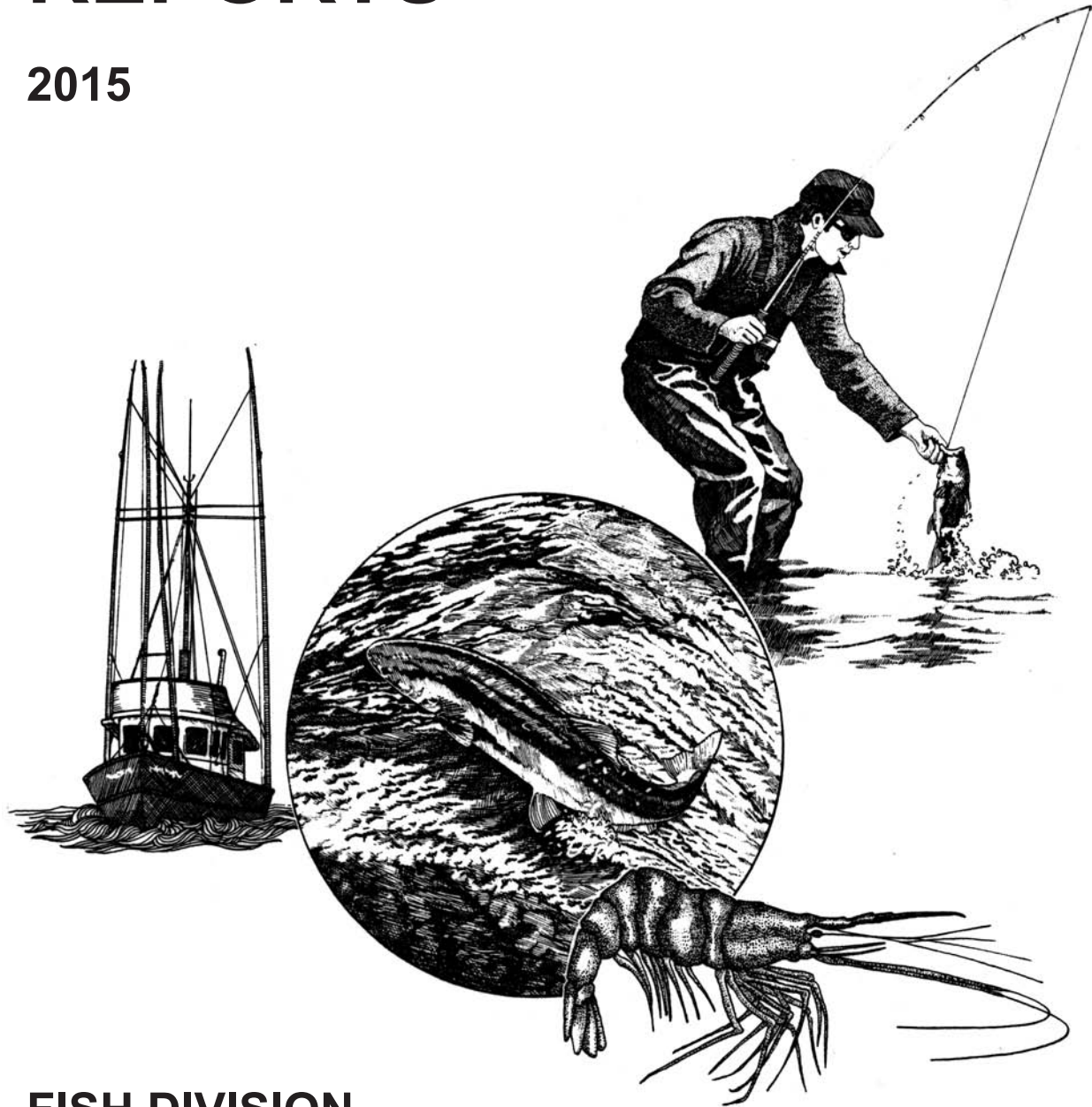


PROGRESS REPORTS

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Temporal Variability in the Distribution and Abundance of a Desert Trout:
Implications for Monitoring Design and Population Persistence in
Dynamic Stream Environments

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**Temporal variability in the distribution and abundance of a desert trout:
implications for monitoring design and population persistence
in dynamic stream environments**

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Abstract

Fisheries management and conservation strategies often rely on an understanding of the abundance of target species. However, providing precise estimates of abundance for species or populations can require a considerable amount of effort in terms of time, or personnel, or both. During protracted sampling events, fish may be moving throughout the target study system, and if these movements are non-random they may bias abundance estimates when not accounted for by sample design. The objective of this study was to evaluate whether spatio-temporal variability in fish distribution and density of redband trout in Rock Creek, Oregon, may bias population-level abundance estimates. Specific emphasis was placed on spatio-temporal variability in distribution and density associated with stream drying. We estimated that the wetted habitat available to redband trout in Rock Creek decreased substantially from 3 June to 2 September 2015. During this time period, we sampled a total of 620 redband trout and uniquely tagged 481 redband trout. We observed movement of six tagged redband trout among samples sites (i.e., 100-m stream reaches) during the study; four fish were recaptured about 0.1 km from their original capture location, one fish was recaptured about 0.2 km from its original capture location, and one fish was recaptured about 1.8 km from its original capture location. Additionally, we did not observe any redband trout among 22 sample sites in the lower 13.1 km of Rock Creek that were sampled prior to desiccation in 2015; despite the fact that redband trout have been observed in this area during previous surveys conducted from 2007 – 2012. Over the sample period we estimated that redband trout abundance decreased from a high of 1,487 individuals to a low of 665 individual. These estimates represent about a 90% decrease in population abundance compared to previous surveys (i.e., surveys conducted from 2007 – 2012); although there were some differences in sampling methodology. Combined, these data suggest that redband trout in Rock Creek are generally not redistributing in response to stream drying, but are likely becoming stranded and die as stream habitats fragment and dry. Additionally, the number of successive years of drought or near-drought conditions, and not just the magnitude of drought in any one year, may contribute the ability to redband trout to recolonize previously dry habitats and may greatly influence the abundance of redband trout. Finally, understanding patterns of stream drying may aid in identifying drought-resistant refuge habitats that warrant special protection.

Introduction

Fisheries management and conservation strategies often rely on an understanding of the abundance of target species. However, providing precise estimates of abundance for species or populations that occur over large spatial extents can require a considerable amount of effort in terms of time, or personnel, or both. Consequently, field crews may spend weeks or months sampling in order to achieve adequate sample sizes to maximize the precision of abundance estimates for a species of interest (e.g., Meeuwig and Clements 2014). During this type of protracted sampling event fish may be moving throughout the target study system, and if these movements are non-random they may bias abundance estimates when not accounted for by sample design.

Visiting sample sites following the order of a random or hierarchical random sampling design should mitigate the effect of fish movement on abundance estimates. However, randomly visiting sample sites in space will generally take more time than other more convenient sampling schemes due to increased travel time between sample sites. Therefore, this type of sampling has greater potential to overlap with seasonally-directed migrations. Additionally, environmental variation (e.g., variation in water quality and quantity) may result in non-random changes in the distribution of fishes. For example, significant portions of many desert streams may dry up during low-water years or during severe droughts. Sampling strategies that take longer time periods to complete are more likely to incorporate periods of environmental variation; therefore, this often overlooked aspect of sample design should be addressed.

The objective of this study was to evaluate whether spatio-temporal variability in fish distribution and density may bias population-level abundance estimates. Specifically, we evaluated whether abundance and density estimates for redband trout (*Oncorhynchus mykiss newberrii*) in the Rock Creek drainage, Oregon, varied as a function of time of sampling during a period of stream drying. We predicted that individual redband trout may be encountered multiple times, in different locations, throughout a prolonged sample period if they are redistributing as a function of time or in response to stream drying. If this occurs, prolonged sampling or sampling during periods of stream drying may over-estimate abundance by counting individual fish more than once. We also predicted that site-level density estimates (based on stream length), and resulting population-level abundance estimates, will increase as a function of time during a period of stream drying if redband trout are redistributing and crowding into non-dry, refuge habitats. Additionally, we characterize patterns of stream drying in Rock Creek and discuss results of this study in relation to past redband trout surveys in this and other areas within the Great Basin.

Methods

Model system

The model system for this study was redband trout in the Rock Creek drainage, Oregon. This system was selected because 1) the presumed high degree of inter- and intra-annual environmental variability experienced by redband trout in this system, 2)

redband trout in this system appear to be resilient to large fluctuations in water availability, and 3) the spatial extent and land-ownership of this system make a study of this nature tractable. For this study, the Rock Creek drainage was defined as the portion of Rock Creek and its tributaries located within hydrologic unit codes (HUC) 171200080402 and 171200080504 that were hydrologically connected by instream flow and that were assumed to have sufficient water volume to support redband trout (Figure 1). Specifically, the study system was assessed on 28 April 2015 and areas that were dry, that were not hydrologically connected to Rock Creek by instream flow, that were excessively shallow or high gradient, or where redband trout were not observed were removed from the sampling frame. The lower boundary of the study system was identified by locating the downstream-most non-dry portion of Rock Creek. The upstream boundary on Willow Creek was selected based on increasing gradient. The upstream boundaries in the headwaters of Rock Creek were identified based on the location of headwater springs or by walking along the stream until redband trout were no longer observed. The resulting sampling frame consisted of 30 km of stream (Figure 1).

Oregon Department of Fish and Wildlife (ODFW) conducted redband trout status surveys annually in this system from 2007 through 2012, with the exception of 2008 (Meeuwig and Clements 2014). These surveys were based on a spatially representative sample design with a similar sampling frame as described above, with the exception that no portion of Willow Creek was included in the sampling frame. Among years, the number of sample sites visited that were dry varied substantially: 56% dry in 2007, 18% dry in 2009, 0% dry in 2010 and 2011, and 75% dry in 2012. These data indicate the nature of the inter-annual variation in water availability experienced by redband trout in this system. Despite the fact that stream drying has often occurred over relatively large sections of the sampling frame in past years, redband trout in this system appear to be abundant relative to other areas in the northern portion of the Great Basin. For example, Rock Creek had among the highest density (fish·m⁻¹) of redband trout among populations examined by ODFW from 2007 through 2012 (Meeuwig and Clements 2014). These data suggest that redband trout in this system are able to persist regardless of presumed high levels of environmental variability.

Sample Site Selection

The sampling frame was divided into 300 contiguous 100-m sample sites and the upstream and downstream coordinates of each sample site were obtained using ArcMap 10.2 (Esri; Redlands, California); all geographic data processing was based on NHDPlus data and a projected coordinate system (UTM Zone 11, WGS84). A generalize random-tessellation stratified (GRTS) sample design was used to produce an ordered list of sample sites such that following the GRTS sample order would result in a spatially well distributed sample (Stevens and Olsen 2004). The GRTS sample draw was implemented using R software (R Core Team 2013) and the *spsurvey* package (Version 3.0) based on an equal probability sample from a finite resource; the finite resource was the list of downstream coordinates for each sample site.

Fish and Habitat Sampling

Fish and habitat sampling occurred from 3 June through 2 September, 2015. Field crews generally sampled sites based on the GRTS sample order with few exceptions (Figure 2). For each sample site, the upstream and downstream boundaries of the sample site were identified using a handheld GPS receiver. If the entire sample site was dry, the site was recorded as a dry site and no other sampling was conducted. If the site was not dry, block nets were placed at the upstream and downstream boundaries of the sample site and water temperature was recorded prior to conducting electrofishing surveys; electrofishing surveys were not conducted if the stream temperature exceeded 21°C.

Depletion Sampling—Fish were sampled using a backpack electrofisher (model LR-24; Smith-Root, Inc.; Vancouver, Washington) and 4-pass depletion sampling (i.e., removal sampling; Hayes et al. 2007). The LR-24 quick setup feature was initially used to select an appropriate power output for the backpack electrofisher until field crews identified appropriate and efficient voltage settings for Rock Creek, which were generally used for the remainder of the sample period. For each electrofishing pass, a two person field crew sampled in a downstream to upstream direction starting at the downstream site boundary and ending at the upstream site boundary. The field crew consisted of one electrofisher operator and one netter, and the field crew took care to sample all available and accessible habitat (Dunham et al. 2009). Portions of Rock Creek were too overgrown with willows or alders or were too deep to effectively sample using backpack electrofishing; therefore, field crews noted the portion of each sample site that was not sampleable. Captured fish were placed in a bucket filled with stream water that was equipped with a battery-operated aerator. After each electrofishing pass, fish were identified to species and redband trout were anesthetized in 26 mg·L⁻¹ AQUI-S® 20E (AQUI-S, Ltd.; Lower Hutt, New Zealand), measured for length (fork length; mm), scanned for the presence of a passive integrated transponder (PIT) tag, and, if no tag was detected, redband trout ≥ 65 mm were tagged with a half-duplex PIT tag; any tui chub (*Gila bicolor*) that were encountered were counted. After fish were processed, they were placed in an in-stream live-well (i.e., 19-L bucket with holes drilled in it) downstream from the sample site while subsequent depletion passes were conducted. After all depletion passes were conducted, and after physical habitat was quantified (see below), block nets were removed and fish were returned to the sample site.

