AN ABSTRACT OF THE THESIS OF

Hazel L. Owens for the degree of Master of Science in Water Resources Science presented on June 17, 2013.

Title: Relationships Between Stream Discharge and Cutthroat Trout Abundance at Multiple Scales in Managed Headwater Basins of Western Oregon

Abstract approved:

Arne E. Skaugset

Relationships between resident cutthroat trout (*Oncorhynchus clarkii clarkii)* and six hydrologic indices were investigated using correlation analysis in two experimental headwater catchments in the foothills of the Cascade Mountains of western Oregon. This investigation was to determine if characteristics of discharge explained inter-annual variability in trout abundance. Eight years of continuous discharge and annual abundance data collected from two contiguous watersheds from the Hinkle Creek Paired Watershed Study were used for this study. Density-discharge relationships were identified separately in the watershed actively managed for timber harvest and in the control watershed. Correlation was determined at multiple stream segments and at the watershed scale to assess the roles of spatial scale and network location on the detectability of density-discharge relationships. A method for improving the spatial coupling of density and discharge measurements within the stream network was also investigated.

No correlations ($r \leq |0.50|$) between hydrologic indices and age-1+ trout density in either watershed were found. Two hydrologic indices were related to the density of age-0 trout: maximum annual discharge ($r = 0.780$) in the control watershed and Q90 summer discharge ($r = 0.697$) in the treated watershed. The correlation between the density of age-0 trout and each of these two indices were similar across individual stream segments, but variability in the magnitude of the correlation suggests that network location plays a key role in facilitating processes that link density and discharge. Variability in the magnitude of the correlation across stream segments also influenced the detectability and interpretability of relationships observed at the extent of a watershed and at the extent of a stream segment. These results indicate that researchers interested in understanding the dynamics of cutthroat trout abundance should consider the effects of discharge on inter-annual variability in abundance of different age classes and the role of network location on the detectability of relationships.

Relationships Between Stream Discharge and Cutthroat Trout Abundance at Multiple Scales in Managed Headwater Basins of Western Oregon

by
Hazel L. Owens

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APPROVED:

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Major Professor, representing Water Resources Science

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Director of the Department of Water Resources

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request

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Hazel L. Owens, Author

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CHAPTER 1- INTRODUCTION

RESEARCH CONTEXT

Resident coastal cutthroat trout (*Oncorhynchus clarkii clarkii)* are ubiquitous in headwater streams in forested basins across western Oregon. In the last century, these populations have experienced widespread declines in abundance driven, in part, by habitat modification from historic forest management activities (Connolly and Gresswell 2008; Reeves et al. 1997). In response, researchers sought to better understand the relationship between cutthroat trout, the stream environment, and the role of disturbances, natural and anthropogenic, on resident cutthroat trout population dynamics. Substantive changes in forest practices to protect aquatic resources were implemented. Today, the primary drivers of natural, inter-annual variability in resident cutthroat trout abundance in headwater streams are poorly understood (House 1995) and questions about the effects of contemporary forest practices on resident cutthroat trout remain. Forest managers, fisheries managers, and policy-makers in the Pacific Northwest are interested in a better understanding of the population dynamics of resident cutthroat trout in forested headwater basins as an important part of understanding the effects of contemporary forest practices on resident cutthroat trout populations.

In 1^{st}- 4^{th} order headwater streams in the foothills of the western Oregon Cascades in the snow-rain transition zone, the environments that support resident cutthroat trout are highly dynamic. Summers are warm and dry and the wet season persists from fall through spring with floods that occur semi-frequently over the life span of a cutthroat trout (Poff and Ward 1989). Timber harvest in these headwater basins is common and many streams are affected by past harvest practices. Adult resident cutthroat trout spawn from late winter to early spring (Quinn 2005; Trotter 1989). Incubation of trout eggs takes place until emergence, when alevins emerge from the yolk-sac and enter the water column as free-swimming trout fry, in the late spring and early summer (Quinn 2005; Trotter 1989). Little is known about the role of environmental factors in the abundance of resident cutthroat trout in space and time in these environments despite ongoing research (Connolly and Gresswell 2008).

OBJECTIVES

To better understand environmental factors related to population dynamics of resident cutthroat trout in managed headwater streams in the western Oregon Cascades relationships between the inter-annual variability in abundance of cutthroat trout and discharge metrics in experimental headwater catchments were studied. This work used eight years of cutthroat trout relative abundance and stream discharge data from the Hinkle Creek Paired Watershed Study. A multi-scale approach was used to determine if observed relationships between discharge metrics and cutthroat trout abundance were consistent at multiple spatial scales and locations within the stream network. This study had four objectives:

- to examine relationships between resident cutthroat trout abundance and stream discharge;

- to compare the above-mentioned relationships across two contiguous watersheds with different management regimes;

- to assess the role of spatial scale and network location on the detectability of these relationships;

- and to explore methods to integrate spatial and temporal datasets in hydro-ecological studies.

CHAPTER 2- LITERATURE REVIEW

DISCHARGE

One environmental factor that may be related to cutthroat trout abundance in forested, headwater basins is stream discharge (Lytle and Poff 2004; Poff and Ward 1989). Discharge is a measure of the amount of water flowing through the stream and is controlled by geologic, climatic, and land use factors. Discharge is a "master variable" because it can affect the population size, structure, and distribution of resident cutthroat trout through effects on aquatic habitat volume, stream velocity, channel hydraulics, water quality, channel geomorphology and bed-load stability at multiple scales (Poff et al. 1997; Resh et al. 1988). Discharge also influences the availability of resources such as refuge, nutrients, food, and spawning habitat (Elwood and Waters 1969; Nehring and Anderson 1993) and biotic processes such as competition, disease, predation, and reproduction (Nelson 1986; Resh et al. 1988; Seegrist and Gard 1972). Extreme high or low discharge can be pulse disturbances that cause widespread or patchy mortality and alter habitat (Erman et al. 1988; Monk et al. 2007; Resh et al. 1988; Seegrist and Gard 1972; Swanson et al. 1998; Townsend 1989).

The role of discharge as a primary control on ecological processes is long established in stream ecology. Seminal work by Poff et al. (1997) introduced the natural flow regime concept (NFRC) that demonstrates 1) the tight linkage between the natural flow regime, the naturally-occurring patterns of stream discharge in the course of a year, and the ecological integrity of streams and rivers and 2) mechanisms by which anthropogenic alterations of the natural flow regime, such as forest management practices, can negatively affect freshwater biota. By linking hydrologic processes to ecologic responses, the NFRC provides a paradigm for hydro-ecological studies across lotic ecosystems. It also supplies a framework for researchers to develop metrics of discharge by describing the natural flow regime with five critical components: magnitude, timing, duration, frequency, and rate of change of streamflow.

Studies from the United States and Europe have observed connections between seasonal variability in flow and the effects of discharge on trout at different life stages. High magnitude or frequency of discharge events during the emergence period have been related to a reduction in the abundance of young-of-the-year trout (hereafter, age-0) (Cattaneo et al. 2002; Erman et al. 1988; Jensen and Johnsen 1999; Latterell et al. 1998a; Liebig et al. 1999; Nehring and Anderson 1993; Nuhfer et al. 1994) due to increased susceptibility of trout fry to mortality or downstream displacement from high flow velocities (Harvey 1987). Scouring of redds during high-magnitude discharge events is thought to provide a mechanism (DeVries 1997; Lapointe et al. 2000) for multiple observations of a negative relationship between age-0 abundance and discharge during incubation (Elwood and Waters 1969; Nehring and Anderson 1993; Seegrist and Gard 1972; Spina 2001; Unfer et al. 2011). Negative effects of high flow disturbance on the age-0 cohort during incubation or emergence can affect population size in subsequent years (Cattaneo et al. 2002; Latterell et al. 1998b; Lobon-Cervia 2007; Nelson 1986). On the other hand, Unfer et al. (2011) found a positive relationship between the abundance of age-0 trout and discharge during the spawning and incubation period so long as the magnitude of discharge was sufficiently high to transport fine bed materials but not damage incubating embryos. This study also found a positive relationship between the abundance of age-0 trout and the magnitude of discharge prior to the spawning period and suggested that high flows prior to spawning can redistribute the bed-load to improve spawning habitat (Unfer et al. 2011). Hakala and Hartman (2004) also documented negative effects of summer droughts on the abundance of age-0 trout.

Negative effects of discharge on trout greater than 1 year of age (hereafter, age-1+) have also been demonstrated. Elwood and Waters (1969) and Seegrist and Gard (1972) reported negative relationships between extreme flood events and the abundance age-1+ trout. Hakala and Hartman (2004) reported negative effects of drought during the summer on age 1+ trout. A previous study on age-1+ cutthroat trout survival from the Hinkle Creek Paired Watershed Study showed that low flows during the fall were related to reduced survival of the sampled PIT-tagged population (Passive Integrated Transponder) (Berger and Gresswell 2009). This relationship is supported by additional studies showing that low flow periods are related to reduced survival of age-1+ trout (Elliott 1987; Xu et al. 2010). These studies suggest that the inter-annual variability in abundance of multiple age classes of cutthroat trout at Hinkle Creek may be related to discharge.

The relative contribution of abiotic factors (habitat template, discharge, water quality, etc.) and biotic processes (competition, predation, disease, etc.) on fluctuations in trout populations is debated (Cattaneo et al. 2002; Elliott 1994; Lobon-Cervia and Rincon 2004; Milner et al. 2003; Quinn 2005; Quist and Hubert 2005). Research on brown trout in headwater streams in England suggests that density-dependent factors, not discharge, are the primary factors that control fish population dynamics (Elliott 1994). However, inconsistencies in results across studies suggest that relationships between fish populations and discharge may depend on the geomorphic, climatic, and ecological context of the stream environment (Elliott 1987). Resident cutthroat trout populations have persisted in headwater streams that are highly dynamic for millennia and they have adapted life-history strategies that make them resilient to flow-related disturbances (Lytle and Poff 2004). Adaptive traits can inhibit the mechanistic understanding of population fluctuations and their relation to processes that operate over longer time scales. Inter-annual variability in the abundance of resident cutthroat trout is linked to a variety of processes; density-dependence, adaptive traits, and synergism among regulating factors may diminish the role of discharge on abundance.

FOREST MANAGEMENT CONTEXT

Past and present forest management, that include clearcut timber harvest, roads construction, roads maintenance, and herbicide application, etc., adds a layer of complexity to understanding population dynamics in headwater basins of western Oregon. Forest management activities may disrupt the natural flow regime and perturb ecological processes in the stream or basin (Poff et al. 1997). Paired-watershed studies in the Pacific Northwest have reported increases in annual water yield after timber harvest. The largest increases occur in the fall and winter and largest proportional increases occur in the spring and summer (Rothacher 1970; Ziemer 1981). Timber harvest also affects the magnitude, duration, and timing of discharge of individual storms, particularly smaller magnitude storms (Hewlett and Helvey 1970; Rothacher 1970; Wright et al. 1990; Ziemer 1981). Timber harvest can influence water temperature, water quality, energy budgets, primary production, and geomorphology (Hartman et al. 1996; Mcculloch and Robinson 1993; Stednick 2008), and can affect salmonid abundance, positively or negatively. (Hartman and Scrivener 1990; Hicks et al. 1991; Poff et al. 1997; Scrivener and Andersen 1984; Stednick 2008; Tonina et al. 2008).

SPATIOTEMPORAL CONTEXT

An important consideration in identifying relationships between discharge and trout abundance is the scale at which effects are observed. Scale has two components: grain and extent. Grain is defined as the size of the individual units of observation and refers to the minimum spatial resolution of the data. Extent is defined as the size of the study area and refers to the scope or domain of the data (Turner et al. 2001). While discharge can affect the dynamics of trout populations at multiple spatial and temporal scales, few studies have conducted investigation at multiple scales simultaneously (Bunn and Arthington 2002; Fausch et al. 2002; Wood et al. 2007). Multi-scale analyses incorporate the hierarchical nature of stream networks to "identify critical processes and the scale at which those processes are acting" (Lowe et al. 2006). This may be important in the context of timber harvest, which can have localized effects on large wood and sediment delivery, microclimatology, air temperature, solar radiation, pool depth, and habitat quality and watershed-level effects on discharge and water quality (FEMAT Team (U.S.) and United States. Forest Service. 1993). Wood et al. (2007) conclude that multi-scale analysis in hydro-ecological studies is needed to identify patterns and differences among scales and help improve assimilation of small scale processes to large-scale management decisions.

Most stream studies make observations at one or more short 'representative reaches' less than 200 m length and draw inference to a spatial extent that extends beyond the scope of the data (Fausch et al. 2002; Townsend et al. 2004). In hydro-ecology, abundance measurements made at small independent reaches are used to identify relationships that are representative of the larger stream or watershed of interest. Absent from the literature are studies that measure abundance at an intermediate extent (1–100 km), an extent that encompasses the important aspects of life history, habitat requirements of multiple age classes, and community ecology affecting stream fishes of interest (Figure 2-1) (Fausch et al. 2002). Intermediate extents are an amalgamation of physical and ecological processes affecting habitat units, reaches, segments, and watersheds and are the extent at which land use management typically is implemented (Fausch et al. 2002).

Location within a given stream network may also be important to the detection of relationships between discharge and abundance (Fausch et al. 2002). Gresswell et al. (2006) demonstrated highly structured spatial variability in patterns of abundance of cutthroat trout across stream segments in headwater basins of western Oregon. Spatial variability in abundance was linked with spatial heterogeneity in physical properties and bedrock lithology (Gresswell et al. 2006). Spatial variability in abundance is not often considered and may obscure relationships between discharge and abundance across stream segments. The importance of the sampling location within a stream network on detectability of relationships between discharge and abundance has important implications for hydro-ecological studies which collect samples from small spatial extents.

In addition, hydro-ecological studies that look for relationships between discharge and abundance may require the integration of biological and hydrological datasets collected at inconsistent resolutions. A survey of the hydro-ecological studies discussed previously revealed that discharge measurements and fish surveys frequently do not consistently occur in a common location and in studies where sampling locations were provided it was common for fish sampling sites and stream gages to be separated by 2–50 km (Cattaneo et al. 2002; Erman et al. 1988; Jensen and Johnsen 1999; Latterell et al. 1998b; Lobon-Cervia 2007; Nehring and Anderson 1993; Nelson 1986; Nuhfer et al. 1994; Spina 2001). While paired measurements occurred in the same geomorphic province (Figure 3-2), they frequently occurred in separate reaches or streams. Decisions about sampling locations are often driven by financial restraints and access, but are sustained by the assumption that the hydrologic conditions at the site of fish sampling are captured at the discharge gaging site. Because discharge is proportionate to drainage area (in a broad sense), and climate-driven hydrologic processes are likely to behave similarly across a watershed, this may be a reasonable assumption if watershed characteristics (geology, geomorphology, aquifer characteristics, land use, vegetation, etc.) are similar. On the other hand, variability in fish habitat characteristics, stream velocity, channel width, pool depth, etc. is ubiquitous across streams and variability in aquifer characteristics, land use management, and geology is ubiquitous across catchments. The assumption that the hydrologic conditions at the site of fish sampling are captured at the gaging site may not always be appropriate but this is rarely acknowledged.

To date, no studies have examined the role of forest management on the detectability of relationships between discharge and cutthroat trout abundance at various spatiotemporal scales. Furthermore, consistent methods to integrate spatially inconsistent datasets in hydro-ecological studies are lacking.

