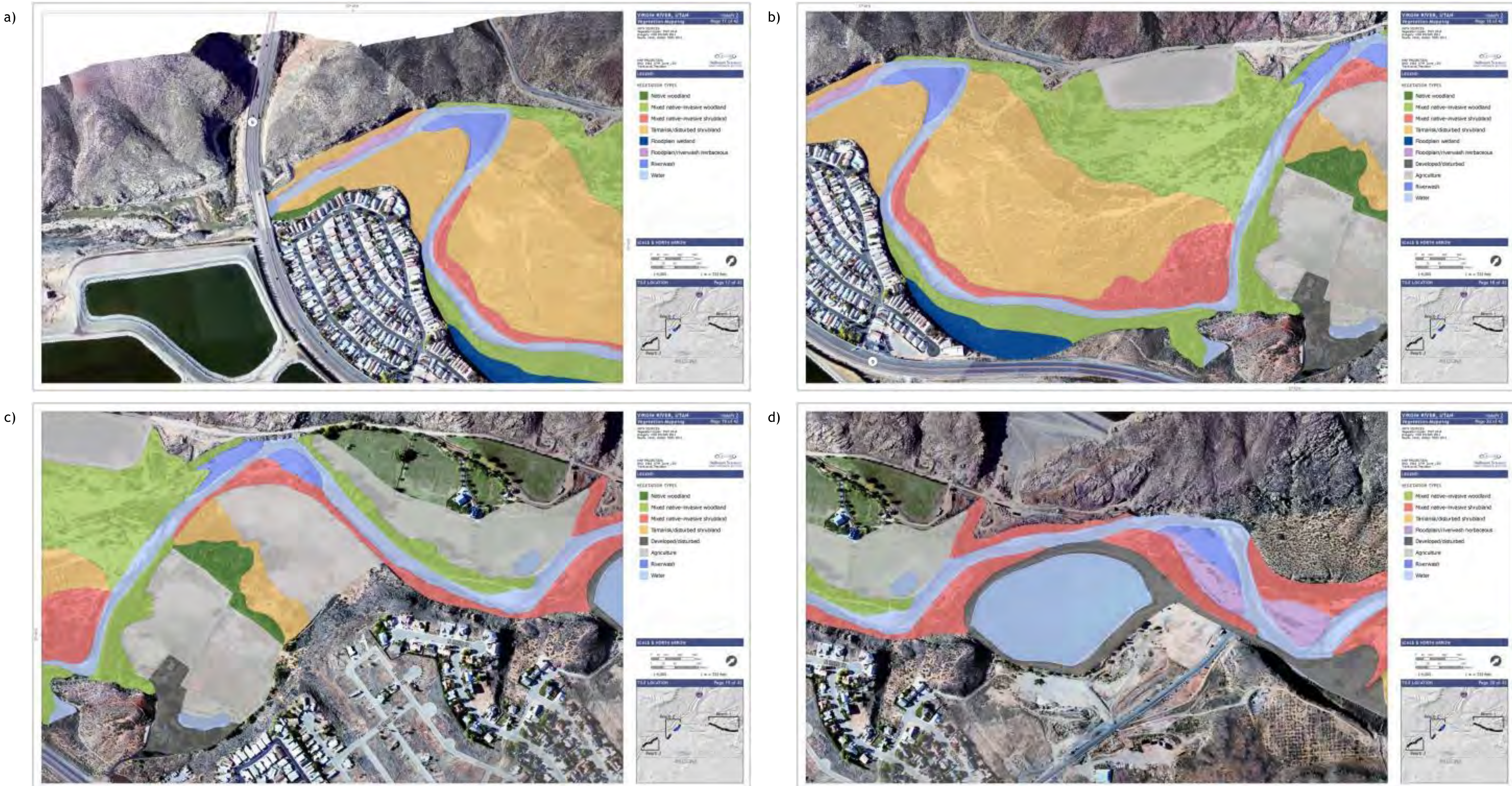


Figure C2.2. Upper Virgin River field-based vegetation mapping for TNC-Utah's Middle Reach near Highway 9 bridge.

a) b)