Mark-Recapture Sampling—In addition to depletion sampling, a subset of sample sites were sampled following a mark-recapture sampling protocol (Hayes et al. 2007). Initially, every fifth sample site from the GRTS draw was designated as a mark-recapture site (i.e., 20% of the sample sites); however, because of the unpredictable nature of stream drying, we had to deviate from this list somewhat. Consequently, about 19% of the sample sites visited during this study were mark-recapture sites. Mark-recapture sites were sampled as above with the exceptions that a single electrofishing pass was made through the sample site (hereafter, marking pass), the fish were processed (as above), the fish were returned to the sample site, and the block nets were left in place overnight. After about 24-h (Peterson et al. 2004), we returned to the mark-recapture site and performed depletion sampling as above (i.e., a standard 4-pass

depletion survey). Therefore, the first pass of the depletion sampling functioned as the recapture pass for the mark-recapture sampling.

Physical Habitat Sampling—At each non-dry sample site, we measured the site length [i.e., the length of the sample site (m) from the downstream boundary to the upstream boundary]. The length of the sample site often deviated from 100 m because of discrepancies between the GIS data and actual stream morphology; therefore, in situ stream length measurements were used to calculate redband trout density metrics. We also measured the sampled site length (i.e., the site length minus the proportion of the sample site that was not sampleable due to vegetative obstructions or excessive depth) and the wetted site length (i.e., the length of the sample site minus any portion of the sample site that was dry at the time of sampling). Additionally, we measured wetted width (m) and stream depth (cm) at 25%, 50%, and 75% of the wetted width at equally spaced transects within the sample site. The first transect was located 5-m upstream from the downstream site boundary and additional transects proceed upstream at 10-m increments until the upstream site boundary was reached.

Mean width and mean depth were calculated for each sample site. Mean width was calculated as the average of wetted widths within each sample site. Mean depth was calculated by summing the three depths recorded for each transect and dividing by 4 to account for 0 depth at each bank (mean transect depth), and then averaging the mean transect depths among transects within each sample site. Mean width and mean depth of sample sites were calculated as a moving average of 20 sample sites (following the GRTS sample order for non-dry sample sites) to provide a qualitative assessment of water quantity in sequential sets of non-dry sample sites; see below for rationale related to selection of 20 sample sites.

Redband Trout Movement among Sample Sites

We predicted that individual redband trout may be encountered multiple times, in different locations, throughout a prolonged sample period if they are redistributing as a function of time or in response to stream drying. To evaluate this prediction, we examined capture histories of tagged fish. We noted the occurrence of recapturing individual fish in a sample site other than the one where the fish was initially tagged; we also noted the distance moved as the stream distance (km) between the initial tagging site and the recapture site (i.e., minimum movement distance).

Changes in Redband Trout Density and Abundance as a Function of Stream Drying

We predicted that site-level density estimates (based on stream length), and resulting population-level abundance estimates, will increase as a function of time during a period of stream drying if redband trout are redistributing and crowding into non-dry, refuge habitats. To evaluate this prediction, we examined spatio-temporal patterns of redband trout density and abundance.

Abundance can be estimated based on depletion sampling or mark-recapture sampling. Site-level redband trout abundance was estimated for the subset of mark-recapture sample sites using the Chapman estimator (Seber 1982):

$$N_{MR} = \frac{(M+1)(C+1)}{(R+1)} - 1,$$

where, N_{MR} is the mark-recapture abundance estimate, M is the number of fish captured and marked (i.e., tagged) on the marking pass, C is the total number of fish captured on the recapture pass, and R is the number of marked fish captured on the recapture pass; this analysis was based on redband trout ≥ 65 mm.

Depletion sampling has been shown to produce biased abundance estimates (Peterson et al. 2004). Therefore, we intended to adjust abundance estimates from depletion sampling based on the relationship between abundance estimates derived from depletion sampling and mark-recapture sampling (e.g., Meeuwig and Clements 2014). However, depletion histories (i.e., the number of fish caught on successive passes) from sampling conducted in this study generally failed to meet the assumptions of the models used to estimate abundance from depletion data (e.g., fewer fish must be captured on successive depletion passes). It is unknown if this is a result of low fish abundance, behavioral responses by fish, or some other factor. Regardless, abundance estimates based on depletion methodologies were deemed not valid.

Exploratory regression analyses (PROC REG; SAS version 9.4; SAS Institute; Carry, North Carolina) revealed that abundance estimates based on mark-recapture sampling were strongly related to the number of fish captured on the marking pass. These regression analyses revealed that two sample sites were outliers based on diagnostic analyses of residual values and that the intercept of the regression model did not differ from zero. Therefore, we fit a linear regression model where N_{MR} was the dependent variable, M was the independent variable, the two outlying variables were not included in the model, and the model was fit without an intercept (Figure 3). We observed a significant relationship between N_{MR} and M ($t = 16.53$, $P < 0.001$) and the resulting model ($N_{MR} = 1.8306 * M$) explained a large proportion of the variance in the N_{MR} ($R^2 = 0.96$, $F_{1,12} = 273.13$, $P < 0.001$). Because the number of fish captured and marked during the marking pass of mark-recapture sampling is analogous to the number of fish captured during the first pass of depletion sampling, we used the parameter estimate from the mark-recapture model to estimate abundance based on the first pass of depletion sampling:

$$N_{SL} = 1.8306 * P_1,$$

where, N_{SL} is the site-level abundance estimate and P_1 is the number of fish captured on the first pass during depletion sampling; this analysis was based on redband trout ≥ 65 mm. Site-level redband trout density (D_{SL} ; fish·m⁻¹) was estimated by dividing the site-level abundance estimate (N_{SL}) by the sampled site length.

Population-Level Redband Trout Abundance Estimates—We estimated population-level redband trout abundance based on site-level density estimates (D_{SL}) for sequential sets

of sample sites (based on the GRTS sample order). Meeuwig and Clements (2014) showed that sampling greater than 20 sample sites resulted in little increase in precision of abundance estimates for redband trout in the Great Basin. Therefore, each sequential set of sample sites included 20 non-dry sample sites. The total number of sample sites over which abundance estimates were made often exceeded 20 because dry sample sites were often encountered interspersed among non-dry sample sites when following the GRTS sample order. Therefore, sample weights were calculated prior to estimating population-level abundance. Additionally we estimated the proportion of the sampling frame that was dry for each sequential set of sample sites based on the GRTS sample order. This estimate of stream drying was based on observations made by field crews following the GRTS sample order. For each sequential set of sample sites, we estimated population-level abundance using R software (R Core Team 2013) and the `spsurvey` package (Version 3.0); variance was estimated using the nearest neighbor estimator (Stevens and Olsen 2003). This analysis also estimates population-level density estimates; therefore, we also present density estimates based on sequential sets of 20 non-dry sample sites. See Box 1 for an example of calculations when no sites visited were dry. See Box 2 for an example of calculations when some of the sites visited were dry.

One sample site had substantially higher redband trout density than all other sites (Figure 4). Additionally, no redband trout were observed in the lower 13.1 km of the sampling frame despite substantial sampling (Figure 5). For example, a total of 22 sample sites were sampled in the lower 13.1 km of the sampling frame, an average of 4 electrofishing passes were conducted at each of these sample sites, and no redband trout were detected. Therefore, we assumed that redband trout were either absent from the lower portion of the sampling frame or they were at very low densities. Consequently, we calculated abundance estimates for the upper drainage (i.e., the upper 16.9 km; 169 sample sites) and the whole drainage separately, both with and without the outlying observation.

Spatio-Temporal Patterns of Stream Drying From Multiple Observations

We estimated the proportion of the sampling frame that was dry at any given time based on observations made during electrofishing surveys (i.e., following the GRTS sample order) and observations made opportunistically or during general reconnaissance. In many instances we knew or assumed that a site was dry before it was visited following the GRTS sample order. For example, we often reconnoitered sample sites if they were near a site that we were sampling for fish abundance. If a sample site was dry during this reconnaissance, it was noted as dry and it was assumed to remain dry for the remainder of the field season. We believe that this is a valid assumption given that 2015 was a relatively low water year (Figure 6) and only a small percentage of the annual precipitation, which could inundate a previously dry sample site, fell during the time period of this study (Figure 7). Conversely, if a sample site was wet we assumed that it was also wet at all times during the study period prior to our observation.

We created a data frame that had one column for each day from 1 June through 17 September 2015 and that had one row for each sample site. We assumed that the

entire sampling frame was wet on 1 June 2015, and final reconnaissance was conducted on 17 September 2015. For each day and sample site for which we knew or assumed the site conditions, we coded the value as wet = 0 or dry = 1. For each column (i.e., day), we used linear interpolation between adjacent sites on a given day to estimate the probability that each un-observed site was dry (value from 0 to 1). Then, for each row (i.e., day) we used linear interpolation between adjacent days for a given site to estimate the probability that each site was dry for un-observed days (value from 0 to 1). This resulted in a complete data frame of columns for each day during the study period and rows for each sample site with values varying from 0 to 1 where a value of 0 represents a site that is known or assumed to be wet on a given day, where a value of 1 represents a site that is known or assumed to be dry on a given day, and where values > 0 or < 1 represent the estimated probability that an un-observed site on an un-observed day was dry.

Results

Fish and Habitat Sampling

We visited a total of 148 sample sites following the GRTS sample order. Fish and habitat sampling was conducted at 78 sample sites and 70 sample sites were dry based on the GRTS sample order. Depletion sampling was conducted at 78 sample sites and mark-recapture sampling was conducted at a subset of 15 of these sample sites. We sampled a total of 620 redband trout and uniquely tagged 481 redband trout. Redband trout varied in length from 34 – 201 mm (Figure 8). We sampled a total of 225 tui chub; all the tui chub sampled were in the lower 19.7 km of the sampling frame, and 80% of the tui chub sampled were in the lower 3.0 km of the sampling frame.

Water availability (i.e., mean width and depth of sample sites) decreased steadily from the onset of the study until late July, at which point water availability remained relatively constant for the remainder of the study period (Figure 9). Based on following the GRTS sample order, the estimated proportion of the sampling frame that was dry was 0% until early July, at which point the proportion of the sampling frame that was dry increased steadily until the end of the sample season when about 70% of the sampling frame was estimated to be dry (Figure 10).

Redband Trout Movement Among Sample Sites

We observed movement among sample sites for 6 of the 481 uniquely tagged redband trout; most of which moved relatively short distances. Four redband trout were recaptured about 0.1 km from their original capture location, one redband trout was recaptured about 0.2 km from its original capture location, and one redband trout was recaptured about 1.8 km from its original capture location.

Changes in Redband Trout Density and Abundance as a Function of Stream Drying

Redband trout density varied from 0.00 – 0.50 fish·m⁻¹ among sample sites, with the exception of one sample site that had a density of 2.93 fish·m⁻¹ (Figure 4). In general, redband trout density did not change as a function of time. Specifically, there was no

increasing or decreasing trend in density as a function of the order in which sites were sampled (Figure 11). There appeared to be a larger number of sample sites with densities of $0.00 \text{ fish}\cdot\text{m}^{-1}$ during early portions of the sample period (i.e., sites at the beginning of the GRTS sample order) (Figure 11; upper panel). However, this was likely a function of sampling sites in the lower portions of the drainage where no fish were observed during this study (Figure 5) despite substantial effort (see Methods). This pattern is not apparent if these lower-drainage sample sites are omitted (Figure 11; lower panel). Although there was little or no pattern in site-level redband trout density as a function of time (i.e., GRTS sample order), redband trout density appeared to be greatest in the middle portion of their distribution in the Rock Creek drainage (Figure 12).

Redband trout abundance estimates were influenced by the sampling frame selection and substantially influenced by the presence of an outlying observation (Figure 13). Early season abundance estimates varied between estimates based on the entire sampling frame versus abundance estimates based on only the upper drainage sites. However, as the sampling season progressed, estimates based on the entire sampling frame became more similar to those based on the upper drainage sites only. This change as the sampling season progressed is a result of early season inclusion of lower drainage sites where we never observed fish and late season omission of lower drainage sites as they became dry and were not sampled. The inclusion of the one outlying observation had a substantial effect on the magnitude and precision of our abundance estimate.

We assumed that abundance estimates from the upper drainage sites without the outlying observation were the most representative estimates because 1) we did not observe any redband trout in the lower drainage sites (Figure 5) despite substantial effort (see Methods) and 2) the outlying observation was extreme and limited to a single observation among 78 sample sites. As such, redband trout abundance varied from a high of about 1,487 to a low of about 665 individuals. We did not observe an increasing pattern of abundance as a function of time, but observed a slight decrease in abundance as a function of time (Figure 13; top-left panel). Additionally, redband trout density estimates based on sequential sets of 20, non-dry sample sites remained relatively constant over the sampling period (Figure 14).

Spatio-Temporal Patterns of Stream Drying From Multiple Observations

Rock Creek began drying by mid-June, beginning at the lower boundary of the study area and some of the headwaters. Additionally, by 15 June, the lowermost portion of Willow Creek was dry, effectively fragmenting Willow Creek from the mainstem of Rock Creek (Figure 15). By 15 July, about one third of the lower sampling frame was dry (Figure 16). By 15 August, about two thirds of the lower-most sampling frame was dry with the exception of portions of Willow Creek (Figure 17). By 15 September, portions of the upper drainage had become fragmented (Figure 18).

Discussion

Spatio-temporal variability in redband trout distribution and density likely do not bias population-level abundance estimates under conditions similar to those in this study. Over the course of the study, we observed little evidence for movement among sample sites by redband trout and we observed relatively constant average redband trout densities. Furthermore, we observed a gradual decrease in population-level abundance over the duration of the study. Together, these observations suggest that redband trout are not moving to refuge habitats as Rock Creek dries, but instead are likely becoming trapped in fragmented habitats as drying occurs.