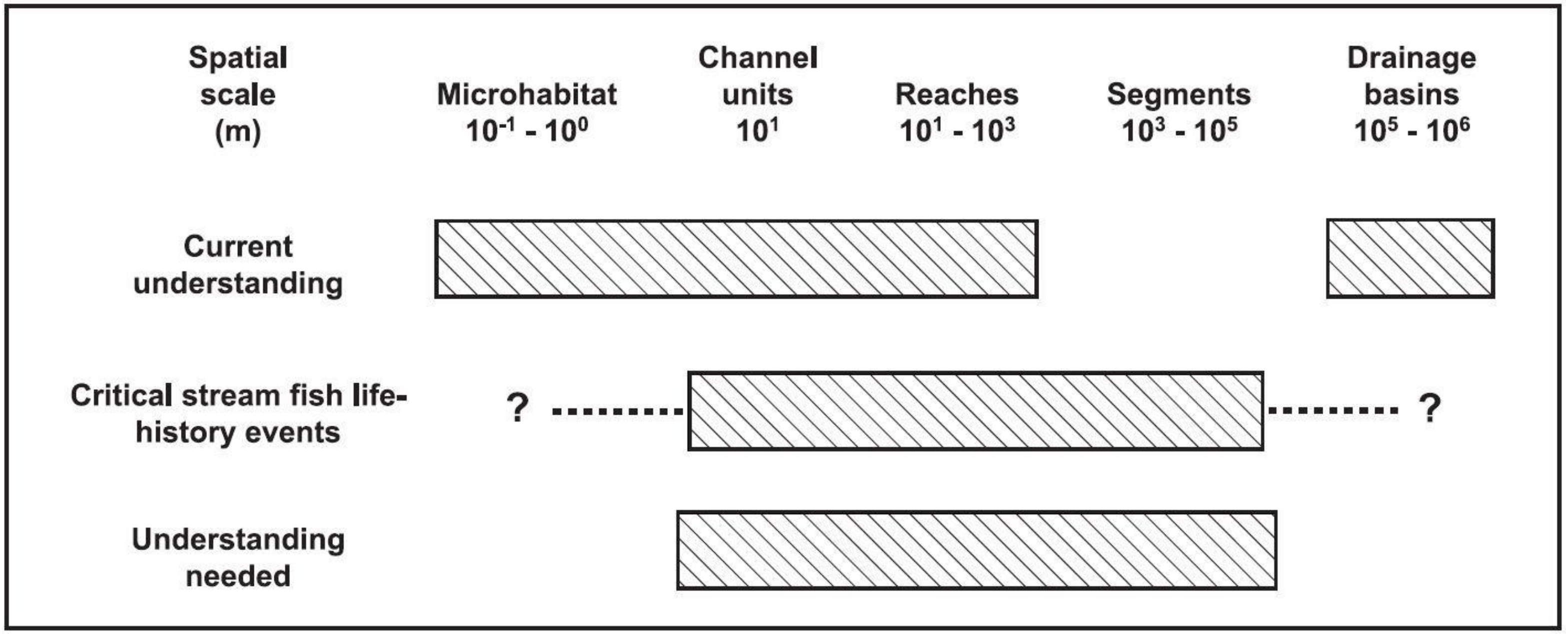

Figure 2-1 Depiction of current understanding of spatial extent for lotic fishes according to Fausch et al. (2002). Diagram shows a spatial framework for studying lotic fishes, the scales currently addressed in research, the probable range of scales likely spanned during the life cycle of a stream fish, and spatial scale where better understanding is needed in stream studies (Fausch et al. 2002).

CHAPTER 3- METHODS

STUDY AREA

Site Characteristics

The study took place in the Hinkle Creek basin, a 2000 ha 3rd-order stream network in the Umpqua River Basin located in the foothills of the western Cascades of southern Oregon (Figure 3-1). The Hinkle Creek basin is located in the transitional snow-zone from 430 to 1100 m elevation. Stream gradients range from 4 –21% (Table 3-1). A mean annual precipitation of 1800 mm falls primarily as rainfall from November–May with intermittent snowfall. Summers are typically warm and dry.

Parent material is basalt and rhyolite with deposits of volcanic sandstones and pyroclastic material (Wells et al. 2000). Soils are characterized by Brown Mountain Basalts in high elevations, volcanolithic, sandstone, conglomerate, laharic brechia, rhyolite and dacit flow in middle elevations, and landslide deposits in lower elevation soils (Wells et al. 2000).

Vegetation composition is predominantly 60 year-old, harvest-regenerated, second-growth Douglas fir *(Pseudotsuga mensiezii)* with lesser amounts of western hemlock (*Tsuga heterophylla)* and western redcedar *(Thuja plicata)* scattered throughout. These conifer species are also present in riparian areas, in addition to hardwoods red alder (*Alnus rubra*) and big leaf maple (*Acer macrophyllum*). Relative ratios of red alder/conifer species in riparian areas tend to increase in lower mainstem segments and decrease in riparian areas along tributaries and the upper mainstem segments. Common understory trees/shrubs include vine maple (*Acer circinatum*), salmonberry (*Rubus spectabilis*), huckleberry (*Vaccinium parvifolium*) and sword fern (*Polystichum munitum*).

Resident cutthroat trout (*O. clarkii*), Pacific giant salamander (*Dicamptodon tenebrosus*), sculpin (*Cottus spp.; C.reticulate and possibly C. gulosus*), and steelhead trout (*Onchorhynchuc mykiss irideus*) are common aquatic vertebrates in the study basin. All species are distributed throughout the fish-bearing portion of the stream network (Figure 3-1). Abrupt transitions between fish-bearing and non-fish-bearing streams occur at barriers to fish passage beyond which no trout were observed in initial surveys. *O. mykiss* at Hinkle Creek are considered primarily anadromous steelhead trout, not resident rainbow trout, due to field observations of length, growth rate, and distribution of age-1+ *O. mykiss* trout (unpublished data from HCPWS). Trout mortality due to angling during the study is unlikely due to low densities of legal-sized trout and poor public access.

Spatial framework

Hinkle Creek is a nested, hierarchical, spatial framework with organization at the geomorphic province, watershed, stream segment, stream reach, and aquatic habitat unit levels (Figure 3-2) (Frissell et al. 1986; Montgomery and Buffington 1998). The study area for Hinkle Creek Watershed is within the western Oregon Cascades geomorphic province and is divided into two contiguous watersheds, North Fork Hinkle Creek (NFH) and South Fork Hinkle Creek (SFH) (Figure 3-1). The NFH and SFH watersheds can each be divided into four mainstem and three tributary stream segments (Figure 3-1). Stream segments can be further subdivided into stream reaches and aquatic habitat units. Stream segments are delineated by tributary junctions and barriers to fish movement and are characterized by differences in drainage area, gradient, active channel width, length, valley floor width, and percent area harvested (Table 2-1). Habitat units are classified by type (pool, riffle-rapid, cascade, and vertical step) according to standards established by Bisson et al. (1982).

Hinkle Creek Paired Watershed Study

The Hinkle Creek basin is managed by Roseburg Forest Products, a private timber company, and was the site of the Hinkle Creek Paired Watershed Study (HCPWS). The HCPWS is a larger study that evaluated the effects of contemporary forest management on headwater streams and took place from 2003–2011. The HCPWS study design consisted of a treatment watershed that had timber harvest in multiple phases (SFH) and a control watershed (NFH). Both watersheds had a history of previous timber harvest. SFH was managed for timber harvest in compliance with Oregon Forest Practices Rules during two harvest entries (ODF 2010) (Figure 3-3). A harvest entry occurred in 2001 prior to the start of the HCPWS and its effects became part of the calibration process. The second harvest entry took place in 2005–2006 along four, non-fishing-bearing reaches, and the third entry took place in 2008–2009 adjacent to fish-bearing mainstem and tributary streams. (Figure 3-3) (ODF 2010). No timber harvest occurred in the control watershed the NFH (Figure 3-3).

The harvesting method employed at all clearcuts was hand-falling and tree-length yarding with a slackline, skyline cable system using a motorized slack-pulling carriage. Log processing occurred at landings. Harvest alongside fish-bearing streams maintained fixed-width riparian buffers. Buffer widths increased with size of the stream, ranging from 50–70ft (ODF 2010). No riparian buffers of merchantable over story conifers were left alongside the non-fish-bearing streams. The harvest entry in 2001 resulted in clearcut harvest on 11 percent of the watershed area. During the first and second harvest entries, clearcut harvest occurred on 14.3, and 12.2 percent, respectively, of the area of SFH. Total area harvested in tributary basins varied by harvest phase (Table 2-1). Additional forest management activities included construction of 3.2 km of new road and reconstruction of 6.4 km of existing road and the application of broad-spectrum herbicide to all harvest areas (excluding areas adjacent to streams) in the fall of 2006.

The HCPWS study site was not randomly chosen, but was selected to meet specific criteria. It was located within the lower-elevation foothills of the western Cascades on privately-owned, industrial forest-land, contained two contiguous watersheds of 40+ year-old Douglas-fir stands, and was managed by a land-owner willing to participate in the study. The locations and timing of timber harvest were not randomly assigned but chosen based on owner preference and preexisting harvest conditions in the SFH watershed.

Table 3-1 Characteristics of stream segments and watersheds at Hinkle Creek. Refer to Figures 3-1 and 3-3

Unit name	Unit type	Drainage area (ha)	Gradient (%)	Active Channel Width (m)	Valley Floor Width (m)	Length (m)	% Logged phase 1	% Logged phase 2	% Logged phase 3	% Logged total
NFHC	Water-shed	857	14	-	-	4620	-	-	-	-
SFHC	Water-shed	1084	12	-	-	6780	11	14.3	12.2	37.5
NM1	Segment	857	4	5.4	37.6	793	-	-	-	-
NM2	Segment	685	6	4.8	37.8	549	-	-	-	-
NM3	Segment	436	8	4.0	23.3	1225	-	-	-	-
NM4	Segment	199	16	2.8	34.3	154	-	-	-	-
NT1	Segment	118	11	2.7	38.0	684	-	-	-	-
NT2	Segment	203	9	2.7	23.7	827	-	-	-	-
NT3	Segment	194	14	3.2	33.8	388	-	-	-	-
SM1	Segment	1084	4	6.7	42.4	780	10	14	12	36
SM2	Segment	944	6	5.6	42.8	722	11	14	9	34
SM3	Segment	523	7	5.2	35.8	1029	7	8	11	26
SM4	Segment	325	10	4.1	19.6	1054	2	>1	8	10
ST1	Segment	112	8	1.9	37.1	1481	4	24	25	53
ST2	Segment	363	9	3.4	29.4	1123	9	16	6	30
ST3	Segment	129	14	3.3	18.6	591	24	33	<1	56

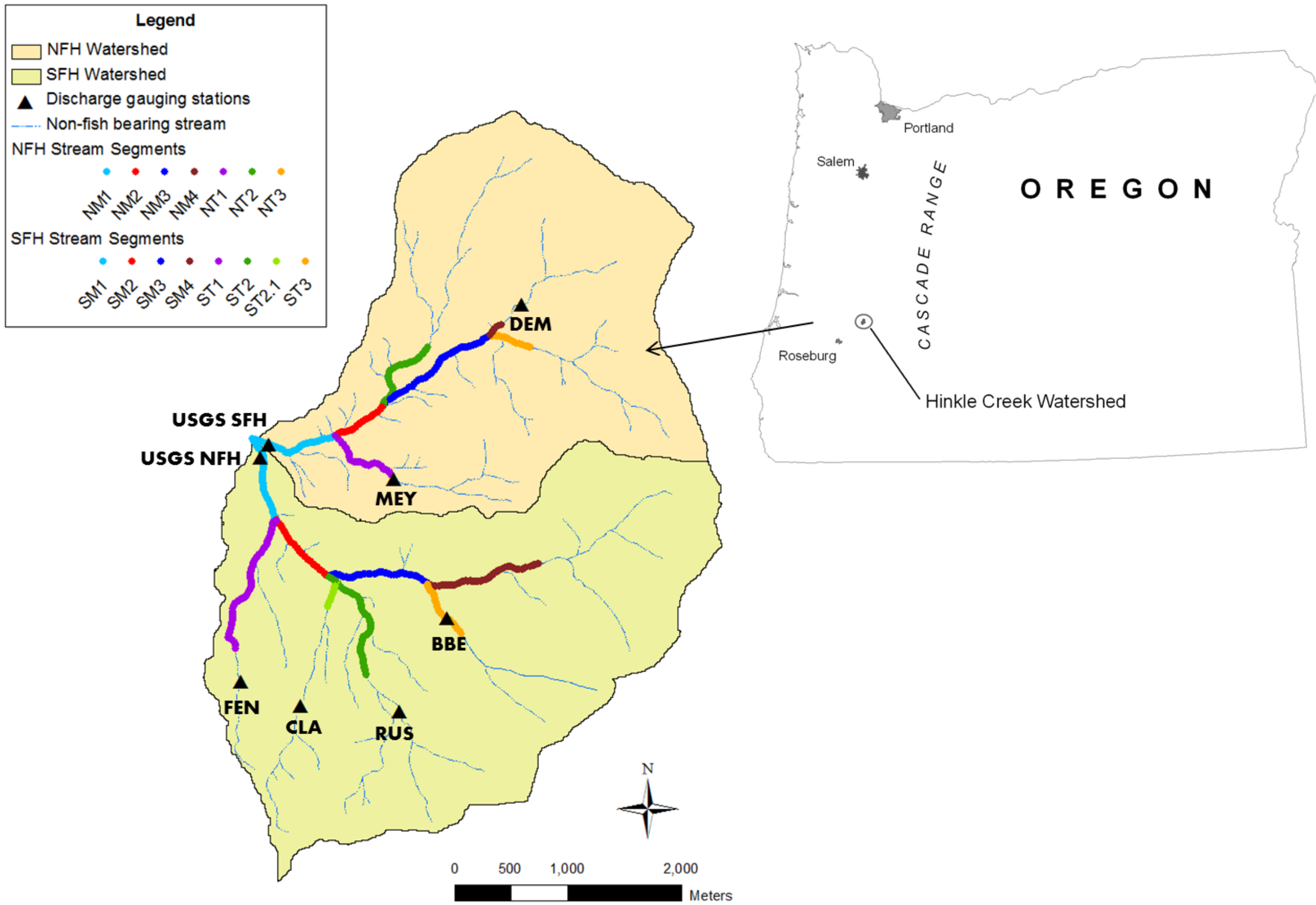

Figure 3-1 The state of Oregon and the Hinkle Creek study site showing fish-bearing streams with segment labels, non-fish-bearing streams, and discharge gaging sites.

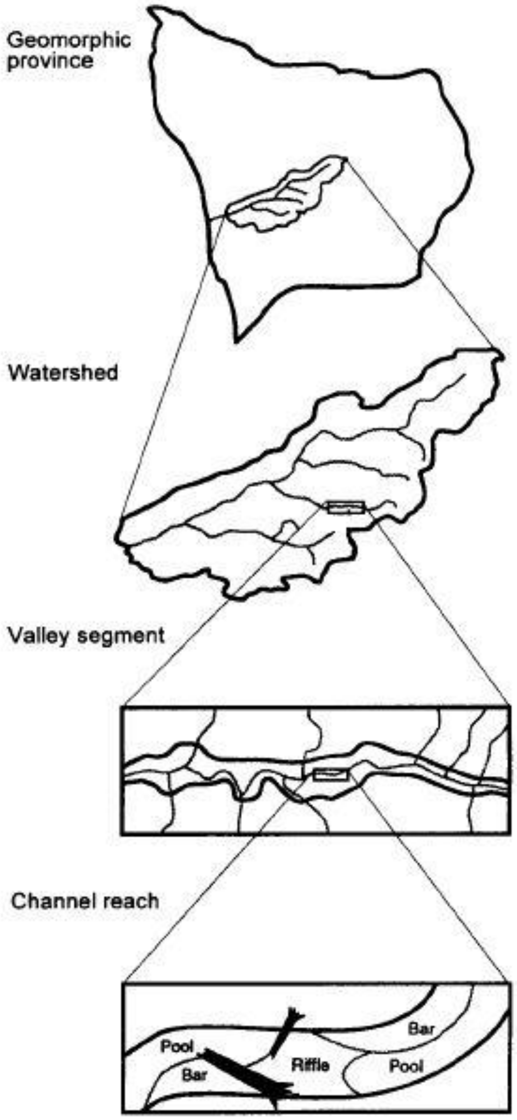

Figure 3-2 Hierarchical spatial framework used at Hinkle Creek, with organization at the geomorphic province, watershed, valley segment, channel reach, and habitat units (Montgomery and Buffington 1998)