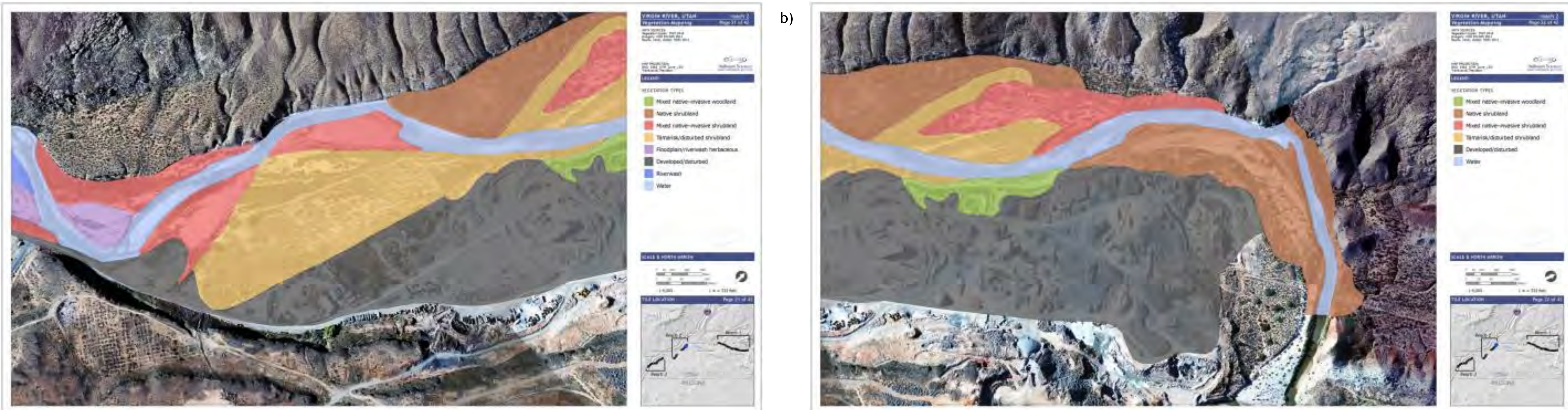


Figure C2.3. Upper Virgin River field-based vegetation mapping for TNC-Utah's Middle Reach near Hurricane, Utah.