Despite the presence of water in the early portion of the sampling period, and substantial sampling effort, we did not detect any redband trout in the lower 13.1 km of the sampling frame; however, we did detect tui chub in this area. This portion of the sampling frame was dry by the end of the sampling period in 2015, and is also the portion of the sampling frame where dry sites have been encountered during surveys conducted from 2007 – 2012 (Figure 19). However, during previous surveys redband trout were detected in this area (Figure 20). The lower portion of the sampling frame (as defined here and in Meeuwig and Clements 2014) appears to dry frequently during low water years, and redband trout recolonization dynamics may be influenced by the frequency of low water years. Specifically, previous sampling did incorporate low water years (i.e., 2007 – 2012; Figure 6), and redband trout were detected in the lower portion of the sampling frame; however, the present study occurred during the fourth year of consecutive low water years, during which time the lower portion of the sampling frame likely dried up annually. Therefore, seasonal availability of water may not be sufficient to promote use of the lower sampling frame by redband trout, whereas some frequency of high-water years may be.

In the present study we estimated that redband trout abundance varied from a high of about 1,487 during the early part of the sample season to a low of about 665 individuals at the end of the sampling season. Therefore, abundance of redband trout in 2015 differed dramatically from previous estimates: 23,638 redband trout in 2007, 14,725 redband trout in 2009, 19,632 redband trout in 2010, 25,391 redband trout in 2011, and 16,676 redband trout in 2012 (Meeuwig and Clements 2014). Although methodologies differed slightly between sampling conducted previously and sampling conducted in 2015, the sampling frame and redband trout capture probabilities were relatively similar between studies (data not shown). Therefore, it is unlikely that minor differences in sampling methodology account for the magnitude of the difference in abundance estimated between the present study and the former study. Consequently, consecutive years of low water may negatively influence population-level abundance of redband trout, in addition to influencing distribution.

The observed patterns of redband trout distribution and abundance in relation to past studies (Meeuwig and Clements 2014) and current environmental conditions (i.e., consecutive low water years) have direct implications for the management of redband trout in this and other systems if future climate scenarios predict more prolonged periods of drought. Redband trout densities were generally greatest in areas of Rock

Creek that still had instream flow at the end of the sampling period. Therefore, identifying and appropriately managing drought resistant refuge habitats may be warranted. Additionally, this conclusion is applicable to other areas in the Great Basin where stream drying occurs frequently. For example, large portions of habitat available to redband trout may dry during low water years for the populations identified as Willow (Chewaucan species management unit), Dry (Goose Lake species management unit), and Eastside (Goose Lake species management unit) Willow Creek in the Chewaucan redband trout management unit (Meeuwig and Clements 2014).

Although we directly detected very little movement of individual redband trout in the present study, and patterns of density and abundance suggest that redband trout are not moving in response to stream drying, alternative methodologies could be used in the future to further address question related to behavioral responses by redband trout to stream drying. Redband trout density and abundance has been shown to be high in the past (Meeuwig and Clements 2014), but also appears to be highly variable based on the present study. Therefore, Rock Creek is an ideal system to evaluate the response of desert dwelling trout to drought and climate change scenarios. Rock Creek is also relatively shallow and narrow; therefore, establishing an array of PIT tag antennas to monitor movement patterns of redband trout may be relatively straightforward. Additionally, the pattern of stream drying observed in Rock Creek highlights the need to understand drying patterns in desert streams in order to identify perennial, drought resistant, refuge habitats. Therefore, further studies that evaluate factors influencing stream drying in desert systems are warranted.

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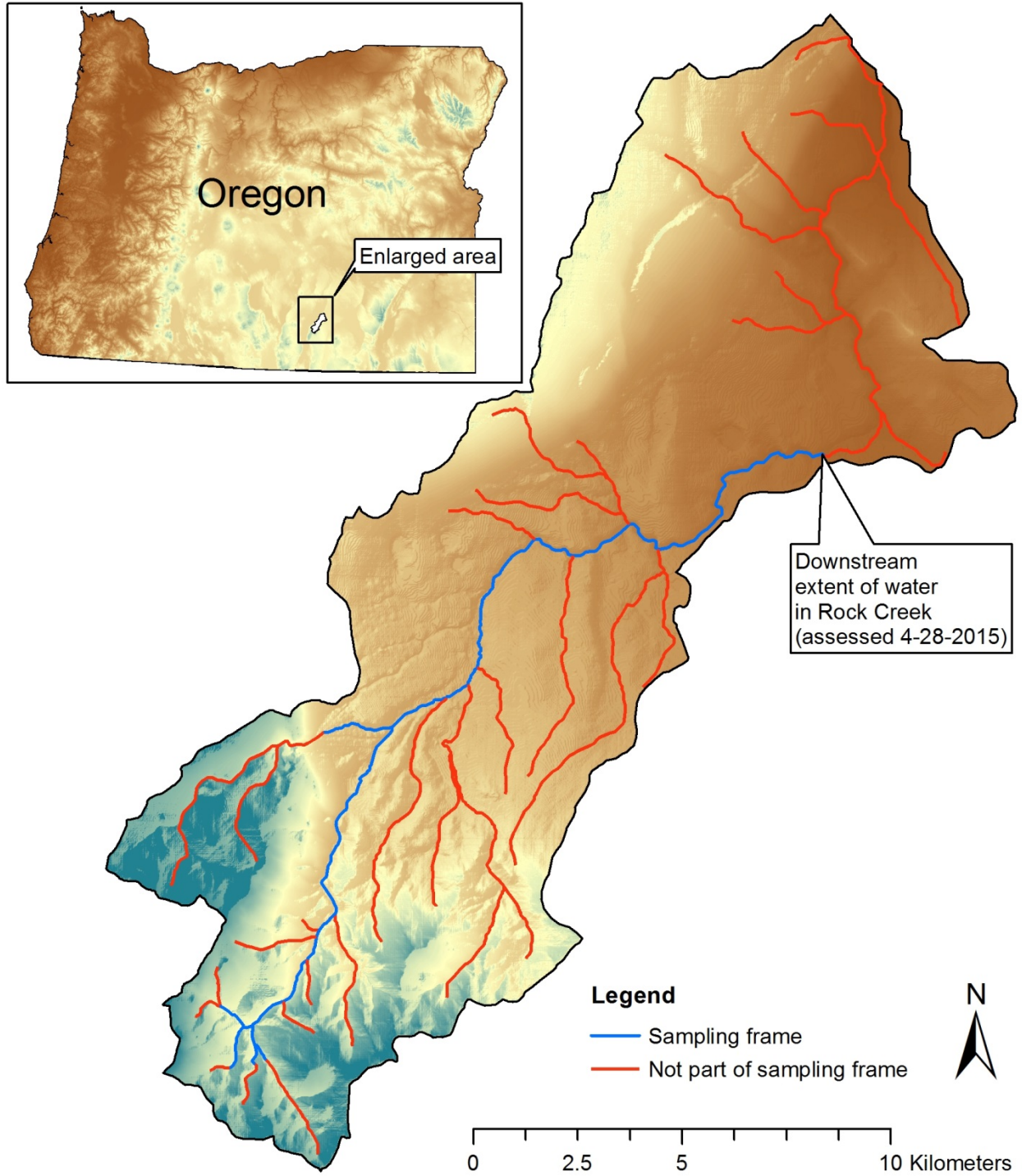


Figure 1. Location of the study system and the sampling frame in the Rock Creek drainage, Oregon.

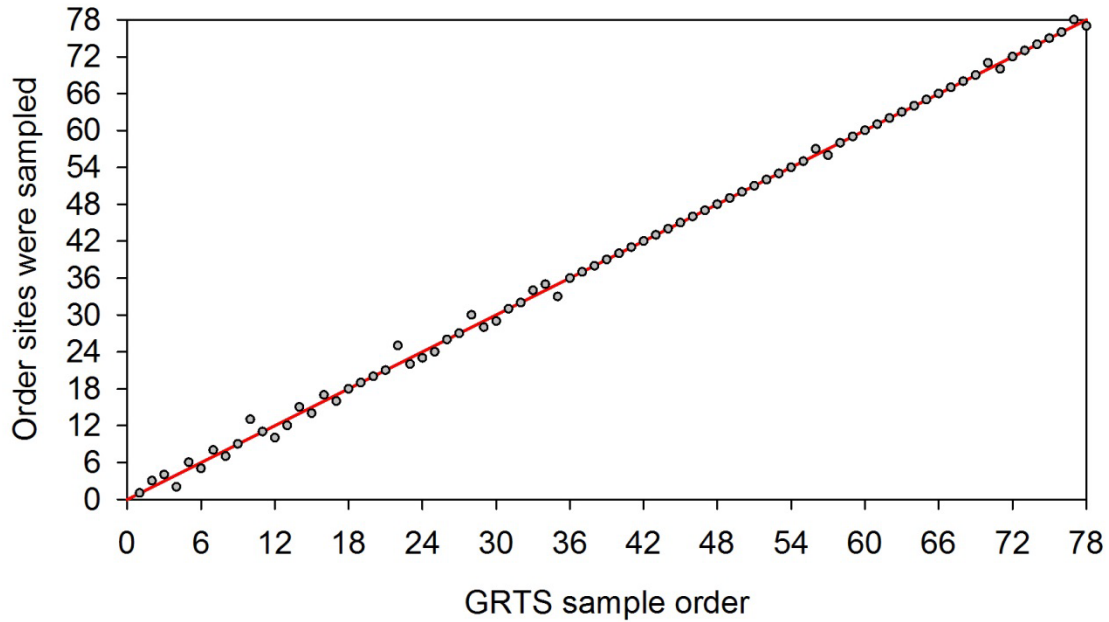


Figure 2. Order sites were sampled related to the pre-defined sample order based on a generalized random-tessellation stratified sample design (GRTS sample order). In general, sites were sampled following the GRTS sample order (i.e., fall on the 1:1 line).

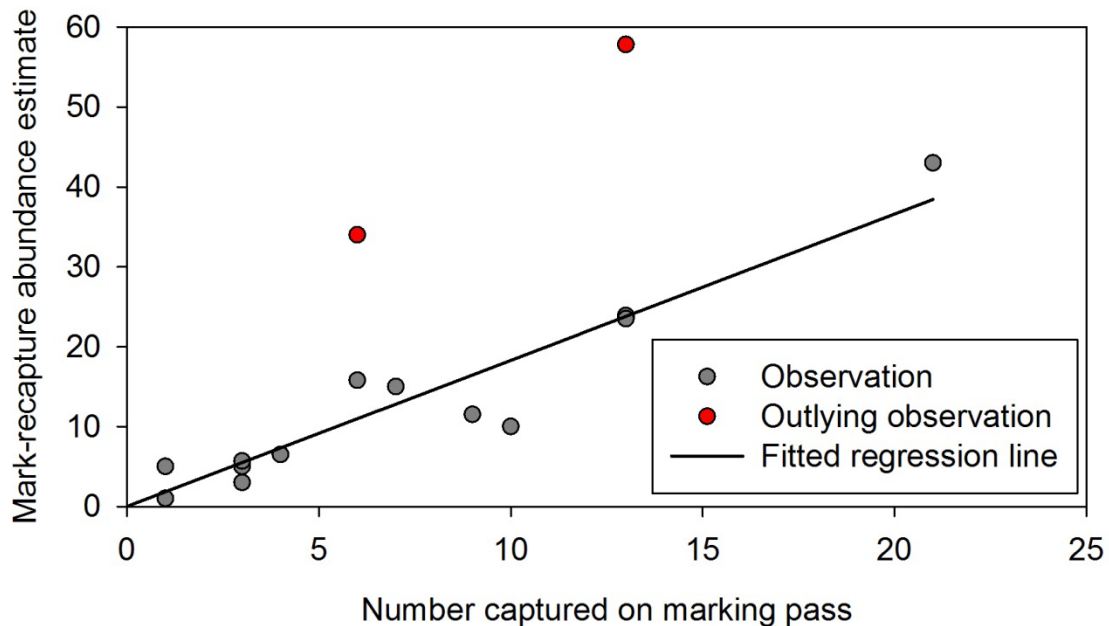


Figure 3. Redband trout abundance estimated from mark-recapture sampling as a function of the number of fish captured on the marking pass. The number of fish captured on the marking pass explained a large proportion of the variation in the mark-recapture abundance estimate ($R^2 = 0.96$, $F_{1,12} = 273.13$, $P < 0.001$). The regression model ($y = 1.8306 \cdot x$) was fit without an intercept and with the outlying observations omitted.