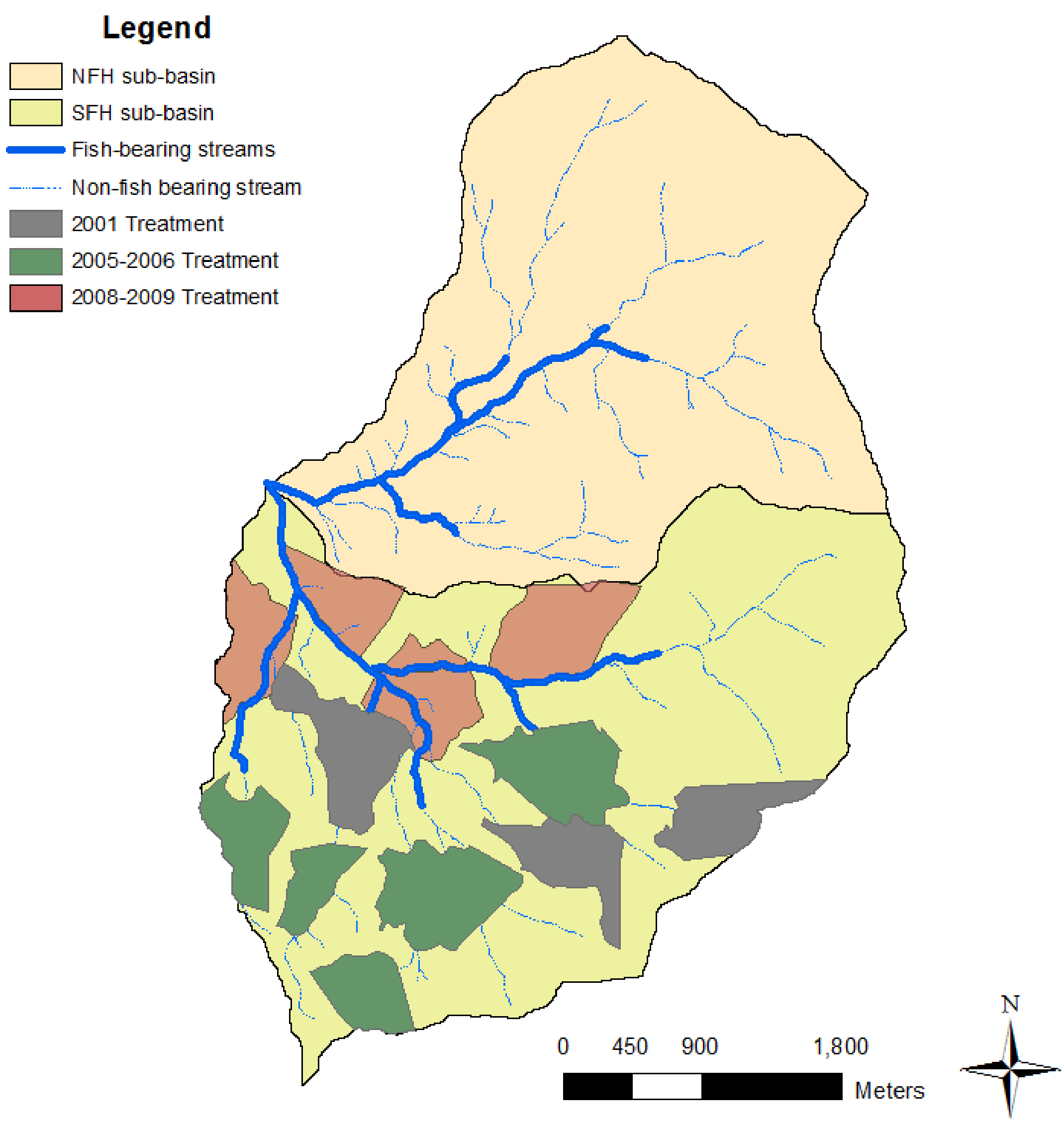

Figure 3-3 The Hinkle Creek Paired Watershed Study treatment plan showing clearcuts and roads and their proximity to fish-bearing and non-fish-bearing streams.

DATA COLLECTION

Trout Surveys

From 2003–2011 between August and September of every year, every pool and cascade habitat unit in the fish-bearing streams at Hinkle Creek were surveyed for cutthroat trout. Riffle habitat units were not surveyed. The survey was carried out using single-pass electro-fishing without block nets. Trout of all age classes were temporarily stunned, collected, counted, weighed and measured to the nearest 1 mm fork length and then returned to the sampled habitat unit. The length and width (in m) of each habitat unit was also measured. The number of trout caught within a habitat unit was defined as the unit catch. The catch probability of single-pass electrofishing is typically less than multiple pass electrofishing but varies by habitat type and fish species (Reynolds et al. 2003). Although single-pass electrofishing typically has lower catch probability than multiple-pass removal methods and does not produce absolute population estimates, it provides a reliable estimate of proportionate abundance within the basin (Bateman et al. 2005). A study in two forested headwater catchments in western Oregon estimated the catch probability of single-pass electrofishing for age-1+ cutthroat trout in pools and cascade habitat units at 74% and 78% (Bateman et al. 2005). Reynolds et al. (2003) found that single-pass electrofishing was as effective as multiple pass electrofishing at estimating the percent abundance of adult and juvenile cutthroat trout and juvenile rainbow trout in headwater streams of the western Cascades. Catch probability for age-0 trout at

Hinkle Creek is unknown but expected to be lower and more variable. The same crew sampled both watersheds in any given year to reduce sampling bias.

Discharge Measurements

Stage, or gage height, was measured at 60 minute intervals from 2003–2011 at two sites near the confluence of both South Fork Hinkle Creek (SFHC) and North Fork Hinkle Creek (NFHC) by the United States Geological Survey (USGS stations 14319830 and 14319835, http://waterdata.usgs.gov/nwis). The USGS estimated discharge using stage versus discharge rating curves developed from continuous measurement of continuous gage height correlated with field measurements of discharge (Buchanan et al. 1969; Gordon 2004). Six additional stream gaging locations were located in the upper non-fish-bearing reaches of the two study watersheds (Figure 3-1). Stream discharge was measured at 10 minute intervals at these locations from 2003–2011 using Montana flumes. The Montana flumes were sized to measure the 100-year return period flow and as a consequence high precision of summer and fall low flows was not possible (http://www.tracomfrp.com/montana.htm).

PARAMETER DEVELOPMENT

Spatiotemporal Framework

Defining the spatiotemporal framework was a fundamental component of analysis. Most studies are limited to abundance measurements collected at the stream reach or stream segment level, but the HCPWS provided an opportunity to calculate abundance for an entire watershed. Abundance was also calculated at individual stream segments (Figure 3-1 and Figure 3-2). Stream segments were determined based on tributary junctions and boundaries between fish-bearing and non-fish-bearing stream reaches and were treated as independent units. In a western Oregon trout movement study, Gresswell and Hendricks (2007) found that the majority of adult cutthroat trout moved between channel units, and few tagged fish moved beyond the stream reach or stream segment scale (>100 m). Unpublished data from HCPWS suggests that < 20% of PIT-tagged cutthroat trout moved between stream segments.

Identifying relationships between abundance and discharge required the matching of abundance measured in watersheds and stream segments with hydrologic indices measured at discrete discharge gaging locations. At the watershed level, discharge was directly measured at the most downstream location within each watershed (NFHC and SFHC). However, at the stream segment level, discharge was not directly measured at the most downstream location within each stream segment. The lack of an association between the location of discharge gaging stations and the location of individual stream segments (hereafter, spatial incongruence) is common in hydro-ecological studies and typically occurs when abundance is measured in one or more stream reaches or segments across a geomorphic province and discharge is measured at one remote gaging site. The common solution is to match abundance from a given stream reach or stream segment with the remote discharge gaging site and to assume that the hydrologic conditions are similar at the two locations. Because discharge was measured at multiple sites within each watershed, the HCPWS provided an opportunity to explore methods that address spatial incongruence at individual stream segments.

Temporal integration required matching continuous discharge measurements with trout abundance measured once at the end of a given water year. Consistent with the literature, this study tests hypotheses that abundance at the end of a water year *n* may be related to hydrologic conditions from the 12 months prior to trout abundance sampling *(*same year) and in some cases the hydrologic conditions from the 24-12 months prior (previous year) (see *watershed level analysis* below).

Abundance

Unit catch was separated into two separate age classes: young-of-the-year trout that emerged in the spring prior to late summer sampling (age-0) and all other trout greater than one year-old (age-1+). Length-frequency distributions were visually inspected for bi-modality to identify the two age-classes (Murphy et al. 1996). The length that separated the trout into age classes varied between 74 and 89 mm. Classification of age-1+ adult trout into additional age classes could not be determined. Previous research on resident cutthroat trout in the Molalla River basin in the western cascades found that the number of age-1 trout was 2.8–10.5 times greater than the number of age-2+ trout during the 10-year study period (House 1995). At Hinkle Creek, it is likely that the age-1+ age class is similarly dominated by the age-1 cohort.

The unit catch of age-0 trout includes an unknown proportion of age-0 steelhead trout *(O. mykiss)*, which were indistinguishable from age-0 cutthroat trout. Age 1+ steelhead trout were restricted to the lower segments of both watersheds (NM1, NM2, NM3, SM1, SM2, SM3, ST2; Figure 3-1) and were present in variable amounts annually (Table 3-2). Densities of age-1+ steelhead were consistently lower than densities of age-1+ cutthroat in both watersheds, which may be indicative of their relative proportions as young-of-the-year (Table 3-1).

Relative density (unit less) of cutthroat trout was used as a measure of abundance to account for 1) the differences in stream length sampled between years 2) differences in carrying capacity across watersheds and stream segments and 3) sampling limitations of single-pass electrofishing. Relative density is the density for a given watershed or stream segment from any particular year divided by the sum of the annual densities in years 2003–2011. For a given stream segment or watershed,

$$\text{Relative Density (RD) for year } n = \frac{\dfrac{\text{unit catch from year } n}{\text{m sampled from year } n}}{\dfrac{\sum_{2003}^{2011} \text{unit catch}}{\sum_{2003}^{2011} \text{m sampled}}}$$

Stream length sampled (in m) is the sum of the length of all habitat units sampled (pools and cascades) within a given stream segment or watershed for a given year. This varies slightly each year due to inter-annual changes in channel characteristics and flow conditions during late-summer sampling (Appendix B). RD was calculated for age-0, age-1+, and all trout (age-0 and age-1+ combined) for the NFH and SFH watersheds and individual stream segments: NM1, NM2, NM34 (the aggregation of NM3 and NM4), NT1, NT2, NT3, SM1, SM3, SM4, ST1, ST2 (the aggregation of ST2.1 and ST2), and ST3 (Figure 3-1). See *Appendix B- Abundance Data* for values of relative density by age class, stream segment, watershed, and year.

Discharge

Hydrologic indices were used to characterize discharge over a period of interest (e.g., year, season). Although hundreds of available and often redundant hydrologic indices have been developed for riverine research, selecting relevant hydrologic indices that capture flow regime properties requires identifying specific study objectives (Olden and Poff 2003). For this study, hydrologic indices were selected based on three criteria:

i. relevance to ecological components of the NFRC
ii. potential influence on various stages of the cutthroat trout life cycle , and
iii. linkage to *a priori* mechanisms that discharge can affect cutthroat trout abundance (see Chapter 1).

Relevance to the ecological components of the NFRC

The components of the natural flow regime expected to influence inter-annual variability in relative density at Hinkle Creek include: timing, magnitude, duration, and frequency of streamflow. The fifth component of the NFRC is the rate of change of streamflow; variability in the rate of change of streamflow was assumed to be similar for a given watershed or stream segment across the eight years of study and was not incorporated into hydrologic index selection.

Bearing on the cutthroat trout life cycle

All six hydrologic indices selected (see below) incorporate timing of streamflow, which is linked to the cutthroat trout life cycle. Individual water years were separated into annual, fall-winter-transition, spawning, emergence, and summer periods defined as October 1–September 30, October 1–January 31, February 1–April 30, May 1–June 30, and July 1–September 30, respectively (Table 3-3). Although transitions between respective life cycle stages are variable across years, these periods were fixed across the eight year study period to allow computation of the hydrologic indices. Periods were determined based on expert opinion, visual observations, and available literature on the cutthroat trout life cycle in western Oregon (Trotter 1989).

Linkage to a priori mechanisms

Six hydrologic indices were calculated for a given water year and at a given gaging station. Hydrologic indices include:

- ***MaxAN***: the maximum annual discharge, which represents the single largest flow in the annual period (October 1–September 30) that could act as a high-flow pulse disturbance event or alter habitat conditions.
- ***Min7FW:*** the minimum 7-day average discharge during the fall-winter transition period (October–January). This represents low flow conditions experienced over seven consecutive days that could act as a persistent low-flow disturbance in the fall.
- ***Q10SP***: the discharge value equaled or exceeded ten percent of the time during the spawning period (February–April). This represents moderate-high flow conditions that could positively or negatively influence spawning success or embryo survival.
- ***MaxEM***: maximum discharge during the emergence period (April–May). This represents the single highest flow that could act as a disturbance to cohort(s) of age-0 trout.
- ***FreqEM***: storm frequency during the emergence period (April–May). This represents the number of storm events that could act as cumulative stressors or disturbances to cohort(s) of age-0 trout.
- ***Q90SM***: the discharge value equaled or exceeded ninety percent of the time during the summer period (July–September). This represents low flow conditions that could positively or negatively influence habitat volume, water

temperatures, holding cover, growth rates, primary productivity, and other factors related to summer survival and mortality.

See Tables 3-3 and 3-4 for expanded definitions of time periods and hydrologic indices. Indices were calculated using the discharge records from all eight discharge gaging stations. ***Min7FW*** and ***Q90SM*** were not calculated at the upper flumes sites due to low precision for low flows. Hydrologic indices were derived from mean daily runoff (in mm), a common measure of unit area discharge. Unit area discharge represents the equivalent depth of water over the upstream catchment area and was used to account for differences in stream size and drainage area across stream segments and watersheds. See A*ppendix C- Hydrologic Data* for values of hydrologic indices by watershed and year.

Table 3-2 Abundance of age-1+ anadromous steelhead and resident cutthroat trout in the Hinkle Creek study area. Count indicates the number of trout detected in the NFH and SFH watersheds. Density is the number of trout (steelhead or cutthroat) over the total length of stream sampled in NFH and SFH for a given year. Density was calculated at the watershed level. Distribution of steelhead was restricted to NM1, NM2, NM3, SM1, SM2, SM3, and ST2; See Figure 3-1 for segment locations within the study area.

	NFH watershed				SFH watershed			
	Count		Density		Count		Density	
Year	**steelhead**	**cutthroat**	**steelhead**	**cutthroat**	**steelhead**	**cutthroat**	**steelhead**	**cutthroat**
2004	15	311	0.007	0.155	52	491	0.020	0.186
2005	6	305	0.004	0.217	9	564	0.004	0.224
2006	5	382	0.003	0.228	9	564	0.003	0.217
2007	75	421	0.047	0.263	14	680	0.006	0.302
2008	53	738	0.029	0.397	9	978	0.005	0.523
2009	37	540	0.025	0.368	89	684	0.047	0.358
2010	136	503	0.096	0.355	203	558	0.109	0.301
2011	137	387	0.097	0.273	250	637	0.143	0.365

Table 3-3 Periods for hydrologic indices and their relationship to the cutthroat trout life cycle.

Period	Code	Definition	Relevance to cutthroat trout life cycle.
Annual	AN	Oct 1–Sept 30	cutthroat trout life cycle based on one-year intervals
Fall-Winter Transition	FW	Oct 1–Jan31	transitional period between dry and wet seasons; discharge is highly variable; winter storms common; early adult spawning may begin as early as December
Spawning	SP	Feb 1–Apr 30	discharge is highly variable; majority of adult trout spawning occurs; eggs incubating;
Emergence	EM	May 1–June 30	discharge is highly variable; stream temperatures rising; majority of adult spawning finished; eggs incubating; trout alevins emerging from the yolk-sac as young-of-the-year
Summer	SM	July 1–Sept 30	discharge is typically low; storm events uncommon; stream temperatures increasing; young-of-the-year rearing and growing

Table 3-4 Definitions of Hydrologic Indices. Italic fonts signify components of the natural flow regime concept represented by the hydrologic indices. Refer to Table 3-1 for definitions of periods.

Hydrologic Index	**Natural Flow Regime Concept**	**Definition**	**References**
MaxAN	*Magnitude, Timing*	Maximum value of daily runoff observed during the annual period.	(Cattaneo et al. 2002; Clausen and Biggs 2000; Nuhfer et al. 1994; Olden and Poff 2003; Richter et al. 1996)
Q10SP	*Magnitude, Duration, Timing*	The runoff value equalled or exceeded 10% of the time observed during the spawning period	(Cattaneo et al. 2002; Clausen and Biggs 2000; Olden and Poff 2003)
MaxEM	*Magnitude, Timing*	Maximum value of daily runoff observed during the emergence period	(Cattaneo et al. 2002; Clausen and Biggs 2000; Nuhfer et al. 1994; Olden and Poff 2003; Richter et al. 1996)
FreqEM	*Magnitude, Frequency, Timing*	Number of storms equaling or exceeding seven times the inter-annual median runoff observed during the emergence period	(Cattaneo et al. 2002; Clausen and Biggs 2000; Olden and Poff 2003; Richter et al. 1996)
Q90SM	*Magnitude, Duration, Timing*	The runoff value equalled or exceeded 90% of the time observed during the summer period	(Cattaneo et al. 2002; Clausen and Biggs 2000; Olden and Poff 2003)
Min7FW	*Magnitude, Duration, Timing*	Minimum value of daily runoff averaged over 7 days observed during the fall period.	(Olden and Poff 2003; Richter et al. 1996)

DATA ANALYSIS

Data analysis was divided into four components, to:

- investigate a method to account for spatial incongruence
- identify & compare correlation between relative density and hydrologic indices at the watershed level;
- identify & compare correlation between relative density and hydrologic indices at the stream segment level;
- explore cohort strength and recruitment strength

Spatial incongruence

The simple regression models of any given hydrologic index in water year *n* on watershed drainage area was used to predict the value of the hydrologic index for each stream segment. This method was developed based on existing methods that use drainage area as a predictor of discharge at non-gaged sites (Gordon 2004; Jennings et al. 1994; Parrett et al. 1990; Risley et al. 2008). The response variable was the value of the hydrologic index measured at the 5 gaged sites in SFH (1 lower, 4 upper) and 3 gaged sites in NFH (1 lower, 2 upper). Indices ***MaxAN***, ***Q10SP***, and ***MaxEM*** from any given year or watershed were computed separately, for a total of 48 regression models (3 indices * 8 years * 2 watersheds). Models were developed separately for the NFH and SFH due to watershed specificity and concerns regarding timber harvest.