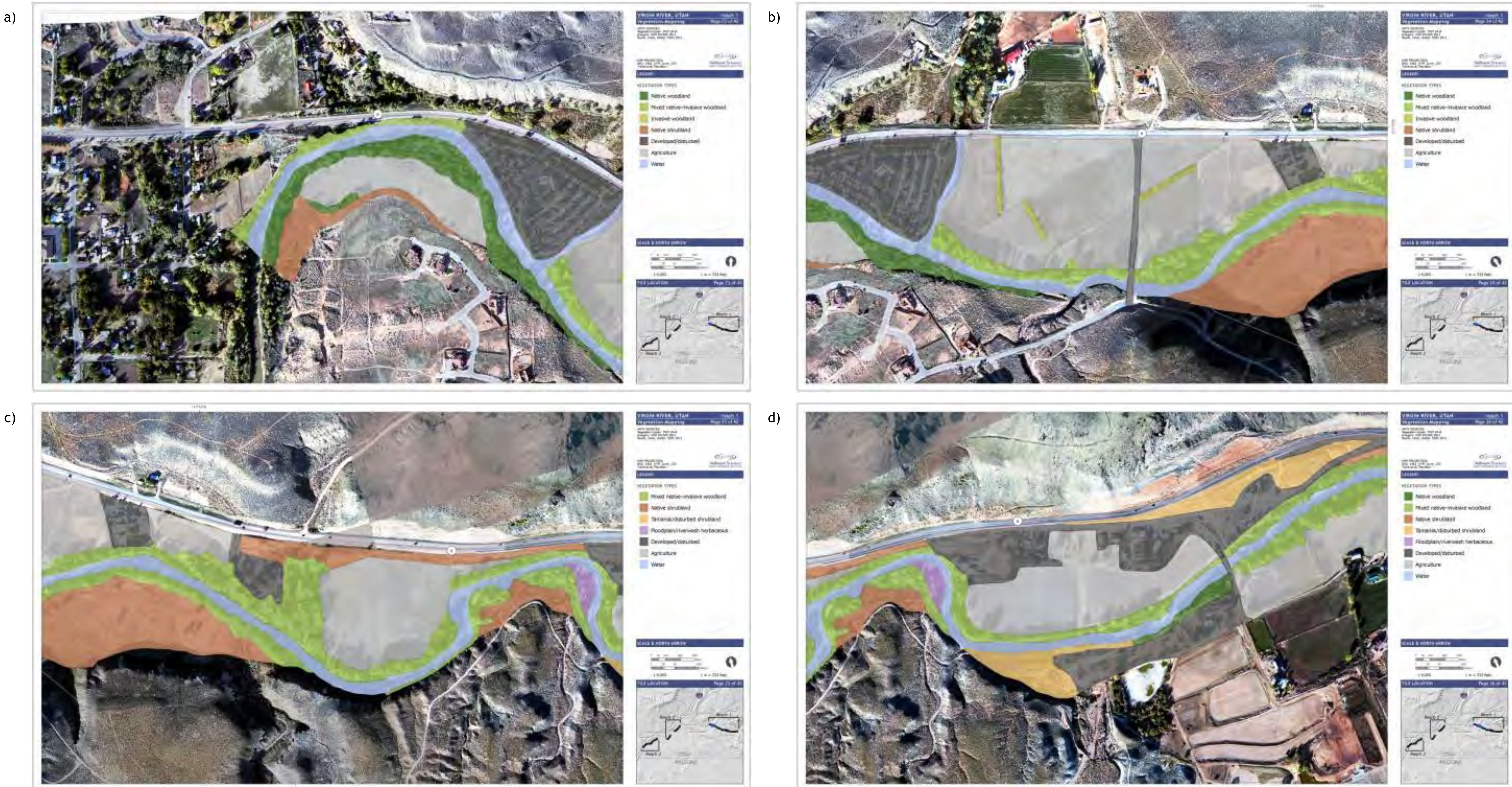


Figure C3.1. Upper Virgin River field-based vegetation mapping for TNC-Utah's Upper Reach near Virgin, Utah.

a) b) c) d)