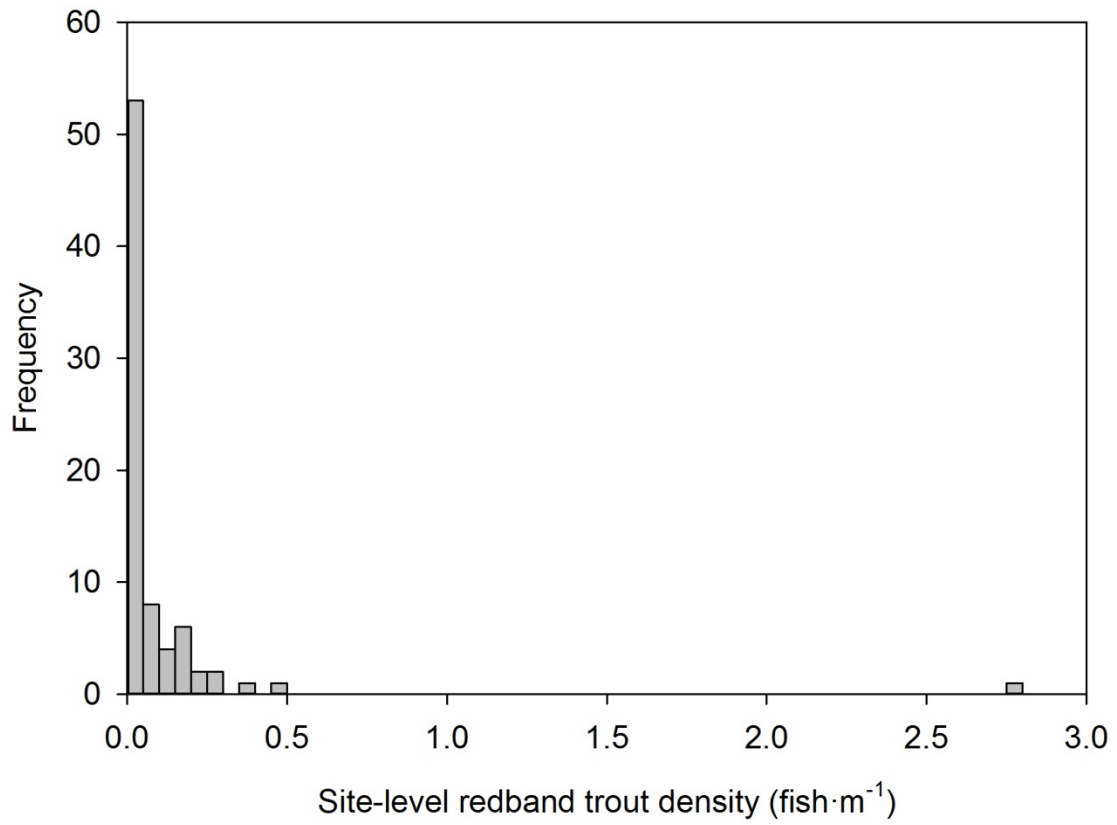


Figure 4. Histogram of the frequency of different site-level redband trout densities.

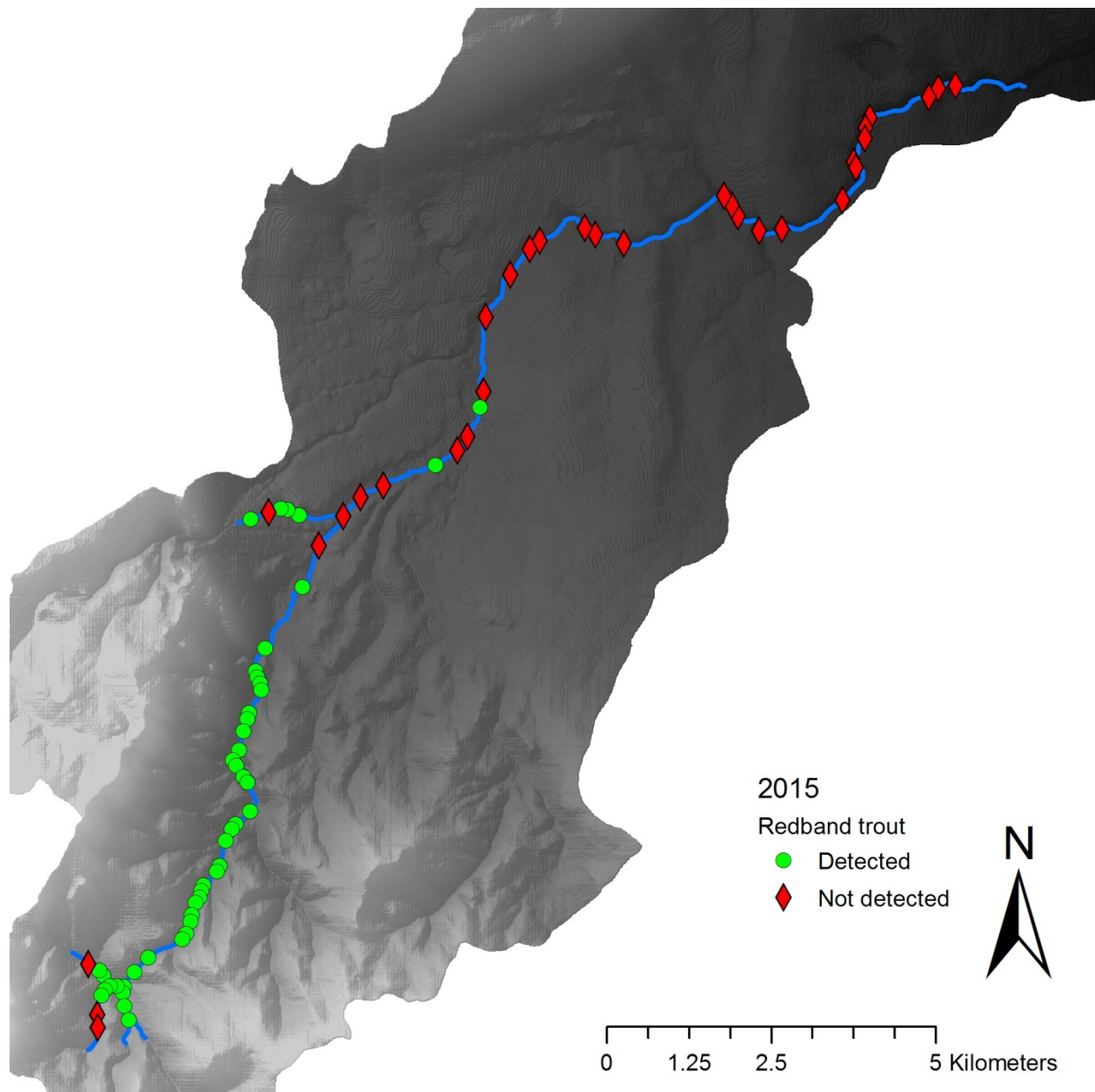


Figure 5. Spatial distribution of sample sites where redband were detected and not detected during sampling in 2015.

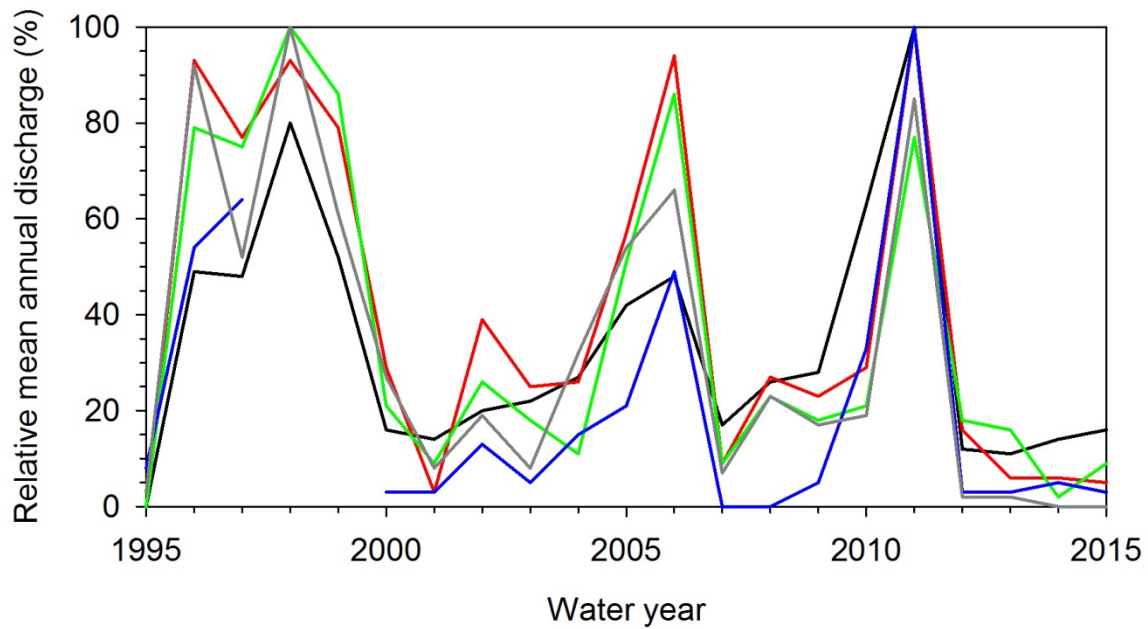


Figure 6. Relative mean annual discharge for Donner und Blitzen River (black), Deep Creek (red), Honey Creek (green), Trout Creek (blue), and Twentymile Creek (gray), Oregon, for the past 20 water-years. These streams represent streams near Rock Creek that have publicly available stream discharge data. Discharge data were downloaded from Oregon Water Resources Department (http://apps.wrd.state.or.us/apps/sw/hydro_near_real_time/; accessed 31 December 2015) for the last 20 water-years. For each stream, relative mean annual discharge was calculated by estimating the mean annual discharge for each year, dividing the mean annual discharges by the maximum mean annual discharge among years, and multiplying that number by 100.

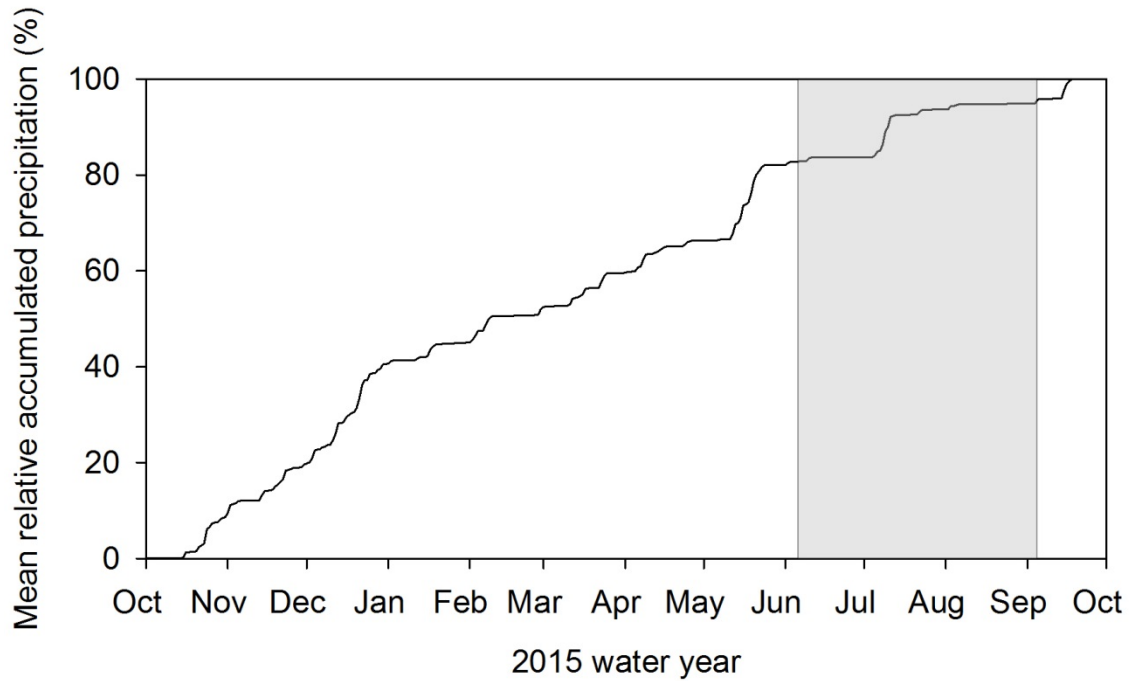


Figure 7. Mean relative accumulated precipitation for the 2015 water year. Precipitation data were obtained for the Donner und Blitzen River, Deep Creek, Honey Creek, Trout Creek, and Twentymile Creek, Oregon, for the 2015 water year (Oregon Water Resources Department (http://apps.wrd.state.or.us/apps/sw/hydro_near_real_time/; accessed 31 December 2015)). These streams represent streams near Rock Creek that have publicly available stream discharge data. For each stream, precipitation accumulation was calculated as a function of total annual accumulation, and then values were averaged by day among streams. Among streams about 12% of the annual precipitation fell during the sampling period.