A general linear model for each watershed and each year for the relationship between hydrologic indices and watershed area of the following form was used:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \varepsilon_i$$

where

Y_i is the observed hydrologic index in m^3/s in water year *n* for: i=1,2,3,4,5 gaged sites in the SFH watershed and i=1,2,3 sites in the NFH watershed

B_0 is the mean hydrologic index when X1 is 0

β_1 the coefficient associated with the explanatory variables X_1

X_i is the watershed area in m^2 for: i=1,2,3,4,5 gaged sites in the SFH watershed and i=1,2,3 sites in the watershed

ε_i is the random error term for the *ith* gaging site where $\varepsilon_i \sim$ Normal $(0, \sigma^2)$, i=1…3 for SFH and i=1…5 for the NFH

Assumptions

Assessing model assumptions (independence, normality, homoscedasticity) with small datasets (n = 3 and n= 5) is difficult, but visual assessments of plots of the residuals against fitted values and normal qq plots revealed that the mainstem USGS gaging sites may be outliers with high influence. Determination of the legitimacy of this regression method was based on a check of model assumptions and a test for influence and leverage using Cook's distance (Ramsey and Schafer 2002). Cook's distance is used in regression to estimate the influence and leverage that individual data points have on a model.

Watershed Level analysis

Exploratory analyses were conducted to identify correlation between RD and hydrologic indices with 8 years of replication for two contiguous watersheds. Because the HCPWS had only eight years of replication and many responses and explanatory variables, measures of statistical significance are not reported. Regression analysis and significance testing are powerful tools when the sample size is sufficiently large and apt, but the probability of type I error increases as the ratio of sample size/candidate variables decreases (Flack and Chang 1987). This study was interested in testing multiple candidate variables (same year and previous year ***MaxAN***, ***Q10SP***, M***axEM***, ***FreqEM***, ***Q90SM***, and ***Min7FW***) against RD for three age classes, with a sample size of 8 years. Power to detect true relationships was low and the potential to identify spurious relationships was high, so the statistical approach was descriptive.

For all three density metrics (age-0, age-1+, and all trout), linear association between relative density and multiple hydrologic indices in a watershed with timber harvest (SFH) and without timber harvest (NFH) were measured using Pearson's r. A hydrologic index was considered strongly related to relative density if $r \geq |0.70|$. The term 'ecologically relevant' was used to describe a hydrologic index that had a strong correlation with relative density ($r \geq |0.70|$). A hydrologic index was considered weakly related if $|0.50| \leq r$ $|0.70|$ and not related if $r < |0.50|$. No precedence was set for the selection of threshold criteria to determine correlations as strong, weak and not related in the hydro-ecology literature. The $r = |0.70|$ threshold was arbitrarily chosen to capture a strong linear dependency and allow for natural environmental variability. Ecologically relevant hydrologic indices identified in this analysis are not necessarily biologically meaningful, but should be considered candidates for future research. Ecologically relevant indices observed in each watershed (NFH and SFH) were compared across the two watersheds, but not tested for differences.

Prior to analysis, multi-collinearity between hydrologic indices was investigated. Collinearity was considered a problem if $r > |0.70|$. Collinearity was present between ***FreqEM*** and ***MaxEM*** from year *n* in both watersheds ($r = 0.917$ in SFH and $r = 0.769$ in NFH) and ***FreqEM*** and ***Q90SM*** from year *n* in NFH ($r = 0.78$). Collinearity between storm frequency and magnitude in the springtime can be explained by climate factors that yielded wetter springs with a higher frequency of storm events and larger storm magnitudes and drier springs with a lower frequency of storm events and smaller storm magnitudes. Collinearity between spring and summer flow conditions can be explained by the serial dependency of summer flows on springtime flows. Therefore, F***reqEM*** was removed from analysis to avoid redundancy. Collinearity was also found between ***MaxAN*** and ***Q90SM*** from year *n* in the NFH ($r = -0.721$). However, mechanistic explanations for this negative correlation were not readily available and neither index was removed from NFH analyses. Additional collinearity between ***Q90SM*** and ***Q10SP*** in the SFH (r = 0.645) was detected, which suggests a relationship between early spring flow magnitude and summer flow magnitudes in SFH. This correlation was not considered strong enough to warrant removal of either index. Collinearity (r > |0.70|) was not identified in the remaining indices (Table 3-5).

Hydrologic indices evaluated in the age-0 analysis were ***Min7FW***, ***MaxAN***, ***Q10SP***, ***MaxEM***, and ***Q90SM*** from year *n* and ***MaxAN*** and ***Q90SM*** from year *n- 1*. ***Q10SP***, ***MaxEM***, and ***Q90SM*** from year *n* can be directly related to age-0 cohort production or mortality. ***MaxAN*** from year *n* and *n- 1*can be indirectly related to age-0 abundance through effects on habitat factors if flow is sufficiently large to redistribute bed-load and/or sediment. ***Min7FW*** from year *n* and ***Q90SM*** from year *n- 1* can be indirectly related to age-0 abundance through effects on individual age-2+ spawner survival that may not manifest in age1+ abundance estimates. Hydrologic indices evaluated in the age-1+ analysis were ***Min7FW***, ***MaxAN***, and ***Q90SM*** from year *n*. All three indices can be directly related to multiple age classes > 1year of age. Hydrologic indices tested in the age-0 and age-1+ analysis were evaluated in the all trout analysis: ***Min7FW***, ***MaxAN***, ***Q10SP***, ***MaxEM***, and ***Q90SM*** from year *n* and ***MaxAN*** and ***Q90SM*** from year *n- 1*.

Assumptions

The calculation of Pearson's r requires few assumptions. For each correlation tested between relative density and a hydrologic index, scatterplots of the variables were used to determine that the association between variables was approximately linear and that no data-points were extreme outliers (all 8 data-points fit the general trend of the data).

Table 3-5 Correlation between hydrologic indices in NFH and SFH. Bold and underlined values indicate collinearity.

NFH						
	MaxAN	Q90SM	Q10SP	Min7FW	MaxEM	FreqEM
MaxAN	1	**<u>-0.721</u>**	-0.198	-0.026	-0.399	-0.581
Q90SM		1	-0.095	0.138	0.527	**<u>0.780</u>**
Q10SP			1	-0.109	-0.444	0.012
Min7FW				1	0.248	0.058
MaxEM					1	**<u>0.769</u>**
FreqEM						1
SFH						
	MaxAN	Q90SM	Q10SP	Min7FW	MaxEM	FreqEM
MaxAN	1	-0.277	-0.153	-0.193	-0.119	-0.307
Q90SM		1.000	**<u>0.645</u>**	0.400	0.484	0.388
Q10SP			1	0.327	-0.306	-0.281
Min7FW				1	-0.141	-0.380
MaxEM					1	**<u>0.917</u>**
FreqEM						1

Stock-recruitment & Cohort Strength

The inter-annual variability of relative trout density may be partially driven by the persistence of cohorts or individuals (hereafter, cohort strength) or the size of the parental stock within a population (hereafter, stock-recruitment). Stock-recruitment and cohort strength were difficult to measure in this study without comprehensive age-class data, but estimates of age-0 cohort persistence, age-1+ cohort persistence, and stock-recruitment were developed. This was only investigated at the watershed level using observations from the 8 years. The Pearson product moment correlation coefficient (hereafter, Pearson's r) was calculated as a measure of linear dependence between:

- age-0 RD in year *n-1* and age-1+ RD in year *n* (proxy for age-0 cohort persistence),
- age-1+ RD in year *n -1* and age-0 RD in year *n* (proxy for stock-recruitment), and
- age-1+ RD in year *n-1* and age-1+ RD in year *n* (proxy for age-1 cohort persistence).

The calculation of Pearson's r requires few assumptions. For each correlation tested (age-0 cohort persistence, stock-recruitment, and age-1+ cohort persistence), scatterplots of the density variables were used to determine that the association between variables was approximately linear and that no data-points were extreme outliers (all 8 data-points fit the general trend of the data).

Stream Segment Level analysis

The purpose of the segment level analysis was to assess and understand the roles of 1) spatial scale and 2) network location on relationships between relative density and hydrologic indices. Based on results from the watershed analysis, relationships investigated at the stream segment level were restricted to ***age-0*** and ***age-1+*** trout. Segment-level analyses built on results from the watershed analysis and tested the same specific combination of hydrologic indices and the relative density of ***age-0*** and ***age-1+*** trout that were previously identified. Pearson's r was calculated as a measure of linear association between relative density of a given age class and hydrologic indices over 8 years in seven stream segments in SFH and six stream segments in NFH. The focus of the stream segment-level analysis was intra-basin comparisons, so relationships within SFH and NFH were assessed independently. The term location refers to a stream segment or watershed. Correlations across scales and stream segments were evaluated for three criteria: consistency, similarity, and network similarity (see definitions below).

Consistency

Consistency was used to determine if the detection of density-discharge relationships was dependent on 1) the scale of observation or 2) location within the stream network.

Consistency measured synchrony in correlation coefficients across all sites in relation to the strong correlation threshold of |0.70| (for a given hydrologic index and age class). For a given hydrologic index and age class, if $r \geq |0.70|$ or $r < |0.70|$ across all sites, relationships with that index were consistent. If $r \geq |0.70|$ and $r < |0.70|$ across all sites, relationships with that index were not consistent. The number of stream segments differed between the two watersheds (6 stream segments in NFH and 7 stream segments in SFH) which affected the probability of consistency. Differences in the probability of consistency were not accounted for due to the exploratory nature of the analysis.

Similarity & network similarity

Similarity and network similarity were used to determine how variable relationships were by location within the stream network. Similarity was used to determine if the strength of the correlation across stream segments was similar by measuring synchrony in correlation coefficients (for a given hydrologic index and age class) between pairs of individual segments in relation to the weak correlation threshold of ± 0.50. Unlike consistency which focused on synchrony across all locations, similarity addresses synchrony between individual segments. For two segments of interest, seg_{ref} and seg_{other}, where

$$\left| r_{seg_{ref}} \right| \geq 0.50 \text{ and } \left| r_{seg_{other}} \right| \geq 0.50,$$

seg_{ref} and $\text{seg}_{\text{other}}$ were considered similar. In this analysis, the emphasis was placed in measuring similarity across stream segments for hydrologic indices that were ecologically relevant at the watershed level. To assess similarity for indices previously identified as ecologically relevant in either watershed, $\text{seg}_{\text{other}}$, was considered similar to the watershed (seg_{ref}) if $\left| \text{r}_{\text{seg}_{\text{other}}} \right| \geq 0.50$. Similarity was also assessed for indices that were previously identified as weakly related in a watershed. For this assessment, $\text{seg}_{\text{other}}$, was considered similar to the watershed (seg_{ref}) if $\left| \text{r}_{\text{seg}_{\text{other}}} \right| \geq 0.50$. Finally, similarity for indices that had a strong correlation in at least one stream segment that were not previously identified as related in a watershed was assessed. For this assessment, seg_{ref} is a given segment and $\left| \text{r}_{\text{seg}_{\text{ref}}} \right| \geq 0.70$. Any given segment, $\text{seg}_{\text{other}}$, was considered similar to the watershed if $\left| \text{r}_{\text{seg}_{\text{other}}} \right| \geq 0.50$.

Network similarity was used to identify hydrologic indices with a narrow range of correlation values across all segments. If the variability in Pearson's r across the segments was less than or equal to 0.40 ($\text{r}_{\text{max-min}} \leq 0.40$), those correlation relationships were deemed to have network similarity. On the other hand, if the variability in Pearson's r across segments was greater than 0.40 ($\text{r}_{\text{max-min}} \geq 0.40$), those correlations did not have network similarity. The arbitrary value of 0.40 was selected *a priori* to allow for natural environmental variability and depict a narrow range of variability across segments. Model assumptions were assessed in the same manner as the density dependence and watershed analysis and were considered satisfactory.

CHAPTER 4- RESULTS

SPATIAL INCONGRUENCE

Linear regression models were developed to predict the values of hydrologic indices for non-gaged locations using the values of the hydrologic indices for the gaged locations and prorated by watershed area for each year. Based on Cook's distance, the values of the hydrologic indices for the gaging stations at NFHC and SFHC (lower sites) had high influence and leverage on the models compared to the values of the hydrologic indices for the gaging stations located on smaller, non-fish-bearing streams (upper sites) (Figure 3-1; Table 4-1). The Cook's distance value for NFHC and SFHC exceeded the Cook's distance value for the non-fish-bearing locations by at least an order of magnitude, in most models. In both watersheds, plots show strong synchrony in temporal trends between hydrologic indices for NFHC and SFHC and hydrologic indices for non-gaged sites (Figures 4-1 through 4-3). However, these plots show only moderate synchrony between hydrologic indices for the non-fish-bearing stream gaging sites and hydrologic indices for the non-gaged locations (Figures 4-1 through 4-3). Discharge measured at NFHC and SFHC was preferred over modeled discharge in the stream segment level analysis because the values of hydrologic indices from NFHC and SFHC had strong influence on the predicted values of hydrologic indices at non-gaged sites. Appendix A contains regression equations, coefficients of determination (r^2), and plots of indices vs. drainage area for all 48 linear models.

Table 4-1 Cook's distance values for NFH, SFH, and non-fish-bearing stream gaging sites in 48 linear models. Regression models were developed separately for maximum annual flow (***MaxAN***), maximum emergence flow (***MaxEM)***, and Q10 spawning flow (***Q10SP***) for each study watershed (NFH and SFH) and year (2004–2011).