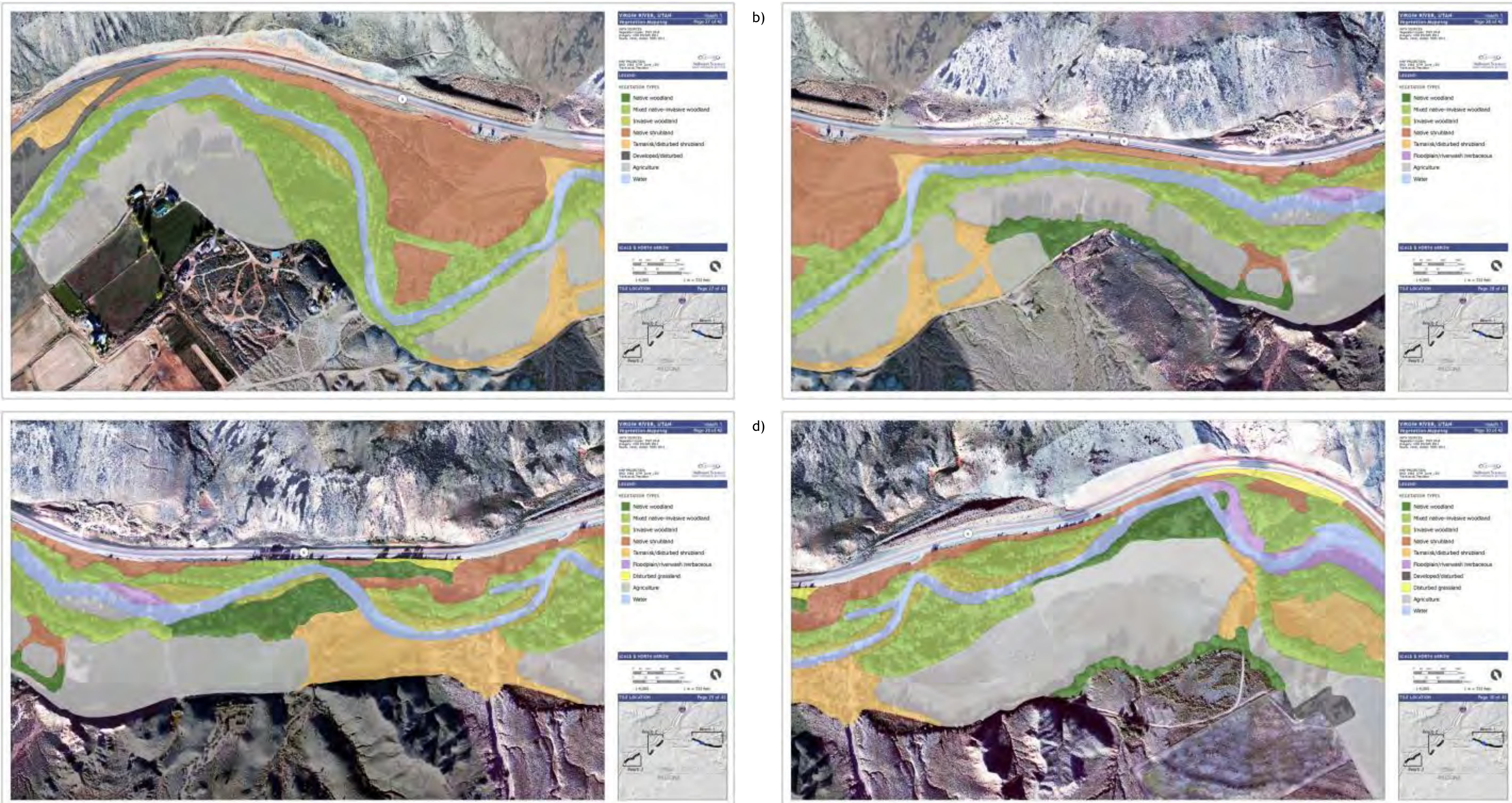


Figure C3.2. Upper Virgin River field-based vegetation mapping for TNC-Utah's Upper Reach upstream of Virgin, Utah.