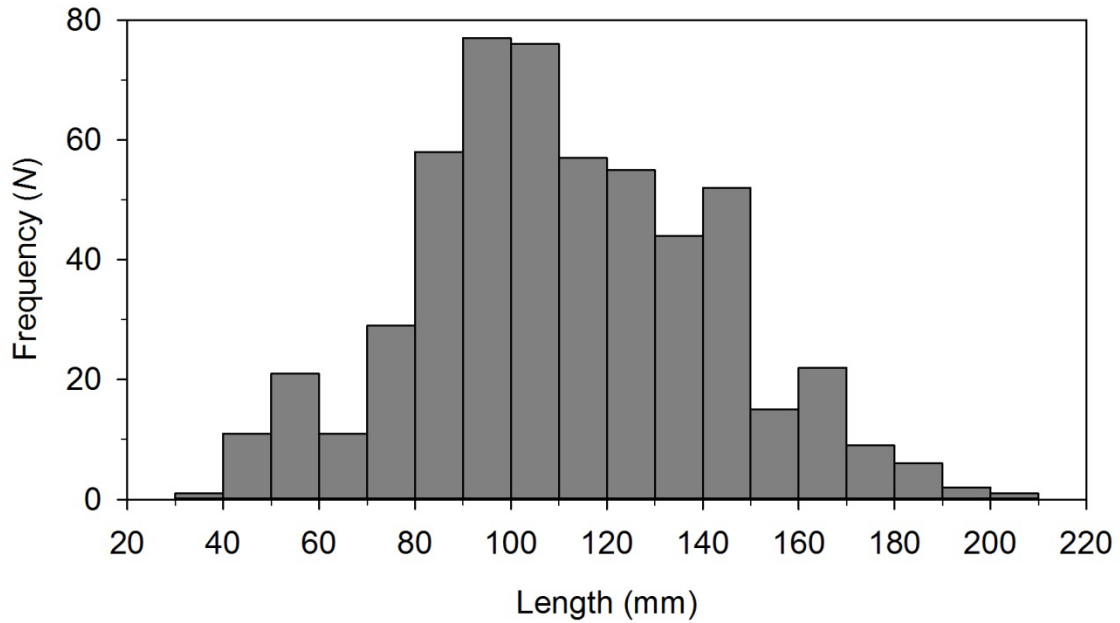


Figure 8. Length frequency histogram for redband trout sampled in Rock Creek.

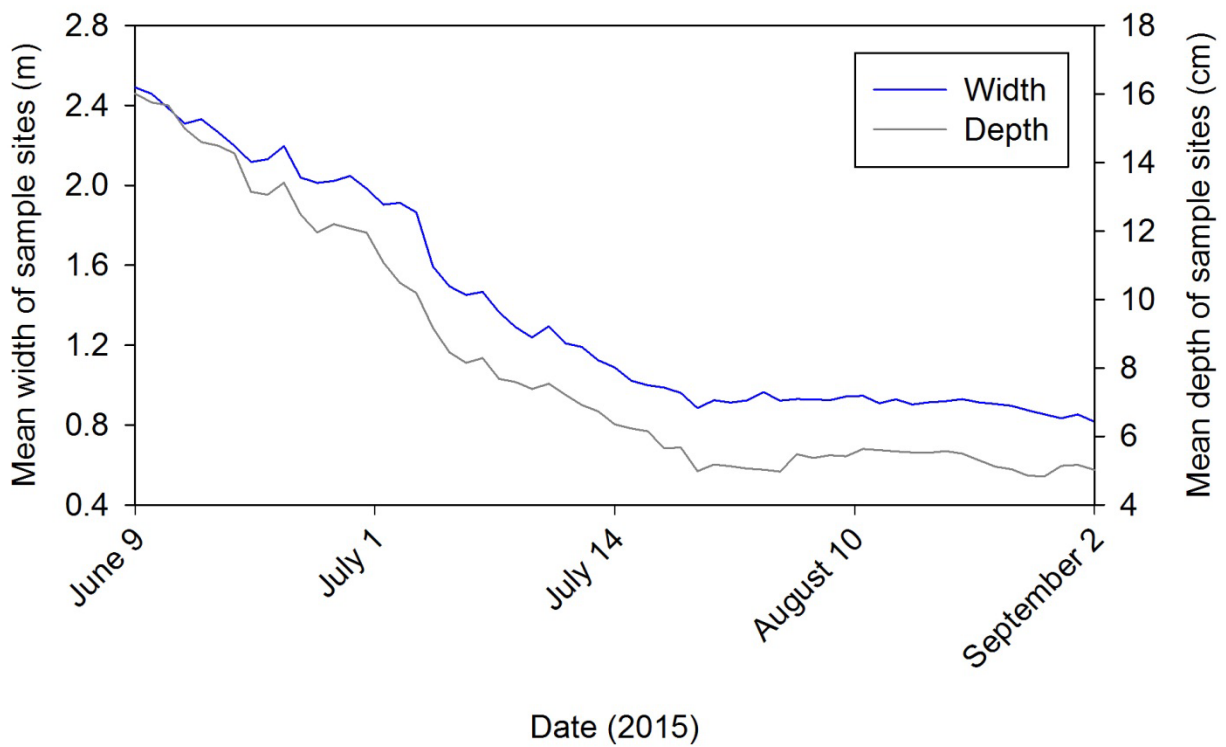


Figure 9. Mean width and depth of sample sites in Rock Creek. A moving average of 20 sample sites was used to calculate mean widths and depths throughout the sampling period.

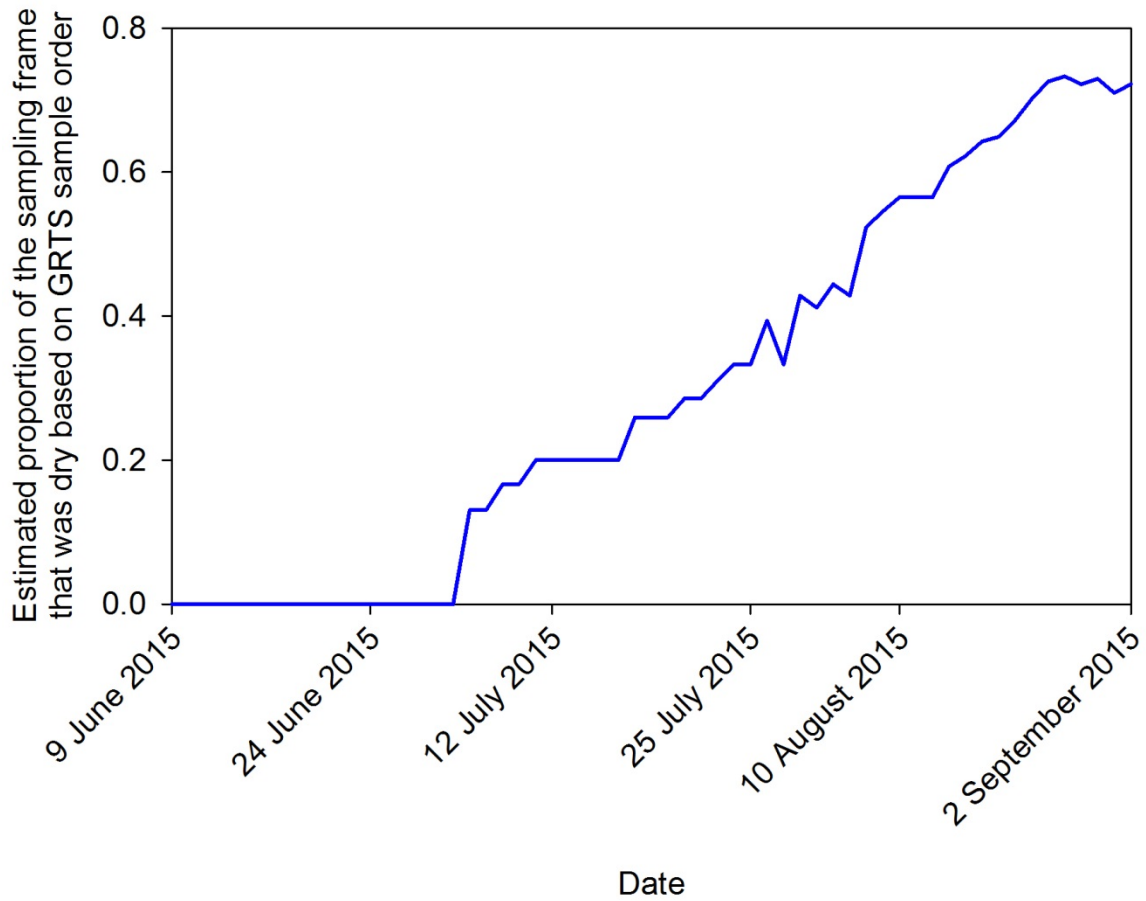


Figure 10. Estimated proportion of the sampling frame that was dry during the sample period. The proportion of the sampling frame that was dry was estimated based on sequential sets of 20 non-dry sample sites visited following a generalized random-tessellation stratified (GRTS) sample design.

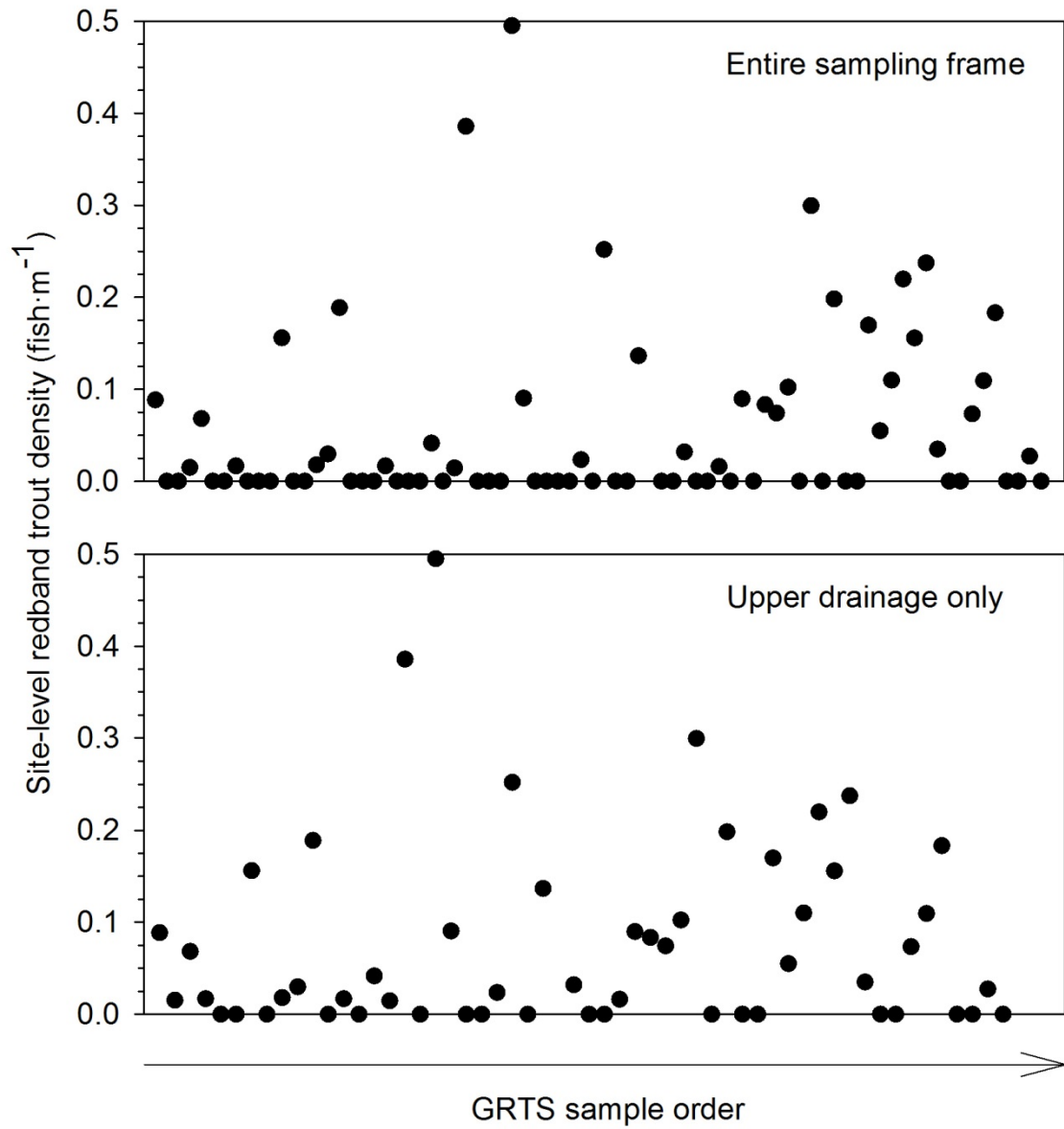


Figure 11. Site-level redband trout density as a function of time based on following the order of a generalized random-tessellation stratified (GRTS) sample design. The top panel includes all sample sites visited (i.e., the entire sample frame). No redband trout were observed in the lower 13.1 km of the sampling frame despite substantial sampling effort. Therefore, the bottom panel includes only sample sites visited in the upper 16.9 km of the sampling frame (i.e., upper drainage only).