	SFH					NFH		
Year	**SFHC**	**BBE**	**CLA**	**FEN**	**RUS**	**NFHC**	**DEM**	**MEY**
	maximum annual flow							
2004	223	0.428	0.034	0.174	0.007	99.1	0.413	0.617
2005	136	0.409	0.185	0.028	0.004	99.1	0.413	0.617
2006	2.01	0.032	0.484	0.177	0.011	99.1	0.413	0.617
2007	0.721	0.287	0.061	0.040	0.235	99.1	0.413	0.617
2008	12.5	0.348	0.075	0.011	0.181	99.1	0.413	0.617
2009	134	0.441	0.122	0.037	0.020	99.1	0.413	0.617
2010	6.08	0.048	0.446	0.214	0.000	99.1	0.413	0.617
2011	26.2	0.357	0.169	0.010	0.087	99.1	0.413	0.617
	maximum emergence flow							
2004	18.7	0.356	0.015	0.000	0.235	99.1	0.413	0.617
2005	222	0.386	0.136	0.116	0.003	99.1	0.413	0.617
2006	51.2	0.391	0.168	0.000	0.059	99.1	0.413	0.617
2007	6.42	0.008	0.410	0.146	0.128	99.1	0.413	0.617
2008	302	0.255	0.092	0.255	0.071	99.1	0.413	0.617
2009	83.7	-	0.338	0.001	0.356	99.1	0.413	0.617
2010	0.187	0.252	0.089	0.074	0.219	99.1	0.413	0.617
2011	120	0.453	0.040	0.054	0.069	99.1	0.413	0.617

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Figure 4-1 continued

SFH						NFH		
Year	**SFH**	**BBE**	**CLA**	**FEN**	**RUS**	**NFH**	**DEM**	**MEY**
	Q10 spawning flow							
2004	117	0.312	0.037	0.185	0.118	99.1	0.413	0.617
2005	303	0.307	0.063	0.268	0.032	99.1	0.413	0.617
2006	9.34	0.287	0.241	0.046	0.067	99.1	0.413	0.617
2007	195	0.355	0.007	0.260	0.040	99.1	0.413	0.617
2008	233	0.391	0.112	0.137	0.003	99.1	0.413	0.617
2009	261	-	0.110	0.141	0.453	99.1	0.413	0.617
2010	3.79	0.313	0.046	0.020	0.237	99.1	0.413	0.617
2011	135	0.453	0.078	0.051	0.037	99.1	0.413	0.617

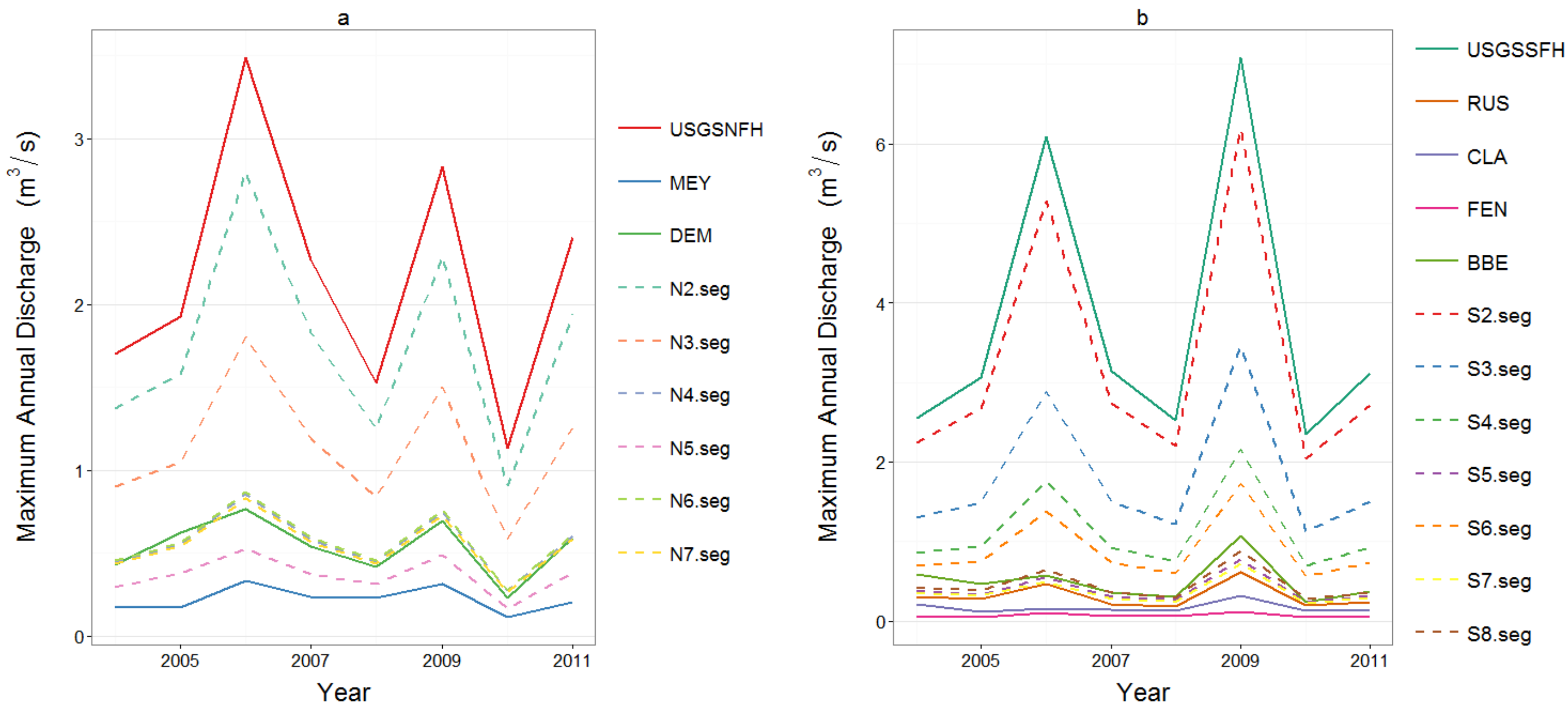


Figure 4-1 Measured (solid lines) and predicted (dotted lines) values of maximum annual discharge (***MaxAN***) plotted by year at gaged and non-gaged locations in a) NFH and b) SFH. Plots show strong synchrony between predicted values of ***MaxAN*** at non-gaged locations and measured values of ***MaxAN*** at NFH and SFH gaging locations. Plots show moderate synchrony between predicted values of ***MaxAN*** at non-gaged locations and measured values of ***MaxAN*** at gaging locations for non-fish-bearing streams. See Figure 3-1 for segment and gaging site locations within the study area.

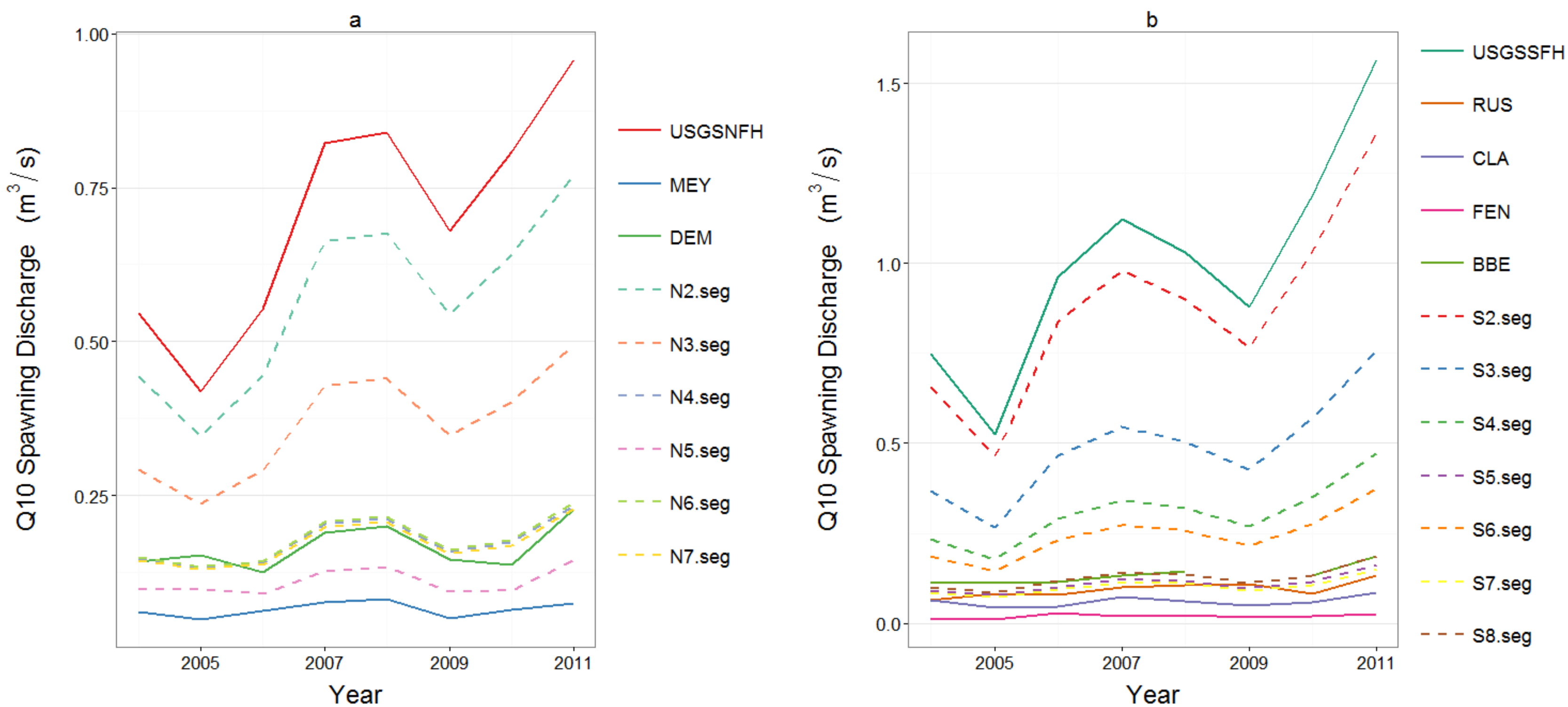


Figure 4-2 Measured (solid lines) and predicted (dotted lines) values of Q10 spawning discharge (***Q10SP***) plotted by year at gaged and non-gaged locations in a) NFH and b) SFH. Plots show strong synchrony between values of ***Q10SP*** predicted for non-gaged locations and measured values of ***Q10SP*** at NFH and SFH gaging locations. Plots show moderate synchrony between values of ***Q10SP*** predicted for non-gaged locations and values of ***Q10SP*** measured at gaging locations on non-fish-bearing streams. See Figure 3-1 for segment and gaging site locations within the study area.

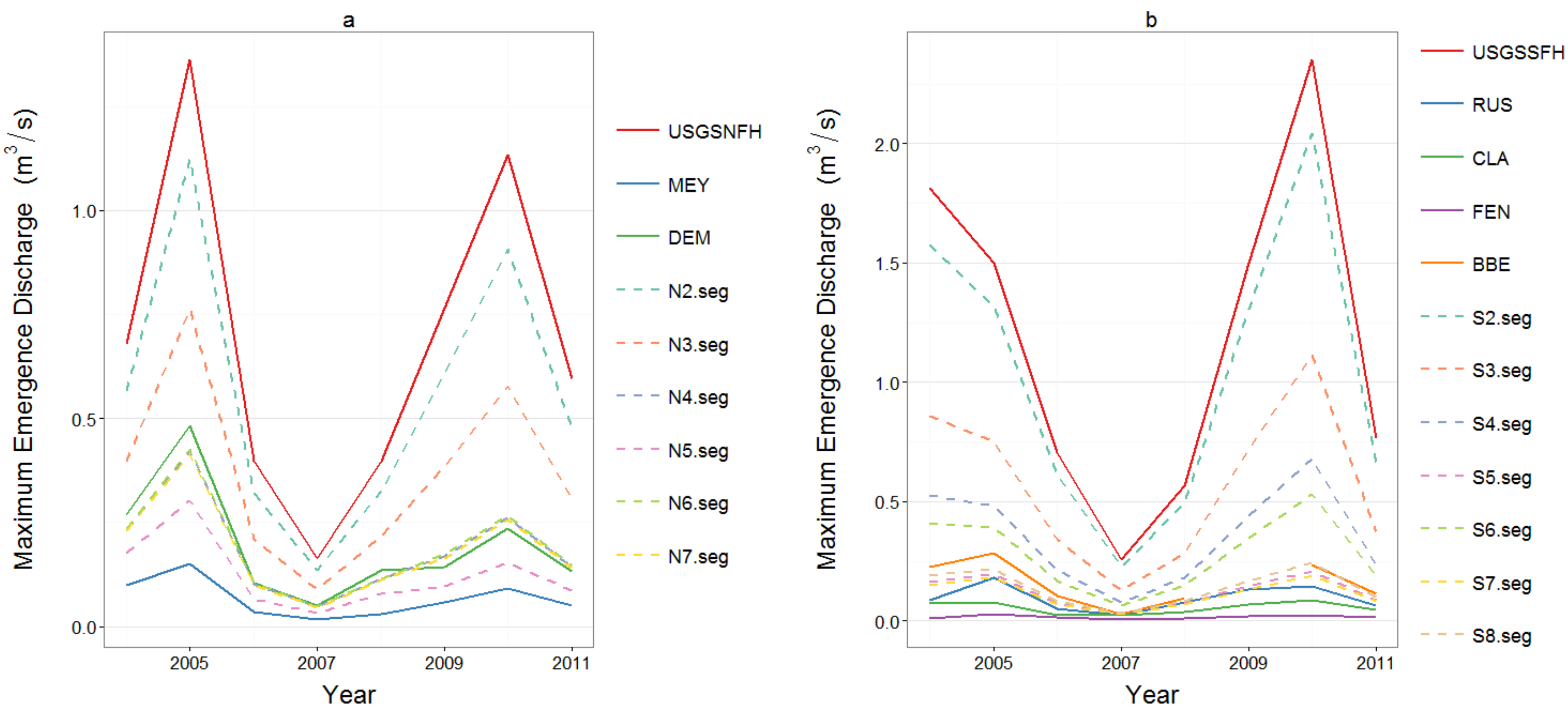


Figure 4-3 Measured (solid lines) and predicted (dotted lines) values of maximum emergence discharge (***MaxEM***) plotted by year at gaged and non-gaged locations in a) NFH and b) SFH. Plots show strong synchrony between values of ***MaxEM*** predicted for non-gaged locations and values of ***MaxEM*** measured at NFH and SFH. Plots show moderate synchrony between values of ***MaxEM*** predicted for non-gaged locations and values of ***MaxEM***

measured at gaging location for the non-fish-bearing streams. See Figure 3-1 for segment and gaging site locations within the study area.

WATERSHED SCALE ANALYSIS

Age-0 trout

Analysis of age-0 trout yielded one ecologically relevant variable (r ≥ |0.70|) in each watershed. In NFH, there was a strong positive correlation between ***age-0 RD*** and ***MaxAN*** (r = 0.780). There was not a similar relationship in SFH (r = 0.217; Table 4-2 & Figure 4-4). ***Age-0 RD*** was positively correlated with ***Q90SM*** for the current year in SFH (r = 0.697). This relationship was weak and negative in NFH (r = -0.549; Table 4-2 & Figure 4-4). The correlation coefficient for SFH, r = 0.697, was sufficiently close to r ≥ 0.70 to be considered ecologically relevant. The correlation between ***age-0 RD*** and ***Q10SP*** for the current year in SFH was weak and positive (r = 0.584; Table 4-2 & Figure 4-4). There was no correlation between ***age-0 RD*** and the remaining four indices tested in the two watersheds (Table 4-2).

Age-1+trout

No correlations were identified between ***age-1+ RD*** and the three indices tested in either watershed (Table 4-2).

All trout

Correlations identified for the ***all trout*** analysis were the same as the correlations identified in the ***age-0*** analysis. There was a strong, positive correlation between ***all trout RD*** and ***MaxAN*** for the current year in NFH (r = 0.710, compared to r = 0.780 for ***age-0 RD***). There was a weak, negative correlation between ***all trout RD*** and

Q90SM for the same year in NFH (r = -0.631 compared to r = -0.549 for ***age-0 RD***; Table 4.3). There were no ecologically relevant relationships between hydrologic indices and relative density of trout in SFH. The hydrologic index with the highest correlation was ***Q90SM*** for the same year (r = 0.637, compared to r = 0.697 for ***age-0 RD***) A weak correlation was identified between ***all trout RD*** and ***Q10SP*** for the same year (r =0.618, compared to r = 0.584 for ***age-0 RD***; Table 4.3). There was no correlation between ***all trout RD*** and the remaining four indices tested (Table 4.3).

Table 4-2 A summary of correlation coefficients for the watershed scale analysis. Pearson's correlation coefficients were calculated at the watershed scale for relative density of ***age-0***, ***age-1+,*** and ***all trout*** and up to 10 hydrologic indices. Bold and underline values indicate strong correlation. Bold and italicized values indicate weak correlation.