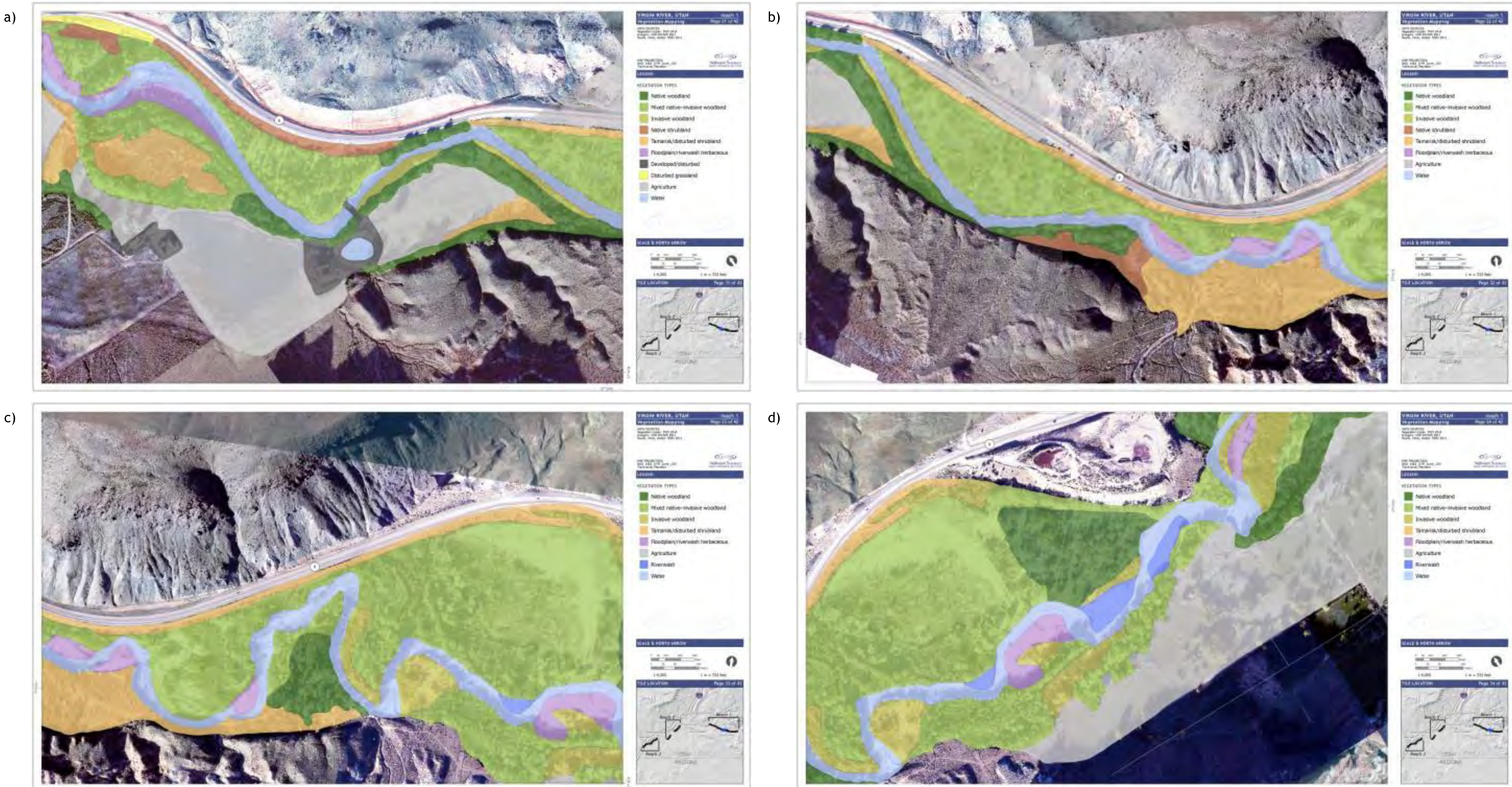


Figure C3.3. Upper Virgin River field-based vegetation mapping for TNC-Utah’s Upper Reach between Virgin and Rockville, Utah.