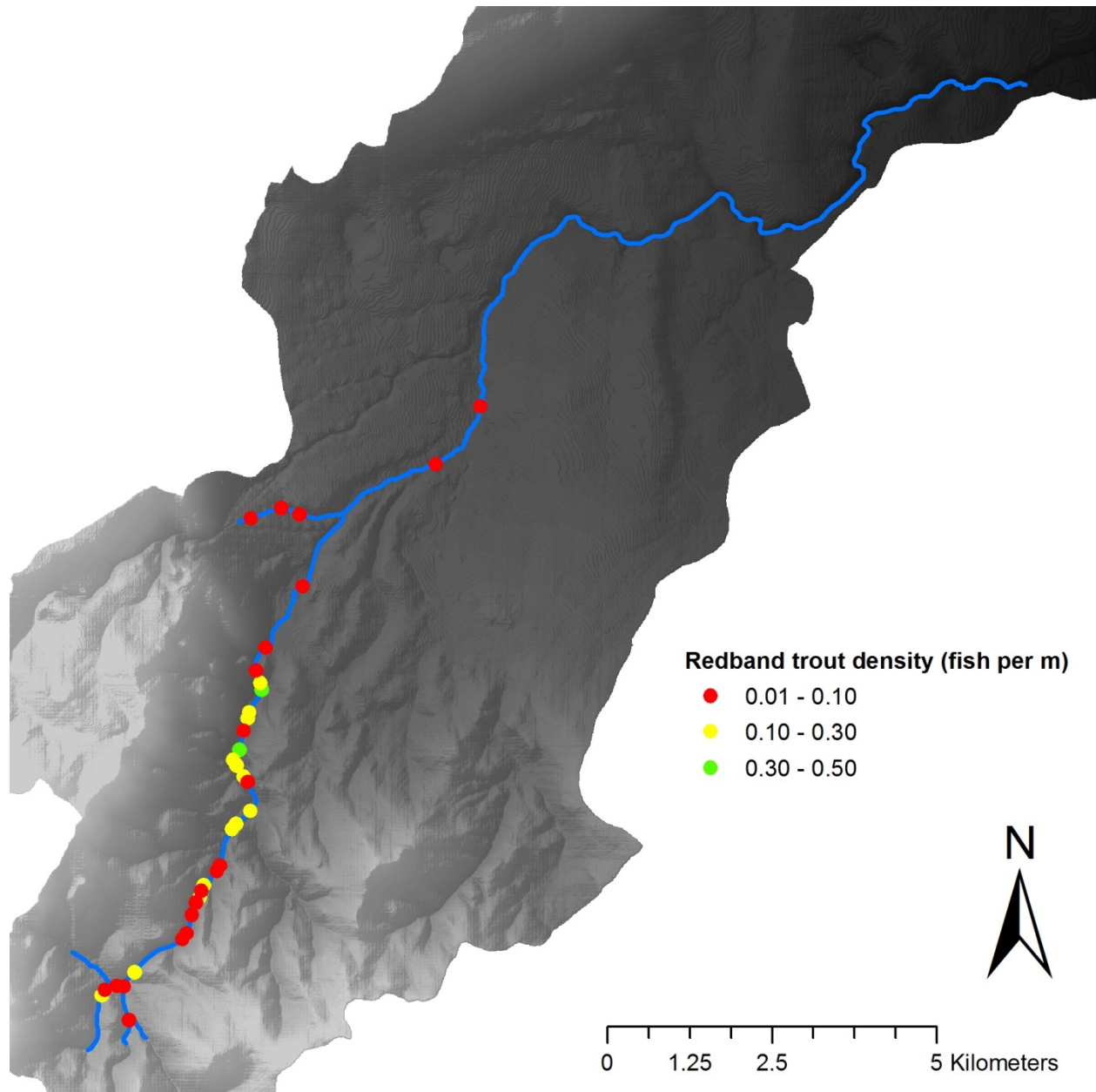


Figure 12. Spatial distribution of redband trout sampled during 2015, and site-specific redband trout densities. Sites where redband trout were not detected are not shown.

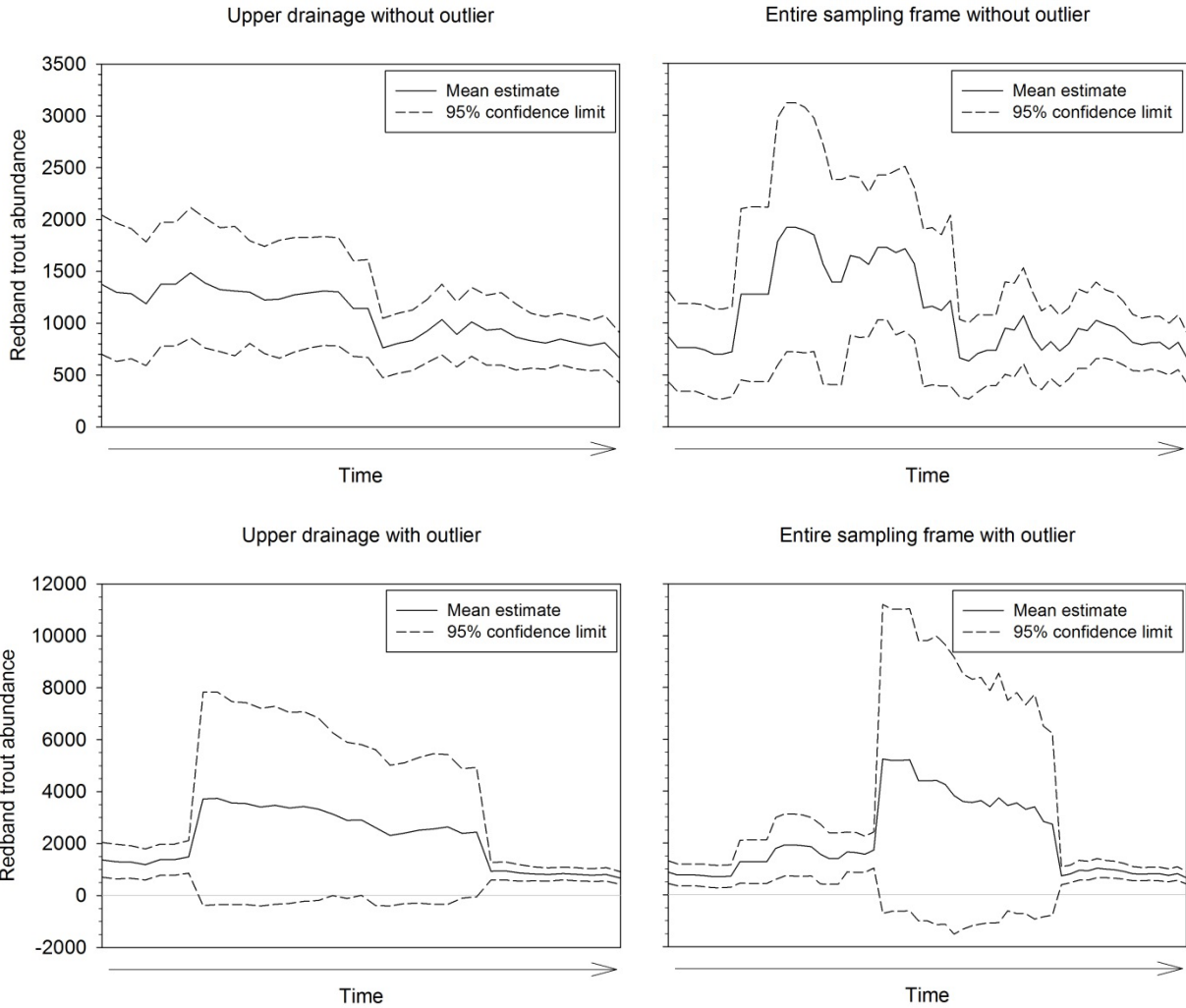


Figure 13: Population-level redband trout abundance estimates as a function of time for redband trout sampled in Rock Creek. Sequential sets of 20 non-dry sample sites were used to calculate redband trout abundance at various times throughout the sample period. Redband trout density at one sample site was considered to be an outlying observation and no redband trout were detected in the lower drainage despite substantial sampling effort. Therefore, abundance was estimated the upper drainage (left panels) and the entire sampling frame separately (right panels), and without the outlying observation (top panels) and with the outlying observation (bottom panels).

Upper drainage without outlier

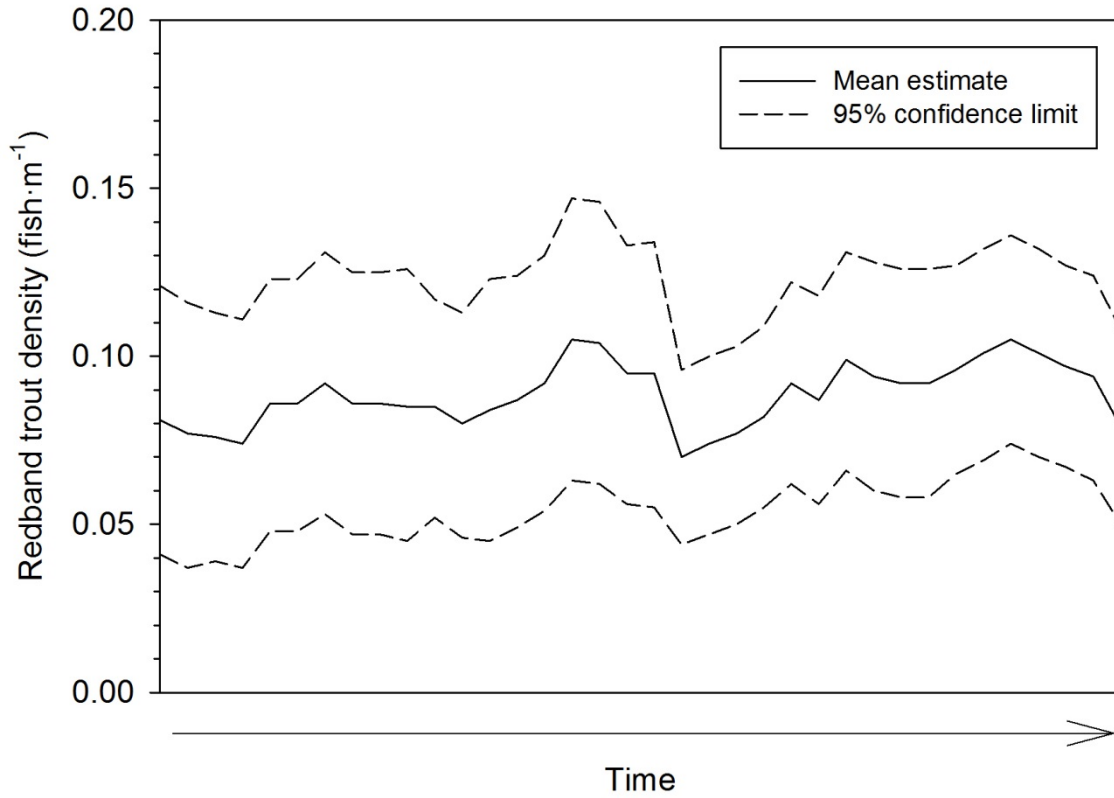


Figure 14. Population-level redband trout density estimates as a function of time for redband trout sampled in Rock Creek. Sequential sets of 20 non-dry sample sites were used to calculate redband trout density at various times throughout the sample period. Redband trout density at one sample site was considered to be an outlying observation and no redband trout were detected in the lower drainage despite substantial sampling effort. This figure only includes observations from the upper drainage and does not include the outlying observation.

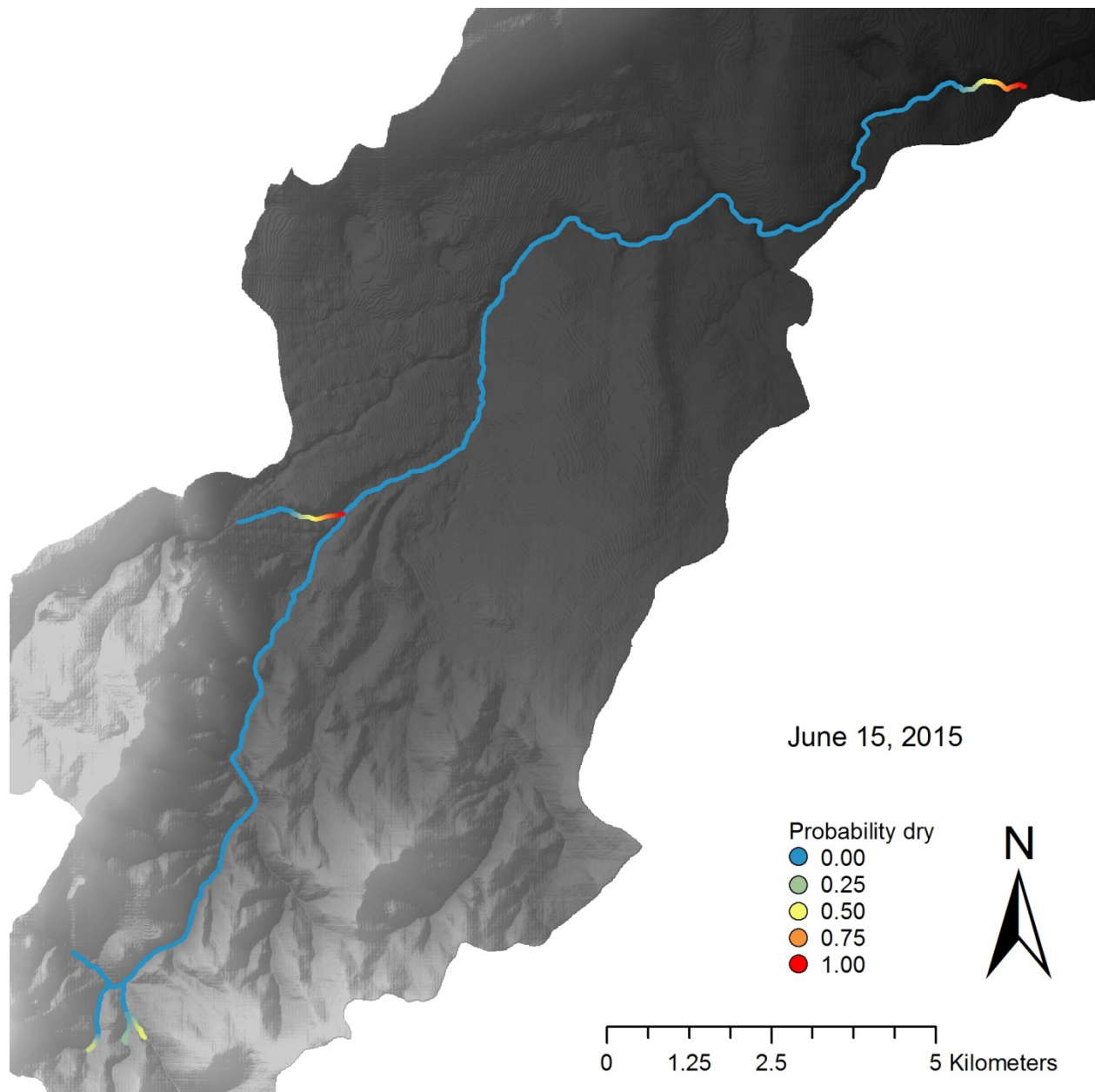


Figure 15. Estimated probability of stream drying in Rock Creek on 15 June, 2015 based on sample site visits following the order of a generalized random-tessellation stratified sample design and on general site reconnaissance. Probability values were calculated based on linear interpolation between sample sites that were known or reasonably assumed to be dry or non-dry. A value of 0 represents a non-dry site and a value of 1 represents a dry site.