		RD age-0		RD age-1+		RD all	
Hydrologic Index	**Year**	**NFH**	**SFH**	**NFH**	**SFH**	**NFH**	**SFH**
MaxAN	*n*	**<u>0.780</u>**	0.217	-0.208	-0.095	**<u>0.710</u>**	0.129
Q10SP	*n*	-0.471	***0.541***	**-**	-	-0.285	***0.618***
MaxEM	*n*	-0.117	0.383	-	-	-0.130	0.137
Q90SM	*n*	***-0.549***	**<u>0.697</u>**	-0.272	0.205	***-0.631***	***0.637***
Min7FW	*n*	0.128	-0.059	-0.199	0.232	0.065	0.055
MaxAN	*n-1*	-0.207	0.442	-	-	-0.193	0.312
Q90SM	*n-1*	0.187	0.286	-	-	0.015	0.203

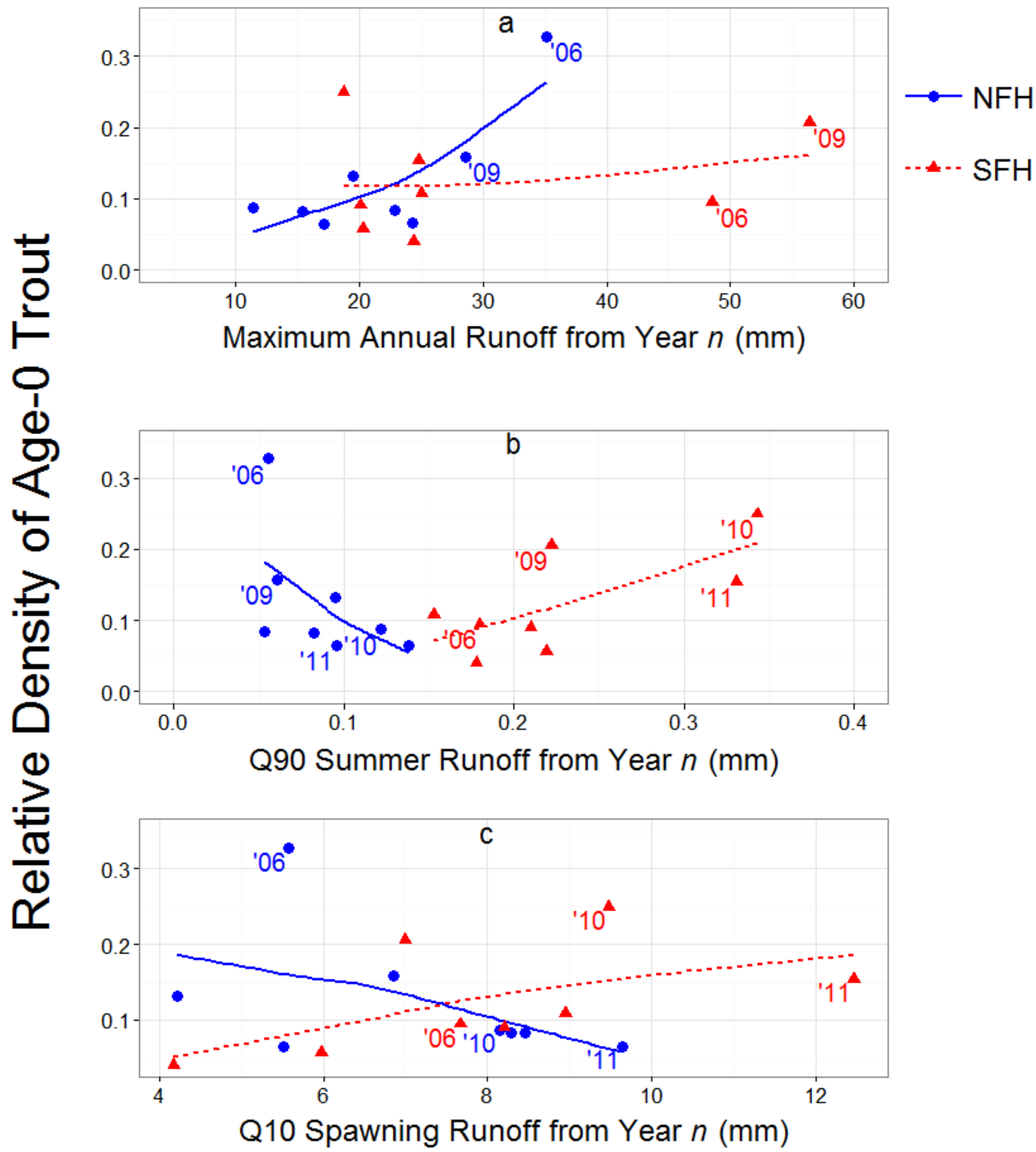


Figure 4-4 Comparisons across NFH and SFH between age-0 relative density and related indices a) ***MaxAN***, b) ***Q90SM***, and c) ***Q10SP*** **(**same year for all three indices). Solid and dashed lines indicate nonparametric smoothing lines to show trends in NFH and SFH, respectively. Labels that denote years indicate potential influence points and contrasting patterns between NFH and SFH. Indices have strong relationships in a) NFH (r = 0.780) b) SFH (r = 0.697) and weak relationships in b) NFH (r = -0.549) and c) SFH (r = 0.541) Note: relative density is a unitless metric.

STOCK-RECRUITMENT & COHORT STRENGTH

Estimates of stock recruitment and cohort strength were analyzed with correlation analysis to determine if cohort persistence or stock-recruitment contributes to inter-annual variability in density. There was a strong positive correlation between the ***age-1+ RD*** and the previous year ***age-0 RD*** in SFH (r = 0.768) but not NFH (r = -0.299). There was a weak positive correlation between age***-1+ RD*** and the previous year ***age-1+ RD*** in NFH (r = 0.660). No correlation was observed between age***-0 RD*** and previous year ***age-1+ RD*** or age***-0 RD*** and same year ***age-1+ RD*** (Table 4-3).

Table 4-3 Correlation coefficients for stock-recruitment and cohort strength at the watershed level. Relative density on the left side of all four comparisons is from the same year. Bold and underlined values signify strong correlation ($r \geq 0.70$). Bold and italicized values signify weak correlation ($|0.50| \leq r \leq |0.70|$)

Relative Density Comparisons	**NFH**	**SFH**
age-1+ RD and previous year age-0 RD (age-0 cohort persistence)	-0.299	**<u>0.768</u>**
age-0 RD and previous year age-1+ RD (stock-recruitment)	-0.176	0.317
age-1+ RD and previous year age-1+ RD (age-1+ cohort persistence)	***0.660***	0.390

STREAM SEGMENT LEVEL ANALYSIS

Consistency

This analysis used consistency to determine if the detection of density-discharge relationships was dependent on 1) the extent of observation or 2) location within the stream network. The primary difference between the two analyses was the removal of the watershed level observation when looking for the effect of location within the stream network. The focus of this analysis was on the detection of an 'ecologically relevant' relationship where $r \geq |0.70|$. Consistency was used to determine if 1) both scales (watershed and stream segments) and 2) all locations within the network (individual stream segments) shared the same strength of relationship (strong or non-existent) (see *Chapter-3 Methods* for the definition of consistency).

Assessing the role of spatial scale

There were no strong correlations between ***age-1+ RD*** and all of the hydrologic indices over eight years in either watershed or in any stream segment (Tables 4-6 & 4-7; Figures 4-8 & 4-9). Thus, the effect of the hydrologic indices was consistent at both scales. Similarly, most hydrologic indices did not have strong relationships with ***age-0 RD (***Tables 4-4 & 4-5). The effect of those indices was also consistent at both scales. However, indices with strong correlation measured at the extent of a watershed (***Q90SM*** in SFH and ***MaxAN*** in NFH) did not have strong correlation at all stream segments. Thus, the effect of these ecologically relevant indices was not consistent at both scales (Tables 4-4 & 4-5; Figures 4-6 & 4-7). An index with a weak correlation with age-0 RD measured at the extent of a watershed in SFH (***Q10SP)*** had strong correlation when measured in individual stream segments. Indices with no correlation at the watershed level (***Q90SM*** from previous year in SFH and ***Q10SP*** from same year in NFH) identified strong correlation when measured in individual stream segments. These results indicate that the detection of ecological relevance varied by the extent of observation for multiple indices.

Assessing the role of network location

Results did not change when the watershed level observation was removed from the comparison. There were no strong correlations between ***age-1+ RD*** and all of the hydrologic indices in any stream segment (Tables 4-6 & 4-7). Most hydrologic indices did not have strong correlations with ***age-0 RD***. The effect of ecologically relevant indices at the watershed scale (***Q90SM*** in SFH and ***MaxAN*** in NFH) was not consistent across stream egments (Tables 4-4 & 4-5). The effect of additional indices (***Q10SP*** in SFH, ***Q90SM*** from previous year in SFH, and ***Q10SP*** in NFH), were not consistent across stream segments. These results indicate that the detection of ecological relevance varied by location within the stream network for multiple indices.

Similarity & Network Similarity

Similarity and network similarity were used to evaluate agreement in correlation values among individual stream segments (see *Chapter-3 Methods* for definitions of similarity and network similarity). Similarity was used to determine if individual stream segments had correlations of similar strength, with emphasis on relationships with weak or strong correlation. Network similarity was used to identify hydrologic indices with a narrow range of correlation values across all stream segments. Similarity was not determined for weak relationships for ***age-1+ trout*** because no strong or weak correlations were identified in the watershed (Tables 4-5 & 4-6).

Similarity

While hydrologic indices that were identified as ecologically relevant to ***age-0 RD*** at the watershed scale (***Q90SM*** in SFH and ***MaxAN*** in NFH) had no consistency, the strength of the relationship was similar across all locations (stream segments and watershed) for both indices. For this assessment, seg_{ref} was the watershed where $r_{\text{seg}_{\text{ref}}} \geq |0.70|$, and any given stream segment was similar if $\text{seg}_{\text{other}} \geq |0.50|$. The relationship between ***age-0 RD*** and ***MaxAN*** was similar for all six stream segments in NFH (Table 4-4 & Figure 4-5). The relationship between ***age-0 RD*** and ***Q90SM*** was similar for all stream segments except SM4 (r = 0.409) and ST2 (r = 0.390) (Table 4-5 and Figure 4-6). These results indicate that similarity for ecologically relevant indices was common.

Similarity occurred less frequently for hydrologic indices that were previously identified with a weak correlation with ***age-0 RD*** (***Q10SP*** in SFH and ***Q90SM*** in NFH) at the watershed level. For this assessment, seg_{ref} was the watershed where

|0.50| ≤ $r_{seg_{ref}}$ ≤ |0.70|, and any given stream segment was similar if $\boldsymbol{seg_{other}}$ ≥ |***0.50***|. In NFH, the relationship between ***age-0 RD*** and ***Q90SM*** was similar in NM34 (r = -0.650; Table 4-4 & Figure 4-5). In SFH, the relationship between ***age-0 RD*** and ***Q10SP*** was similar in SM3 (r = 0.602), SM4 (r = 0.815), ST1 (r = 0.790), and ST3 (r = 0.792; Table 4-5 & Figure 4-6).

Hydrologic indices that had a strong correlation in at least one stream segment that were not previously identified as weakly or strongly related to ***age-0 RD*** in a watershed showed less similarity. For this assessment, seg_{ref} is a given stream segment where $r_{seg_{ref}}$ ≥ |0.70|, and any given stream segment was similar if $\boldsymbol{seg_{other}}$ ≥ |0.50|. ***Age-0 RD*** was negatively correlated with ***Q10SP*** for the current year in NFH in NT2 (r = -0.815). This relationship was similar in NM2 (r = 0.-667; Table 4-4 and Figure 4-5). ***Age-0 RD*** was positively correlated with ***Q90SM*** from previous year in SFH in ST1 (r = 0.737) and ST3 (r = 0.732). This relationship was similar in SM4 (r = 0.525 Table 4-5 and Figure 4-6). These results indicate the similarity for these indices occurred infrequently.

Multiple hydrologic indices not previously identified with weak or strong correlations at the watershed scale had weak correlations with ***age-0 RD*** ($r_{seg_{ref}}$ ≥ |0.50|) in at least one stream segment (Tables 4-4 & 4-5).

Table 4-4 A summary of correlation coefficients (Pearson's r) for ***Age-0 RD*** and seven hydrologic indices in NFH. Bold and underlined values indicate ecologically relevant correlations where r ≥ |0.70|. Bold and italicized values indicate weak correlations where |0.50| ≤ r ≤ |0.70|. For a given hydrologic index, *Range* indicates $r_{max} - r_{min}$ across the seven hydrolocic indices. Values of Range with underlined values indicate network similarity. See Figure 3-1 for segment locations within the study area.

Age-0 Relative Density									
Hydrologic Index	**Year**	**NFH**	**NM1**	**NM2**	**NM34**	**NT1**	**NT2**	**NT3**	**Range**
MaxAN	*n*	**0.780**	***0.598***	***0.648***	**0.837**	**0.767**	***0.544***	***0.656***	0.544 – 0.837
Q90SM	*n*	***-0.549***	-0.363	-0.488	***-0.650***	-0.462	-0.297	-0.380	-0.650 – -0.297
Q10SP	*n*	-0.471	-0.498	***-0.667***	-0.283	-0.413	**-0.815**	-0.385	-0.815 – -0.283
MaxAN	*n-1*	-0.207	-0.133	-0.356	-0.093	-0.199	***-0.505***	-0.306	-0.505 – -0.093
Q90SM	*n-1*	0.187	0.130	0.406	0.064	0.208	***0.687***	0.293	0.064 – 0.687
MaxEM	*n*	-0.117	-0.013	0.222	-0.364	-0.313	0.363	-0.183	-0.364 – 0.363
Min7FW	*n*	0.128	0.208	0.197	0.082	0.278	0.253	0.487	0.082 – 0.487

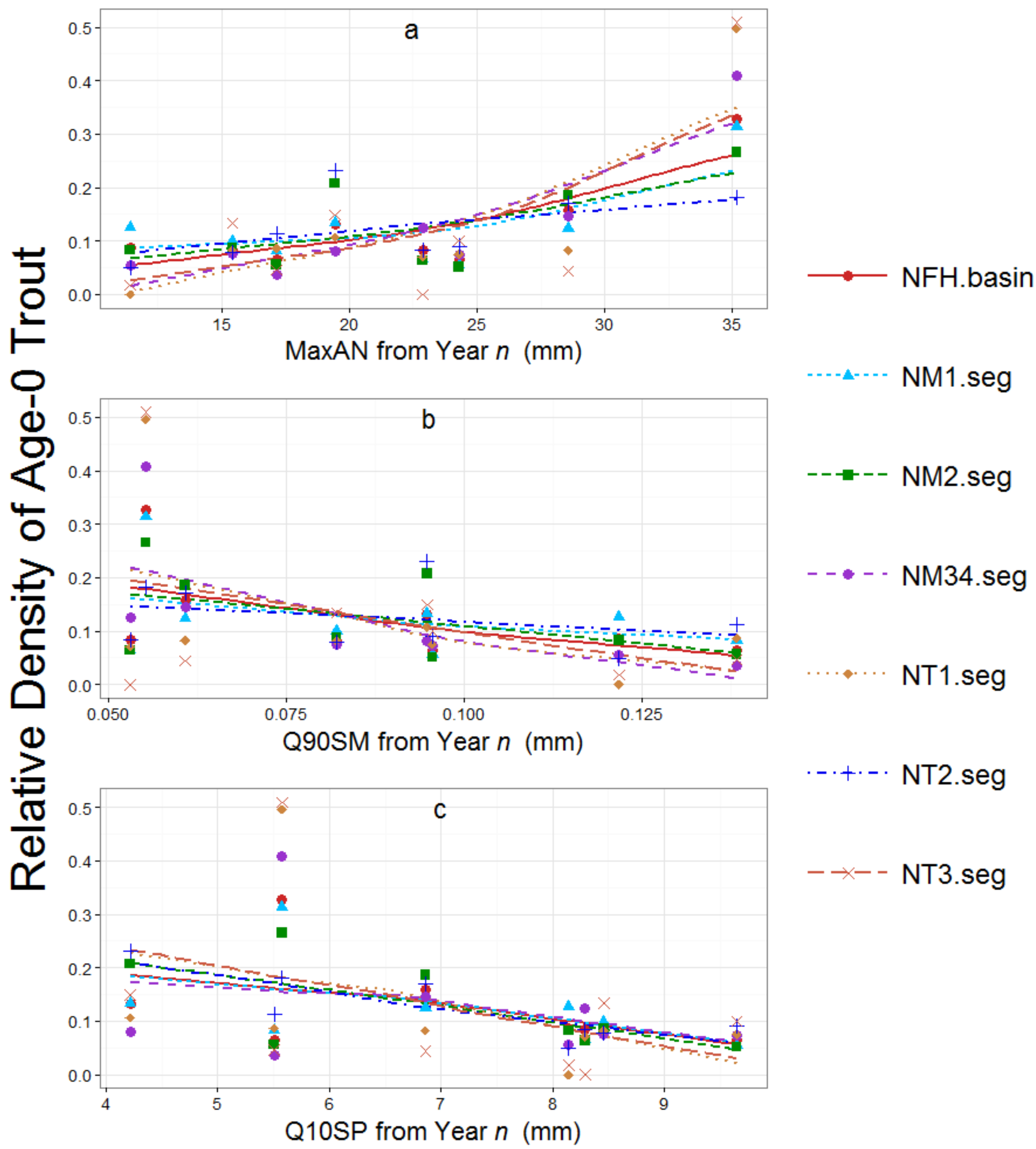


Figure 4-5 Relationships between ***Age-0 RD*** and ecologically relevant hydrologic indices at seven locations in NFH that includes : a) ***MaxAN***, b) ***Q90SM***, and c) ***Q10SP*** (same year for all three indices). Solid and dashed lines indicate nonparametric smoothing trends for the associated site (see legend). In plot a) r ≥ |0.70| in NFH, NM34 and NT1; in plot b) r ≥ |0.50| in NFH and NM34; in plot c) r ≥ |0.70| in NT2. See appendix B for plots of the four additional indices.

Table 4-5 A summary of correlation coefficients (Pearson's r) for ***Age-0 RD*** and seven hydrologic indices in SFH. Bold and underlined values indicate ecologically relevant correlations where $r \geq |0.697|$. Bold and italicized values indicate weak correlations where $|0.50| \leq r \leq |0.70|$. For a given hydrologic index, *Range* indicates $r_{max} - r_{min}$ across the seven hydrologic indices. See Figure 3-1 for segment locations within the study area.