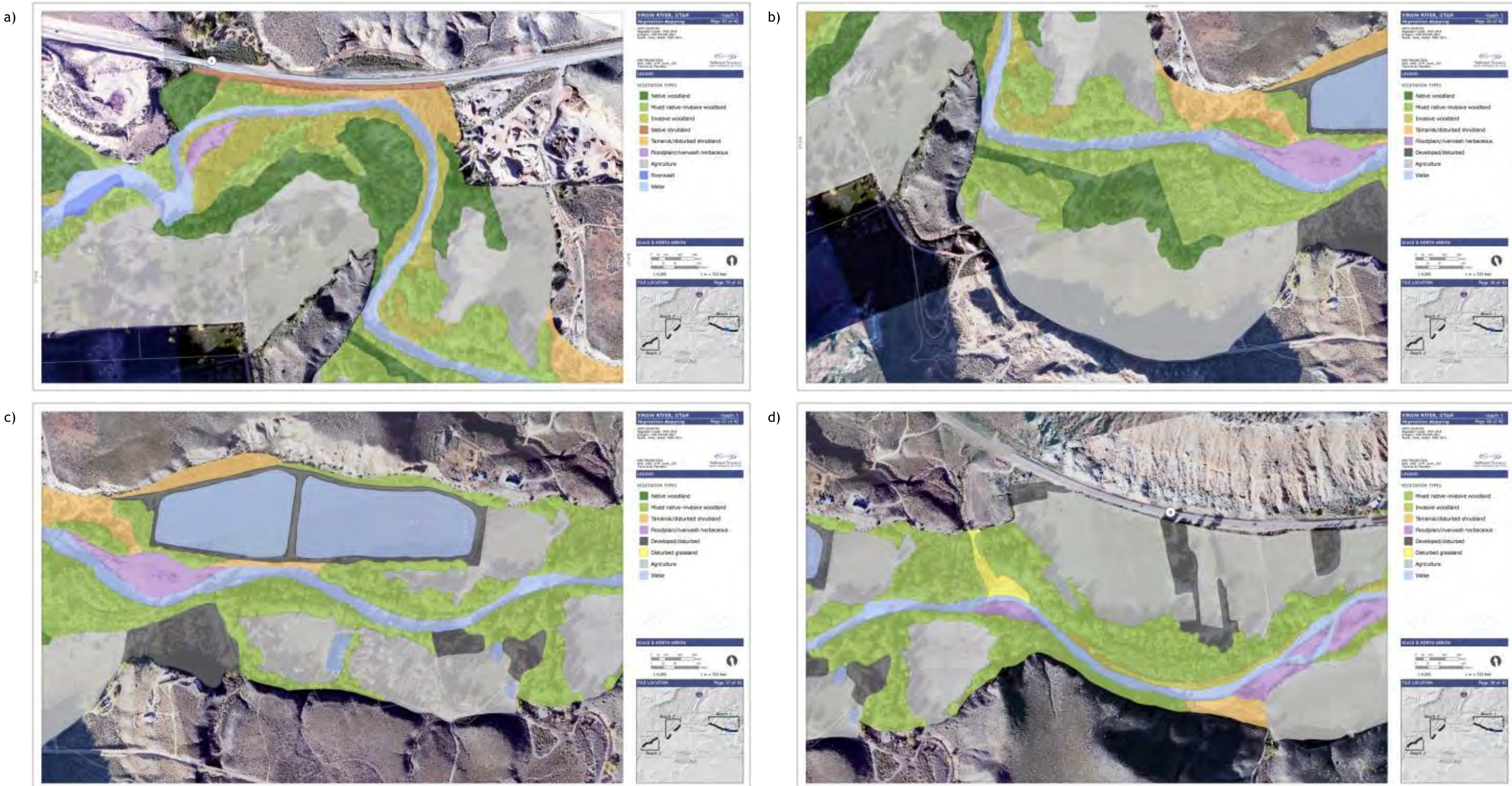
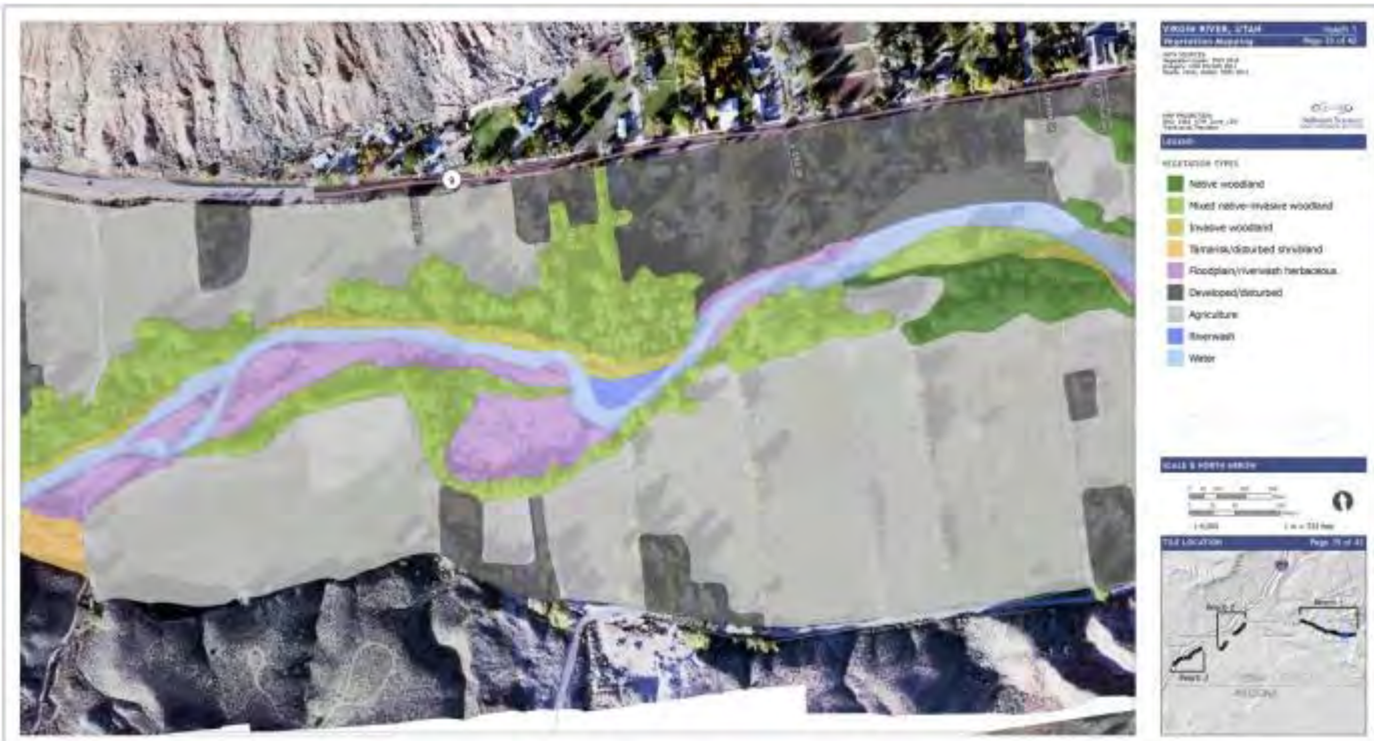