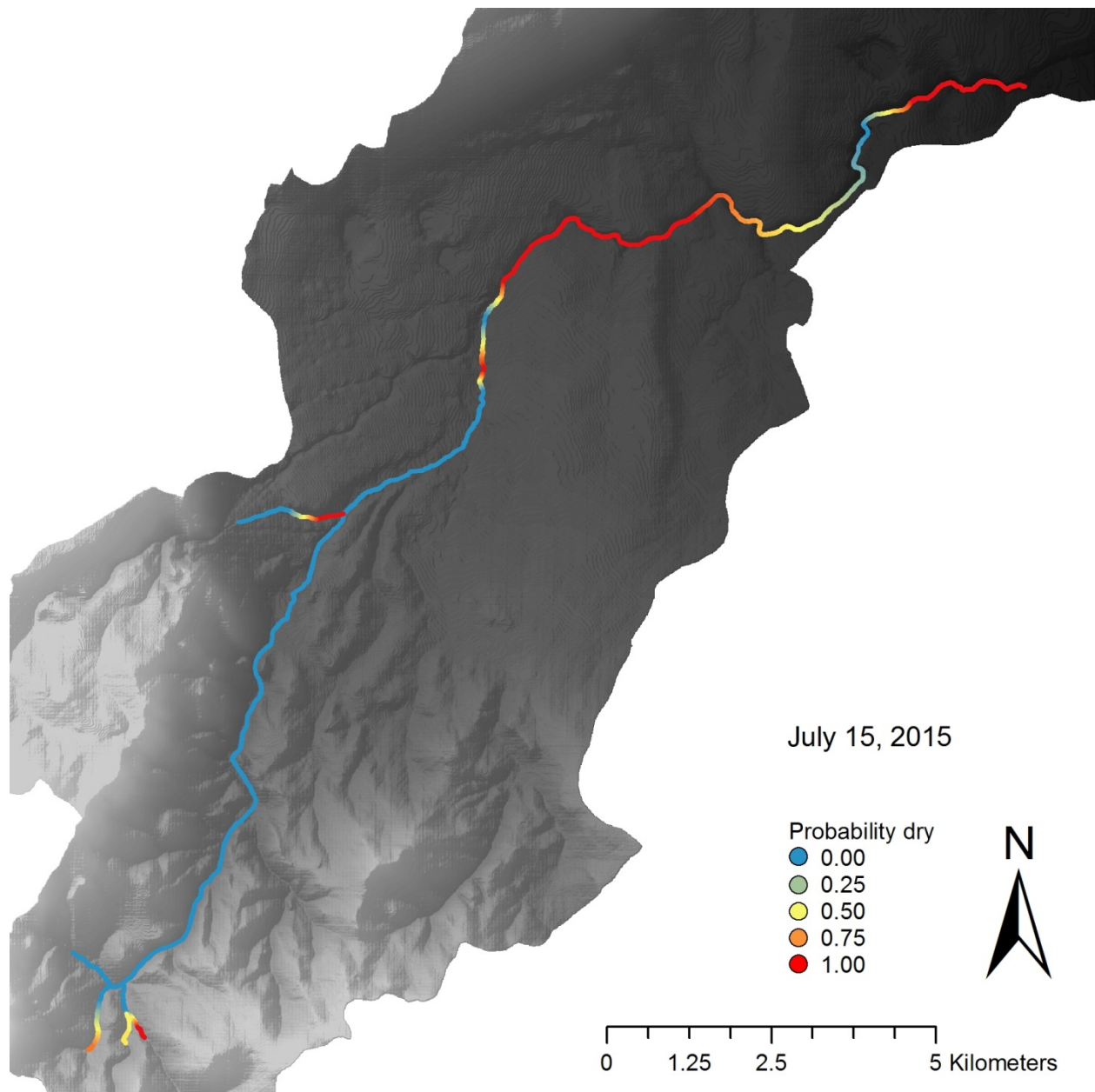


Figure 16. Estimated probability of stream drying in Rock Creek on 15 July, 2015 based on sample site visits following the order of a generalized random-tessellation stratified sample design and on general site reconnaissance. Probability values were calculated based on linear interpolation between sample sites that were known or reasonably assumed to be dry or non-dry. A value of 0 represents a non-dry site and a value of 1 represents a dry site.

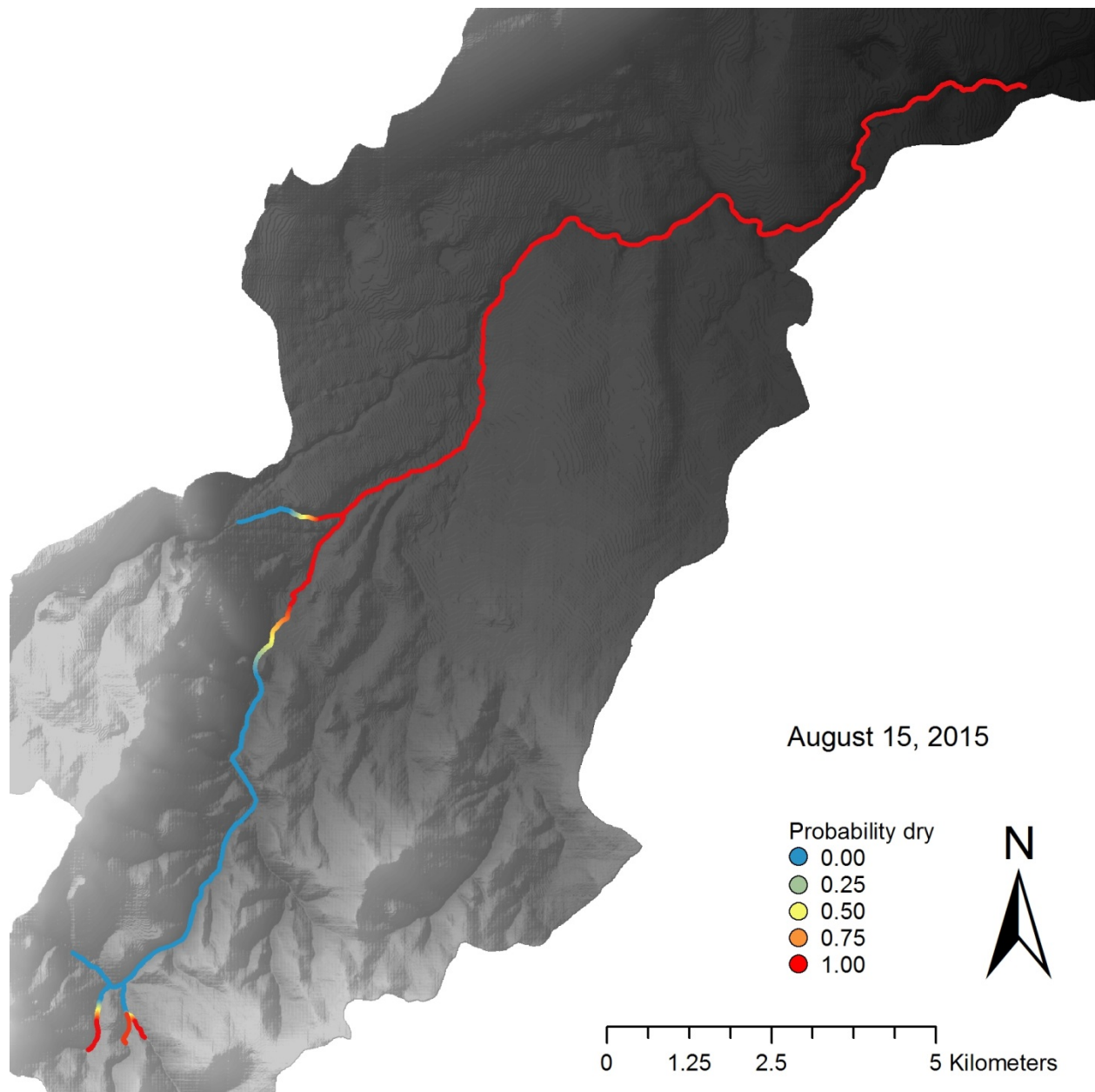


Figure 17. Estimated probability of stream drying in Rock Creek on 15 August, 2015 based on sample site visits following the order of a generalized random-tessellation stratified sample design and on general site reconnaissance. Probability values were calculated based on linear interpolation between sample sites that were known or reasonably assumed to be dry or non-dry. A value of 0 represents a non-dry site and a value of 1 represents a dry site.

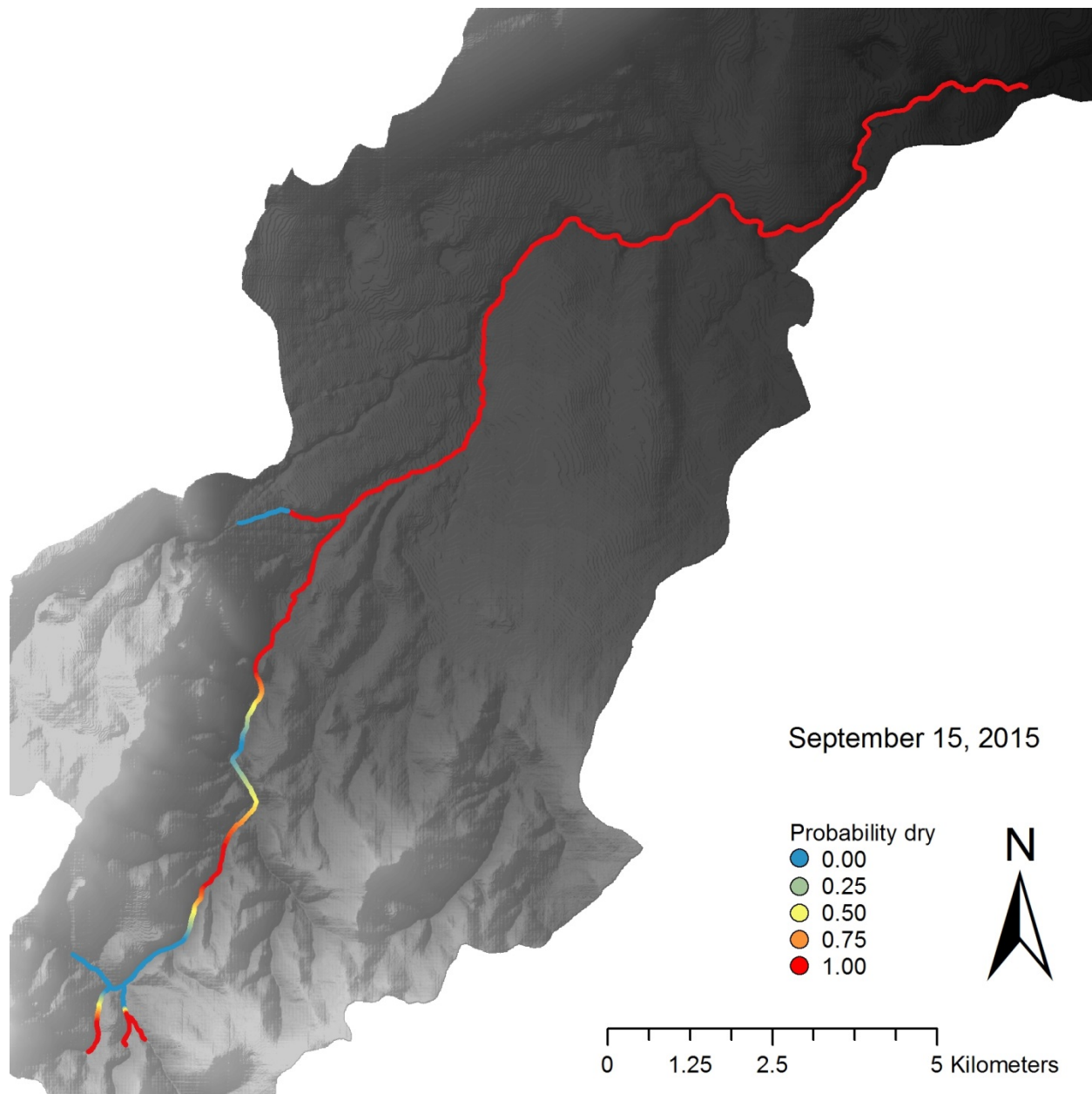


Figure 18. Estimated probability of stream drying in Rock Creek on 15 September, 2015 based on sample site visits following the order of a generalized random-tessellation stratified sample design and on general site reconnaissance. Probability values were calculated based on linear interpolation between sample sites that were known or reasonably assumed to be dry or non-dry. A value of 0 represents a non-dry site and a value of 1 represents a dry site.