Age-0 Relative Density										
Hydrologic Index	**Year**	**SFH watershed**	**SM1**	**SM2**	**SM3**	**SM4**	**ST1**	**ST2**	**ST3**	**Range**
Q90SM	*n*	**0.697**	***0.503***	***0.674***	***0.544***	0.409	***0.705***	0.390	***0.827***	0.390 – 0.827
Q10SP	*n*	***0.541***	0.206	0.378	***0.602***	**0.815**	**0.790**	0.221	**0.792**	0.206 – 0.815
Q90SM	*n-1*	0.286	-0.085	0.105	0.399	***0.525***	**0.737**	0.421	**0.732**	-0.085 – 0.737
Min7FW	*n*	-0.059	-0.300	-0.049	0.059	-0.027	***0.581***	0.061	0.499	-0.300 – 0.581
MaxAN	*n-1*	0.442	***0.678***	0.407	-0.035	0.294	-0.304	-0.216	0.339	-0.304 – 0.678
MaxEM	*n*	0.383	***0.573***	0.489	0.035	-0.260	-0.147	0.278	0.146	-0.260 – 0.573
MaxAN	*n*	0.217	0.104	0.156	0.411	-0.022	0.026	***0.678***	-0.302	-0.302– 0.678

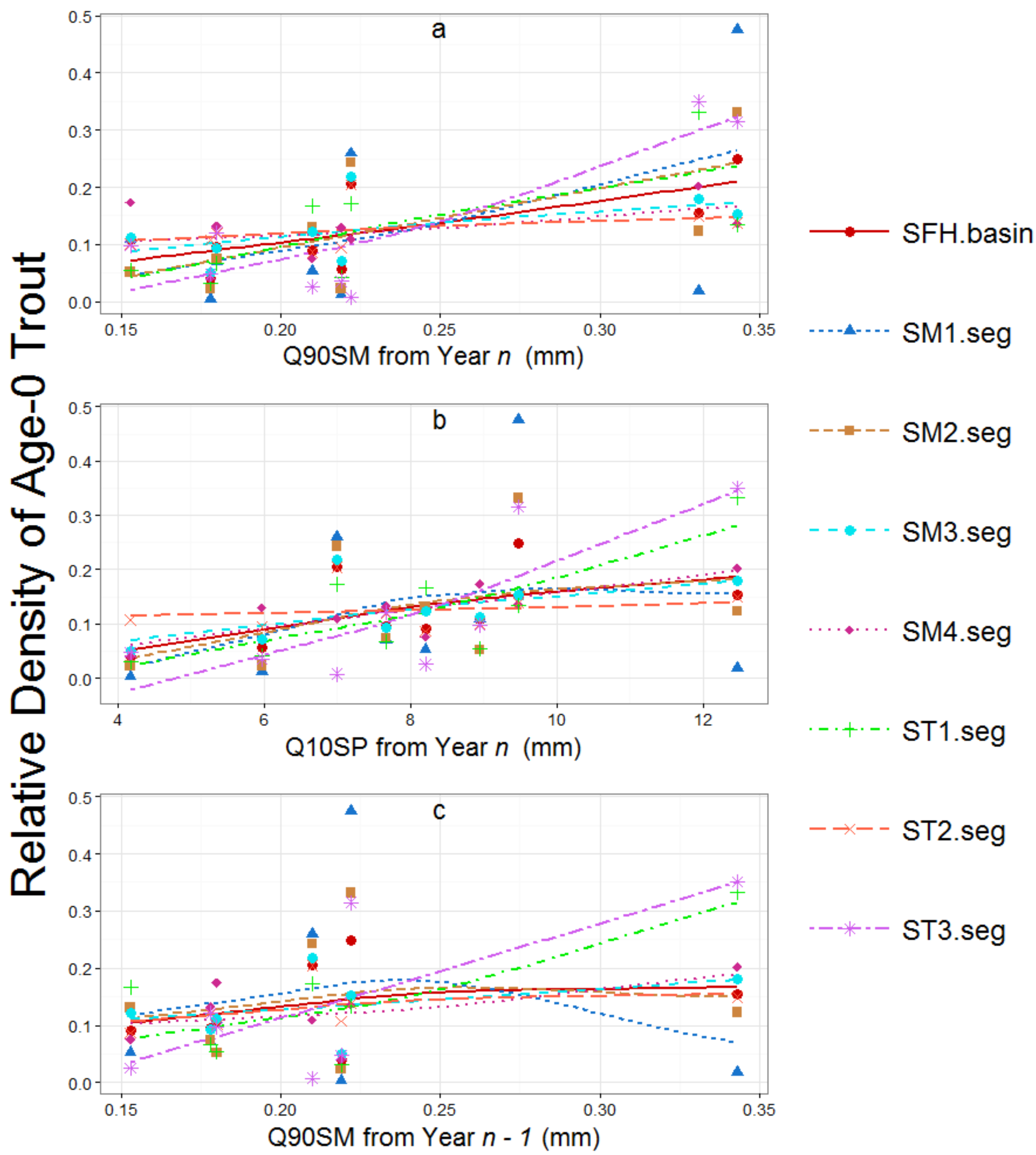


Figure 4-6 Relationships between ***Age-0 RD*** and ecologically relevant hydrologic indices at eight locations in SFH that includes : a) ***Q90SM***, b) (***Q10SP***) (same year for both indices), and c) the ***Q90SM*** from previous year. Solid and dashed lines indicate nonparametric smoothing trends for the associated location. In plot a) $r \geq |0.697|$ in SFH, ST1, and ST3; in plot b) $r \geq |0.70|$ in SM4, ST1, and ST3; and in plot c) $r \geq |0.70|$ in ST1 and ST3. See appendix B for plots of the four additional indices.

Table 4-6 A summary of correlation coefficients (Pearson's r) for ***Age-1+ RD*** and four hydrologic indices in NFH. Bold and italicized values indicate weak correlations where |0.50| ≤ r ≤ |0.70|. For a given hydrologic index, *Range* indicates $r_{max} – r_{min}$ across the seven units. See Figure 3-1 for segment locations within the study area.

Age-1+ Relative Density									
Hydrologic Index	**Year**	**NFH watershed**	**NM1**	**NM2**	**NM34**	**NT1**	**NT2**	**NT3**	**Range**
Min7FW	*n*	-0.199	0.068	0.400	-0.407	0.164	-0.202	0.031	-0.407 – 0.400
Q90SM	*n*	-0.272	-0.219	-0.495	-0.101	-0.003	-0.262	-0.337	-0.495 – -0.003
MaxAN	*n*	-0.208	-0.170	0.072	-0.344	-0.386	-0.079	0.432	-0.386 – 0.432

Table 4-7 A summary of correlation coefficients (Pearson's r) for ***Age-1+ RD*** and four hydrologic indices in SFH. Bold and italicized values indicate weak correlations where |0.50| ≤ r ≤ |0.70|. For a given hydrologic index, *Range* indicates $r_{max} – r_{min}$ across the eight locations. See Figure 3-1 for segment locations within the study area.

Age-1+ Relative Density										
Hydrologic Index	**Year**	**SFH watershed**	**SM1**	**SM2**	**SM3**	**SM4**	**ST1**	**ST2**	**ST3**	**Range**
Min7FW	*n*	0.232	-0.053	-0.183	0.216	0.431	0.159	0.089	0.412	-0.183 – 0.431
Q90SM	*n*	0.205	0.171	-0.282	0.013	0.374	0.254	0.255	0.123	-0.282 – 0.374
MaxAN	*n*	-0.095	-0.063	-0.036	-0.355	-0.117	0.275	0.204	-0.285	-0.355 – 0.275

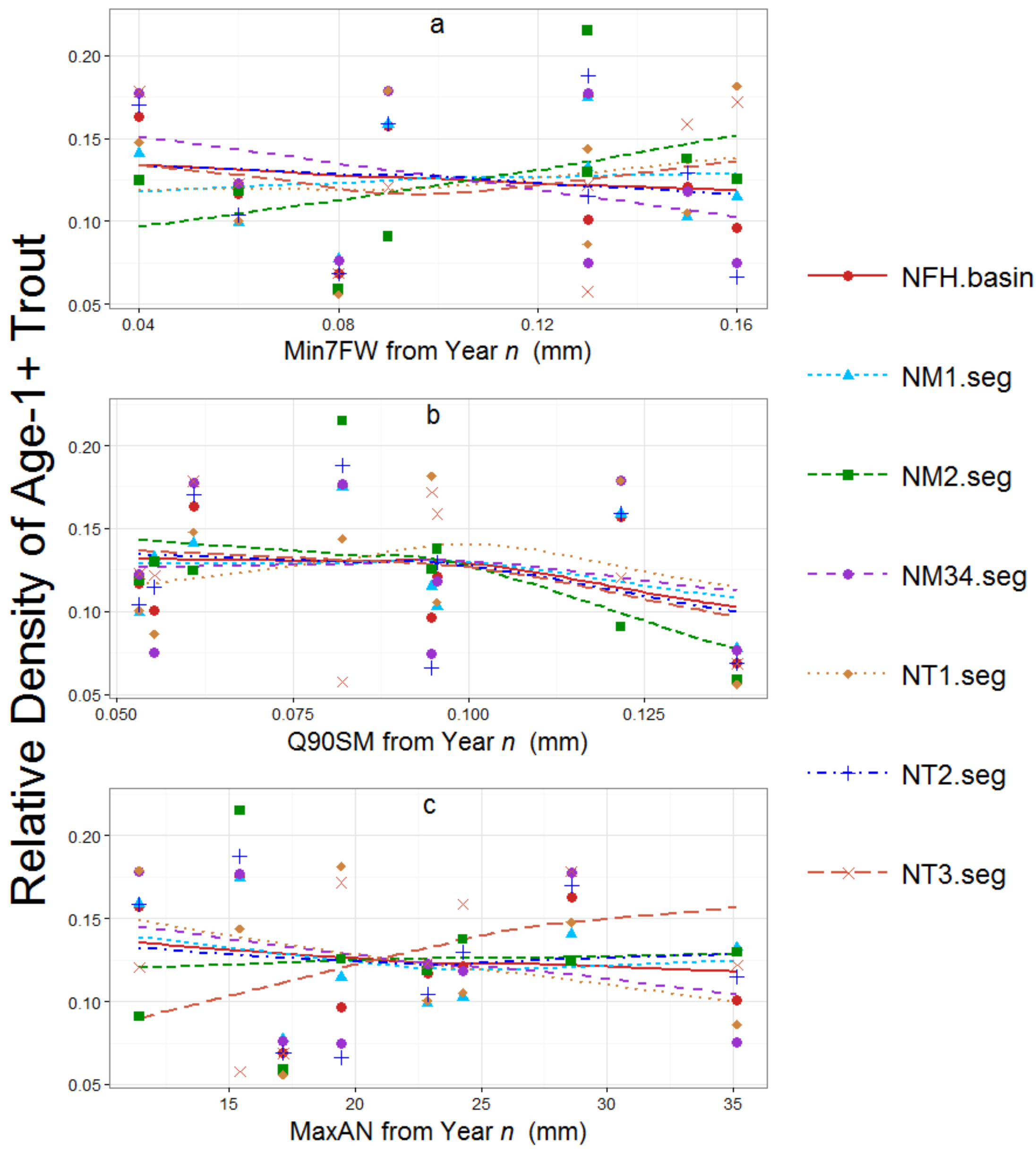


Figure 4-8 Relationships between ***Age-1+ RD*** and unrelated hydrologic indices at seven locations in NFH that includes : a) ***Min7FW***, b) ***Q90SM*** and c) ***MaxAN*** (same year for all three indices). All indices are from the current year. Solid and dashed lines indicate nonparametric smoothing trends for the associated location (see legend).

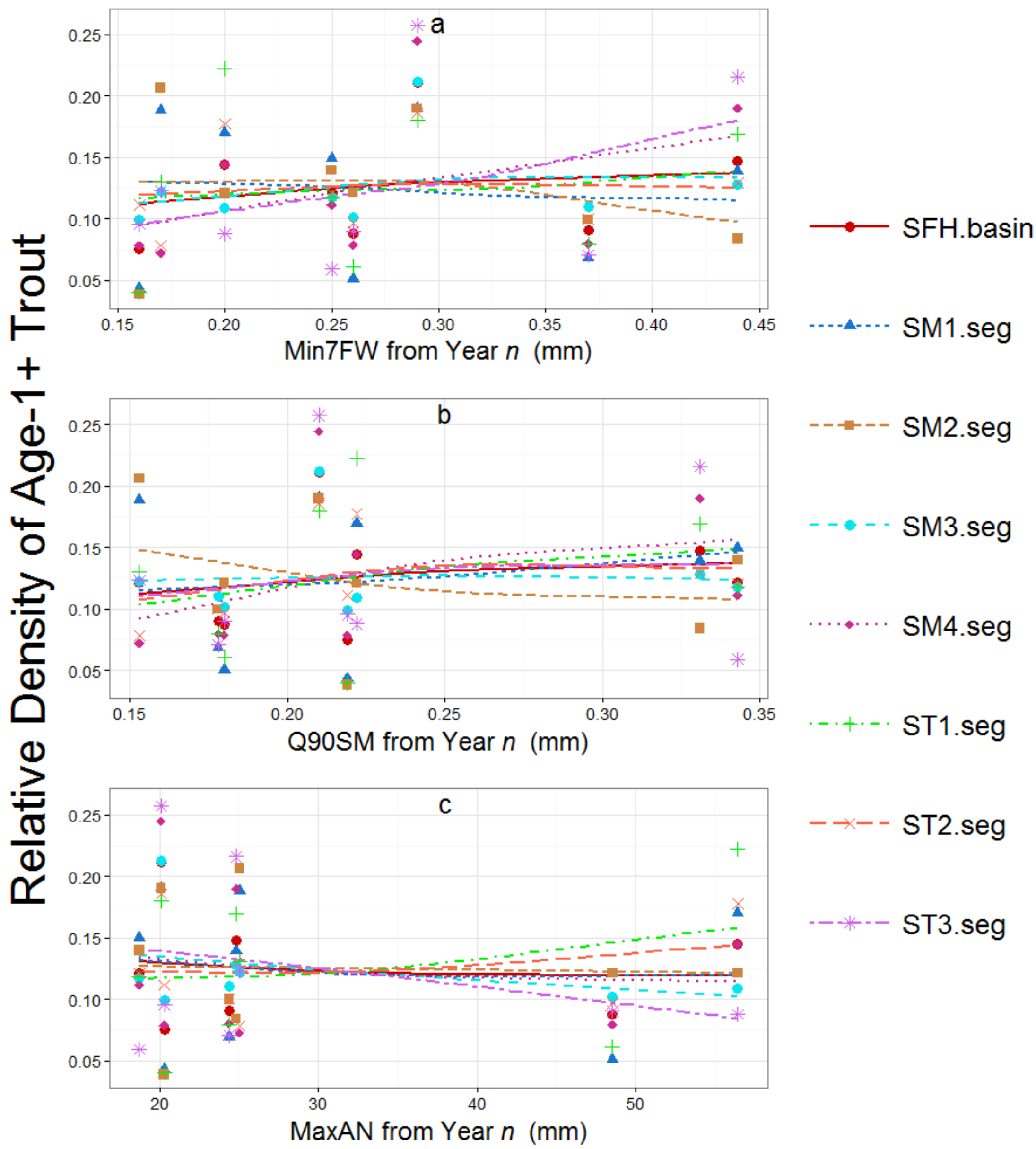


Figure 4-9 Relationships between ***Age-1+ RD*** and unrelated hydrologic indices at eight locations in SFH that includes : a) ***Min7FW***, b) ***Q90SM***, and c) ***MaxAN*** (same year for all three indices). All indices are from the current year. Solid and dashed lines indicate nonparametric smoothing trends for the associated location (see legend).

CHAPTER 5- DISCUSSION

SPATIAL INCONGRUENCE

Spatial incongruence is pervasive in hydro-ecological studies, including this one. A method was developed to predict hydrologic indices at non-gaged locations using simple regression models of hydrologic indices for a given watershed and year versus watershed area. The magnitude of the watershed areas of the non-gaged locations was midway between the area of the entire watershed (NFHC and SFHC) and the watershed area of the upstream gages on non-fish-bearing streams. This method was rejected due to high influence and leverage from the NFHC and SFHC gaging locations. Predicted indices were strongly driven by NFHC and SFHC and the models provided redundant information. Consequently the findings of this study were not likely to change regardless of the dataset used for analyses and measured data was preferred over synthetic data.