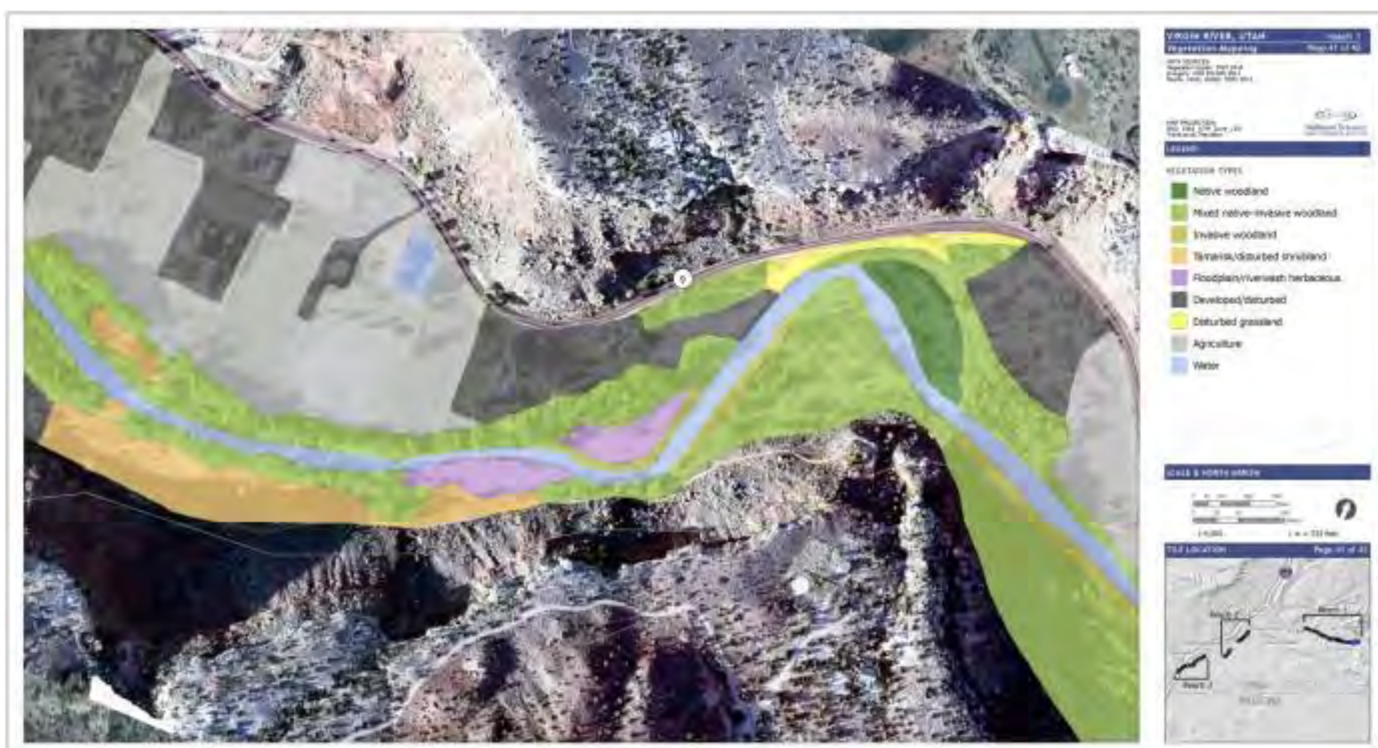
Figure C3.4. Upper Virgin River field-based vegetation mapping for TNC-Utah's Upper Reach downstream of Rockville, Utah.