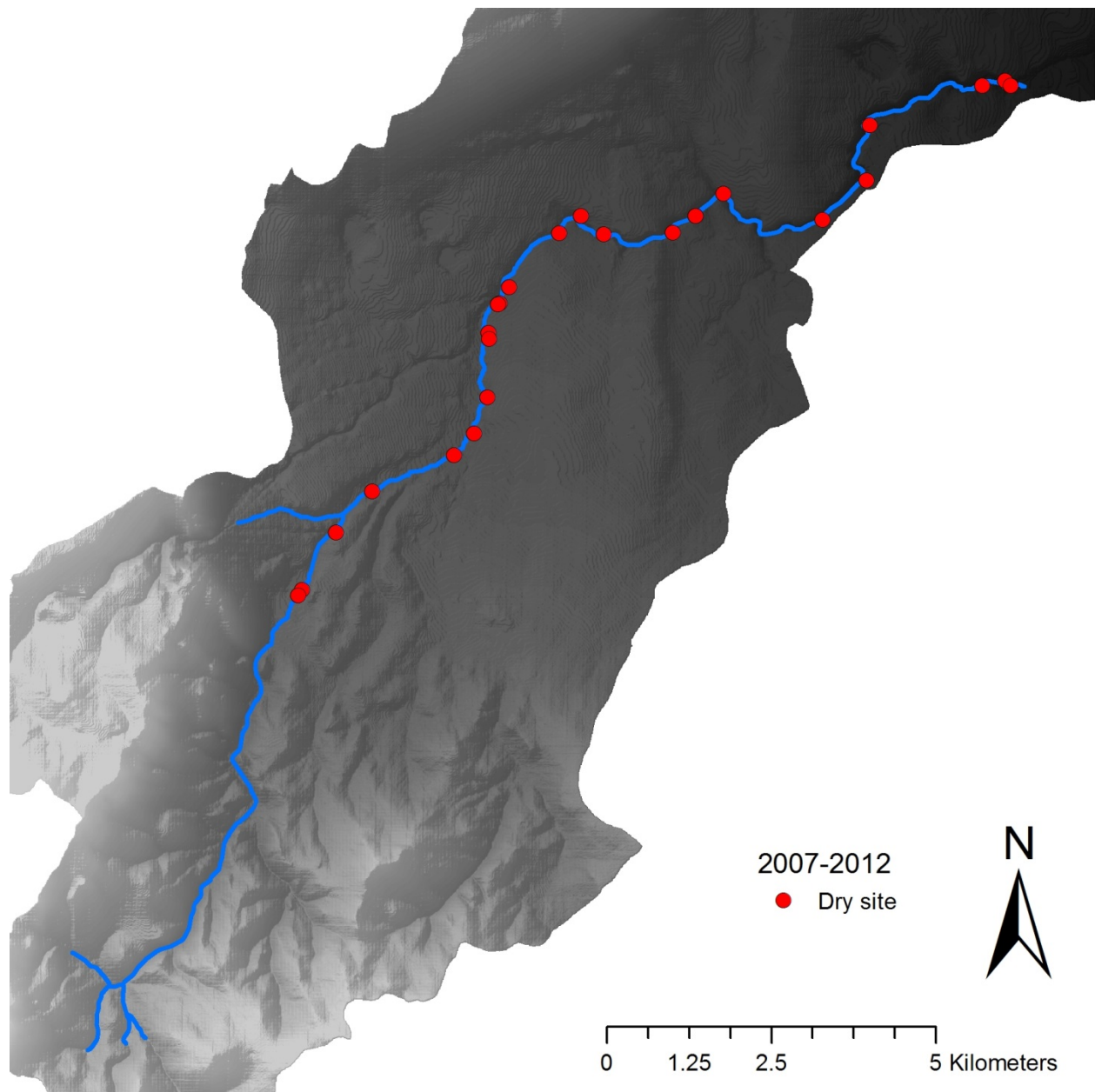


Figure 19. Spatial distribution of sample sites that were dry sites during redband trout surveys conducted in Rock Creek during the period 2007 – 2012 (Meeuwig and Clements 2014).

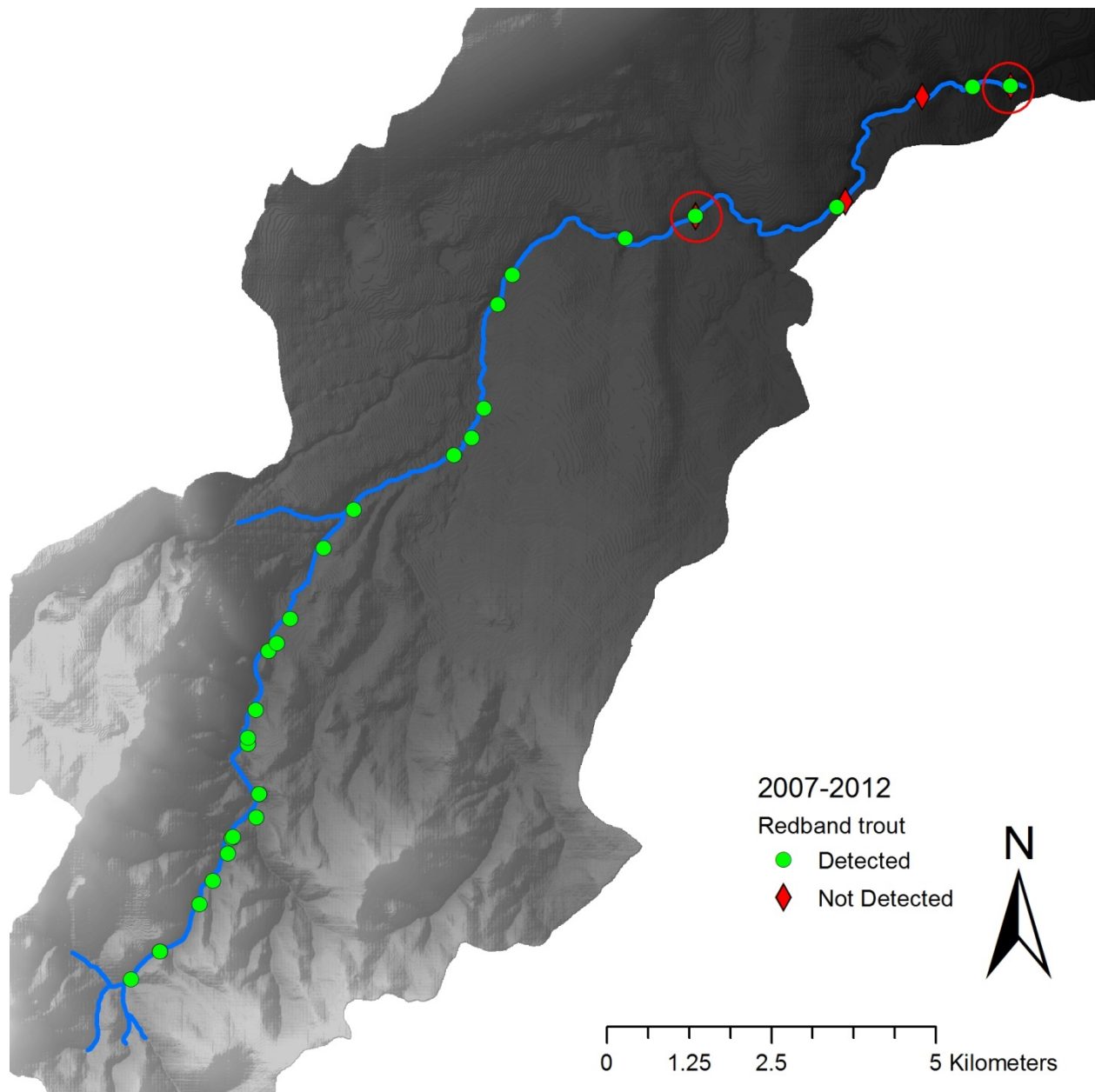


Figure 20. Spatial distribution of sample sites where redband trout were detected and not detected during redband trout surveys conducted in Rock Creek during the period 2007 – 2012 (Meeuwig and Clements 2014). Circled sites are sites where redband trout were detected in some years, but not in others.

Box 1—This example shows the method for calculating population level abundance for a sequence of 20, non-dry sample sites. The table shows the GRTS sample order, the unique site code for the individual sample sites, the site status (i.e., dry or non-dry), the calculated site-level redband trout density (D_{SL}), the sample weight, and the proportional abundance. Because all of these sites were non-dry, only 20 total sites were needed to calculate population-level abundance in this example.

The sample weight was calculated as the sample frame length in m divided by the total number of sites visited. This example is for the upper drainage sites only (i.e., the upstream-most 169 sample sites), so the sample weight is 845:

$$\text{Sample weight} = \frac{(169 \text{ sample sites}) * (100 \text{ m per sample site})}{20 \text{ sample sites visited}} = 845$$

The proportional abundance is calculated as the site-level abundance (D_{SL}) times the sample weight, and the population-level abundance is the sum of proportional abundances.

GRTS sample order	Site code	Site Status	D_{SL} (fish·m ⁻¹)	Sample weight	Proportional abundance
2	Rock-174	Non-dry	0.0151	845	13
3	Rock-237	Non-dry	0.0680	845	57
4	Rock-265	Non-dry	0.0167	845	14
5	Rock-290	Non-dry	0.0000	845	0
6	Rock-137	Non-dry	0.0000	845	0
7	Rock-214	Non-dry	0.1559	845	132
8	Rock-282	Non-dry	0.0000	845	0
9	Rock-132	Non-dry	0.0178	845	15
10	Rock-190	Non-dry	0.0296	845	25
11	Rock-230	Non-dry	0.1887	845	159
12	Rock-157	Non-dry	0.0000	845	0
13	Rock-297	Non-dry	0.0168	845	14
14	Rock-161	Non-dry	0.0000	845	0
15	Rock-276	Non-dry	0.0414	845	35
16	Rock-144	Non-dry	0.0145	845	12
17	Rock-203	Non-dry	0.3858	845	326
18	Rock-270	Non-dry	0.0000	845	0
19	Rock-193	Non-dry	0.4952	845	418
20	Rock-229	Non-dry	0.0903	845	76
21	Rock-153	Non-dry	0.0000	845	0
					$A_{PL} = 1,298$

Box 2—This example shows the method for calculating population level abundance for a sequence of 20, non-dry sample sites. The table shows the GRTS sample order, the unique site code for the individual sample sites, the site status (i.e., dry or non-dry), the calculated site-level redband trout density (D_{SL}), the sample weight, and the proportional abundance. Because dry sites were interspersed among non-dry sites, a total of 34 sample sites had to be visited to achieve the desired number of non-dry sample sites (i.e., 20) to calculated population-level abundance in this example. Also, this example is for the upper-most 169 samples sites so the GRTS sample order does not include some sites that were in the lower 13.1 km of the sampling frame, but the GRTS sample order is in sequence for the upper drainage sites.

The sample weight was calculated as the sample frame length in m divided by the total number of sites visited. This example is for the upper drainage sites only (i.e., the upstream-most 169 sample sites), so the sample weight is 497:

$$\text{Sample weight} = \frac{(169 \text{ sample sites}) * (100 \text{ m per sample site})}{34 \text{ sample sites visited}} = 497$$

The proportional abundance is calculated as the site-level abundance (D_{SL}) times the sample weight, and the population-level abundance is the sum of proportional abundances.

GRTS sample order	Site code	Site status	D_{SL} (fish·m ⁻¹)	Sample weight	Proportional abundance
52	Rock-268	Non-dry	0.0319	497	16
53	Rock-256	Dry			
55	Rock-140	Non-dry	0.0000	497	0
56	Rock-220	Non-dry	0.0000	497	0
57	Rock-286	Non-dry	0.0161	497	8
60	Rock-209	Non-dry	0.0897	497	45
63	Rock-177	Dry			
64	Rock-186	Non-dry	0.0832	497	41
65	Rock-224	Non-dry	0.0740	497	37
68	Rock-258	Dry			
69	Rock-236	Non-dry	0.1023	497	51
72	Rock-163	Dry			
73	Rock-291	Dry			
75	Rock-148	Dry			
76	Rock-218	Non-dry	0.2995	497	149
77	Rock-280	Non-dry	0.0000	497	0
79	Rock-133	Dry			
80	Rock-192	Non-dry	0.1982	497	99
81	Rock-234	Non-dry	0.0000	497	0
84	Rock-155	Dry			
85	Rock-255	Dry			
88	Rock-259	Dry			
89	Rock-250	Non-dry	0.0000	497	0
92	Rock-205	Non-dry	0.1697	497	84
95	Rock-273	Non-dry	0.0549	497	27
96	Rock-198	Non-dry	0.1100	497	55
97	Rock-228	Non-dry	0.2197	497	109
100	Rock-154	Dry			
101	Rock-293	Dry			
104	Rock-223	Dry			
105	Rock-246	Non-dry	0.1557	497	77
108	Rock-206	Non-dry	0.2372	497	118
111	Rock-168	Dry			
112	Rock-200	Non-dry	0.0349	497	17

$A_{PL} = 933$