a)



b)

c)



d)

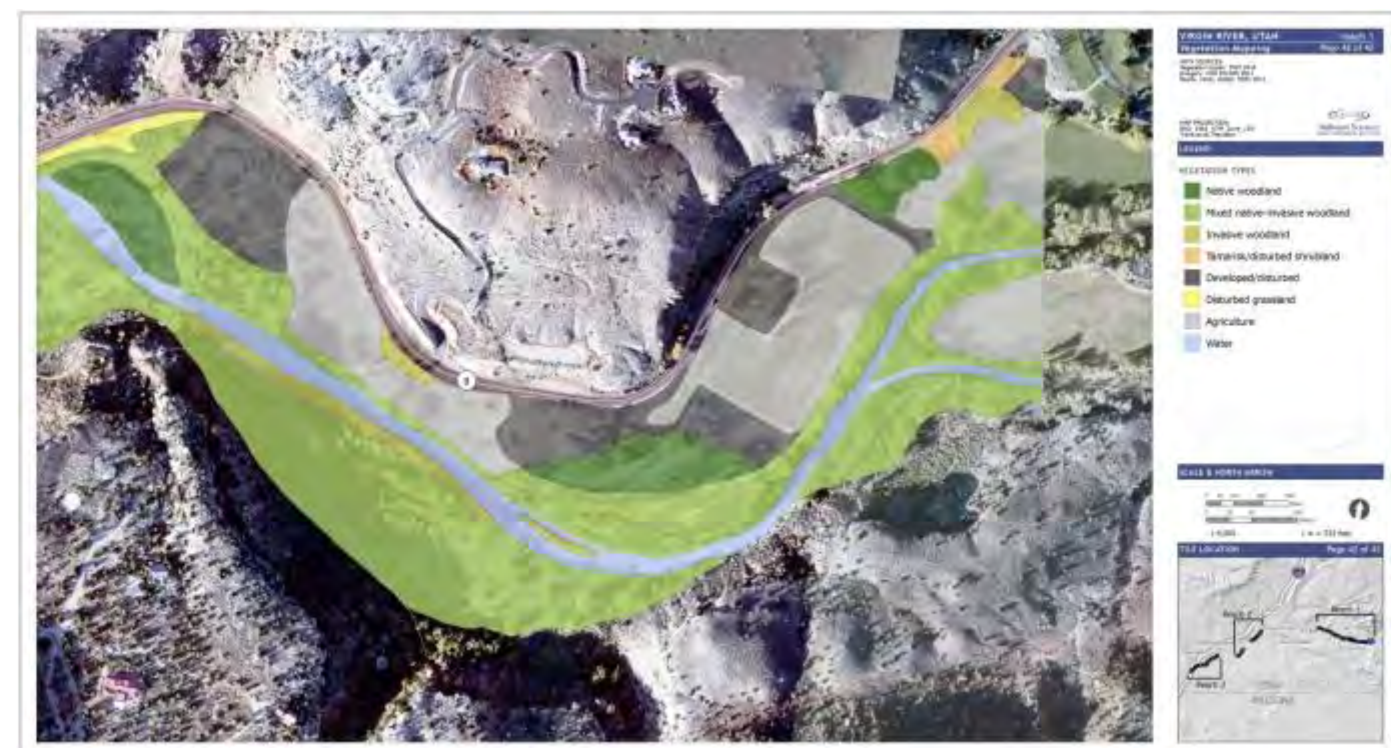


Figure C3.5. Upper Virgin River field-based vegetation mapping for TNC-Utah's Upper Reach near Rockville, Utah.