There are many ways that the model used to predict indices could be improved. The primary cause of high leverage was a small sample size and poor representation of data at the larger end of the drainage area distribution. Small sample size also prevented the use of additional model parameters commonly used to predict discharge at non-gaged sites, such as channel gradient, channel width, channel length, and elevation (Gordon 2004). Adding gaging locations from basins of similar size or with larger drainage areas might have improved model fit. Gaging stations from lower down in the drainage network with a matching discharge record were not available. Combining NFH and SFH into one regression equation was considered but disregarded due to potential differences in hydrology due to the effects of timber harvest on storm attributes (discussed below).

Improved methods to reduce spatial incongruence may not be beneficial to hydro-ecology. The HCPWS had a high density of gaging stations (3-5 gaging sites per 1000 hectares), but most of the time gaging stations are owned and operated by governmental or private sector entities and are sparsely distributed. Reducing spatial incongruence was worthy of consideration in the HCPWS, but is not feasible in most practical applications. Inspection of Figures 4-1 to 4-3 show alignment of the trends in the hydrologic indices over time between stream gaging stations. Similarity in hydrologic behavior in the watershed supports the assumption that patterns in discharge at gaging sites are representative of the fluctuations in discharge across the watershed (e.g. non-gaged reaches and segments). Thus, spatial incongruence may not me a substantial weakness in hydrological studies of small watersheds.

WATERSHED LEVEL ANALYSIS

It is not possible in this study to assign cause and effect relationships between ecologically relevant hydrologic indices and the relative density of cutthroat trout for age-0, age-1+, and all trout. It is also not possible to identify synergistic effects of multiple hydrologic indices on relative density. Hydrologic indices with weak and/or strong correlation with the relative density of any age class of cutthroat trout should be considered in future research.

Age-0

SFH watershed

In the SFH watershed, ***Q90SM*** was correlated with age-0 relative density. This strong positive correlation was supported in stream segments ST1 and ST3 and weaker positive correlations were supported in stream segments SM1, SM2, and SM3 (Table 4-5). Summer low flows in western Oregon limit habitat availability, with reductions in stream volume, water depth, and surface area in riffles and lateral habitats preferred by age-0 trout (Moore and Gregory 1988; Rolls et al. 2012; Rosenfeld et al. 2000). Increased water temperatures, reduced flow velocities, reduced macroinvertebrate drift, and lower dissolved oxygen may occur during summer low flows (Bjornn and Reiser 1991; Rolls et al. 2012). Adverse changes in physical habitat during summer low flows can affect behavioral, physiological, and ecological processes that affect the abundance of age-0 salmonids (Bjornn and Reiser 1991; Quinn 2005; Rolls et al. 2012). The adverse effects of summer low flows have been well documented (Elliott 1985; Hakala and Hartman 2004). Drought was a chief factor in the reduction of survival of age-0 brown trout in two small streams in England (Elliott 1985) and was related to a 67% reduction in age-0 brook trout populations in forested headwater streams in West Virginia (Hakala and Hartman 2004). In controlled experiments from

Oregon and Montana, reductions in summer low flow were related to reduced abundance of juvenile steelhead and resident brook trout, respectively (Kraft 1972; White et al. 1981). Results from SFH support the idea that increases in discharge during low flows may be related to increases in relative density of age-0 trout.

A weak, positive correlation between age-0 relative density and ***Q10SP*** was also identified. This relationship is supported by strong correlations in stream segments SM4, ST1, and ST3 and a weak correlation in SM3. Unfer (2011) reported a positive relationship between age-0 recruitment and discharge before or during the spawning period in the absence of extreme storms. Thus, high flows can benefit redds. Fines may be flushed from the gravels and oxygen flow to developing embryos may be stimulated as long as the streamflow doesn't scour the redd and remove the incubating eggs (Quinn 2005; Unfer et al. 2011). At Hinkle Creek, storms that occurred during spawning periods were not large enough to scour redds and cause embryo mortality (Figure 5-1). Results from SFH may support the idea that increases in ***Q10SP*** are correlated with increases in relative density of age-0 trout. However, speculation about this relationship may be confounded by weak collinearity between ***Q90SM*** and ***Q10SP*** (r = 0.645) and strong positive correlation between ***age-0 RD*** and ***Q90SM***.

NFH watershed

In NFH, ***age-0 RD*** was related to ***MaxAN***. This strong positive correlation was supported in stream segments NM34 and NT1 and through weaker correlations in all remaining stream segments (Table 4-2). ***MaxAN*** represents the maximum daily peak in a given year. In NFH, 6 of 8 maximum annual peak flows had return intervals less than one year. Peak flows with return periods greater than one year are more likely to redistribute sediments, coarse bed materials, and large wood, alter spawning redds and other habitat types (Swanson et al. 1998; Swanston 1991). The largest peak flow during the study period occurred in 2006, and had a return interval of approximately 13 years based on a partial duration series frequency analysis with eight years of observations (Figure 5-1). The second largest peak flow occurred in 2009, and had recurrence interval of approximately 10 years (Figure 5-1). Based on field observations, both storms had sufficient discharge and stream power to cause changes in the stream channels. The two largest values of the relative density of age-0 trout were in 2006 and 2009 (Figure 5-4). Both storms occurred prior to spawning activity (December–January) and so impacts of the storms on density of age-0 trout are indirect through effects on habitat or the spawning generation.

Unfer (2011) reported a positive correlation with maximum discharge prior to spawning and the abundance of age-0 brown trout in an alpine river. Similarly, Dodds et al. (2012) observed a significant increase in the abundance of age-0 cutthroat trout after an extreme winter flood event in a small headwater stream in the western Cascades. Both studies proposed that the capacity for large peak flows to improve spawning habitat could explain the observed relationships. Unfer (2011) concluded that large storms improved spawning habitat by flushing fines from the gravels and Dodds et al. (2012) concluded that the large flood redistributed boulders and gravels to create extensive gravel deposits.

Other studies report negative impacts of extreme flood events on trout abundance (Elwood and Waters 1969; Erman et al. 1988; Seegrist and Gard 1972) due to increased mortality from high-flow disturbance. It is possible to put streamflow in the study watersheds during the study period into hydrologic perspective. Figure 5-2 shows the maximum annual peak flows for, nominally, the last 100 years at the North Umpqua River at Winchester, Oregon, a USGS gaging station near the Hinkle Creek Study watersheds. The maximum annual discharges for the study years are delineated towards the end of this record. Observation of this record reveals that the storms experienced by the study watersheds during the last decade were not extreme. Compared to those studies that report negative impacts of extreme flood events, unremarkable peak magnitudes in 2006 and 2009 may explain the positive relationship between ***MaxAN*** and ***age-0 RD***.

The results from NFH support the idea that annual peak flows greater than the mean annual flood ($T_r > 2.3$ years) may be related to high values in the relative density of age-0 trout. A possible explanation may be that the 2006 and 2009 peak flows increased the mortality of resident cutthroat trout. Thus, there may be an increase in fitness in the surviving spawners that could contribute to higher-than-usual relative densities of age-0 trout in 2006 and 2009. While this scenario is supported by the age-0 trout data in NFH, it is not supported by the age-1+ trout data.

A weak, negative correlation was identified between the relative density of age-0 trout and the ***Q90SM*** in NFH, and that correlation is supported by a weak correlation in NM34. A possible explanation for this relationship is an increase in habitat volume of riffles and lateral habitats and connectivity across habitat types that could increase mobility of piscivorous adult trout into the preferred habitat of age-0 trout. Increases in habitat supporting larger age-0 cohorts may also facilitate negative density-dependent cohort size regulation. A confounding collinearity between ***MaxAN*** and ***Q90SM*** may also account for this observation. A strong positive correlation between ***MaxAN*** and ***age-0 RD*** (r = 0.780) and strong negative collinearity between ***MaxAN*** and ***Q90SM*** (r = -0.721) support a negative relationship between ***age-0 RD*** and ***Q90SM***.

Limitations

This study was limited to a small sample size of eight years. Detection of relationships was vulnerable to the influence of outliers. An outlier in NFH, the 2006 value of ***age-0 RD***, has strong influence on the relationships between age-0 RD and both ***Q90SM*** and ***MaxAN*** (Figure 5-3). Removal of this data point does not change the trend of the correlation, but it does change the magnitude (r = 0.467 for ***MaxAN*** and r = -0.472 for ***Q90SM***; Figure 5-3). There is no justification to remove this point, but it does point out the challenge of a small dataset with unequal representation of the data across the range of variability, which indicates the need for long-term studies to detect the consequences of less frequent events. A further complication in the analysis of the age-0 trout data is the presence of age-0 steelhead trout. Age-0 steelhead trout were indistinguishable from age-0 cutthroat trout given the way fisheries data was collected.

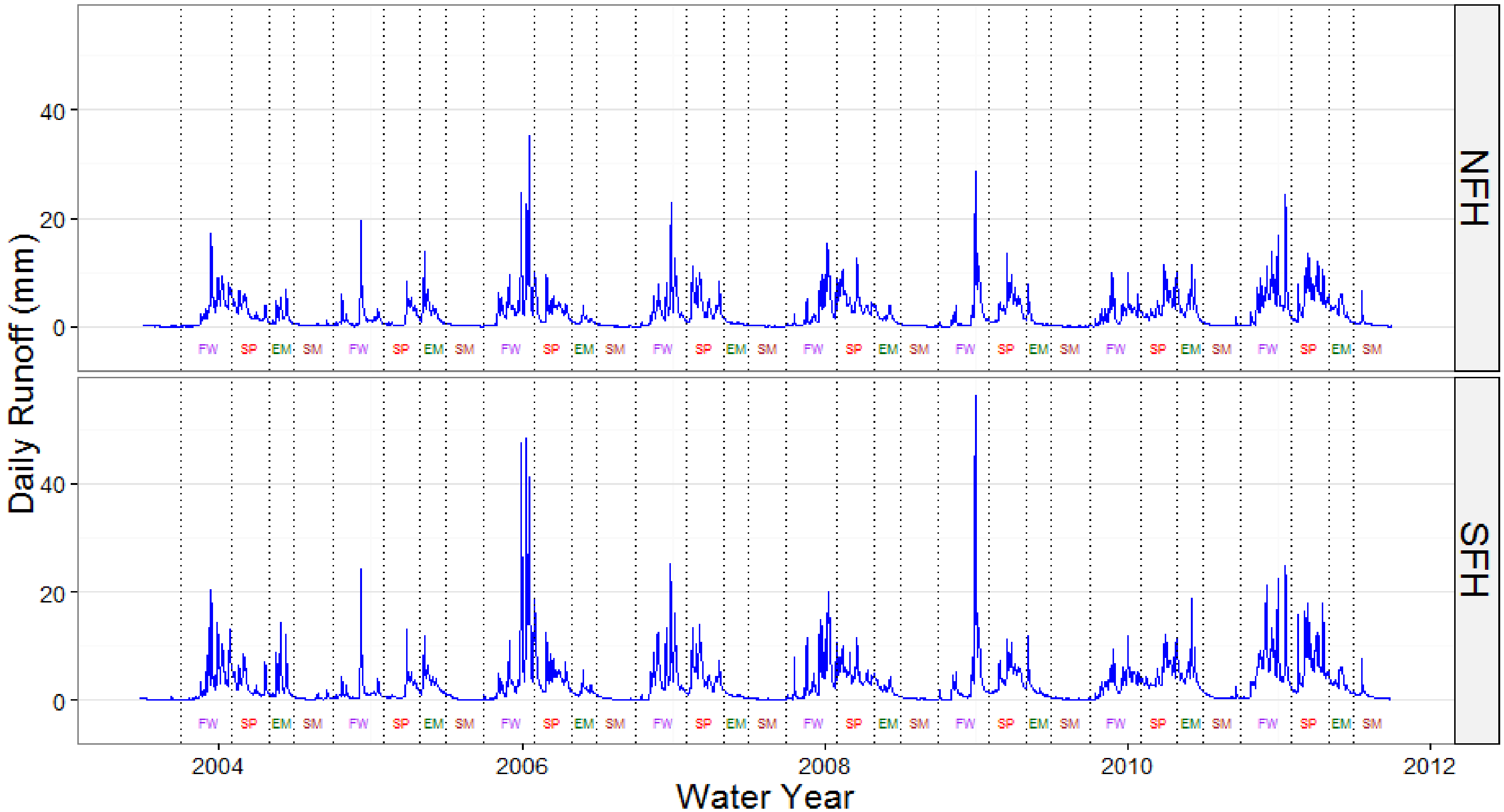


Figure 5-1 Study period hydrograph at Hinkle Creek. Graph shows unit area discharge (mm) over eight years (2003–2011) in the NFH and SFH watersheds. Text labels indicate seasons: fall-winter transition period (FW), spawning period (SP), emergence period (EM), and summer period (SM). The 2006 and 2009 peaks in NFH and SFH are synthetic data.

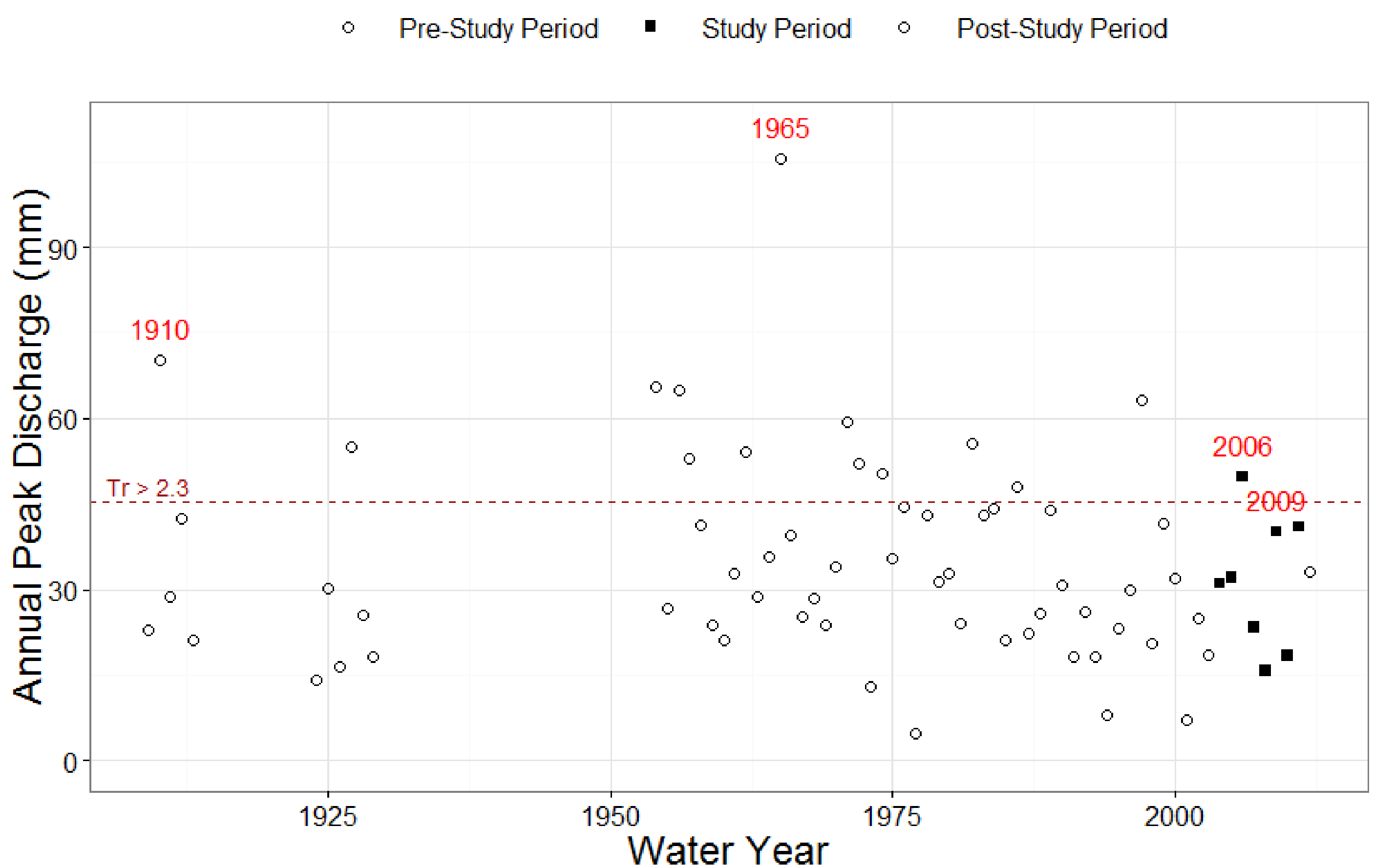
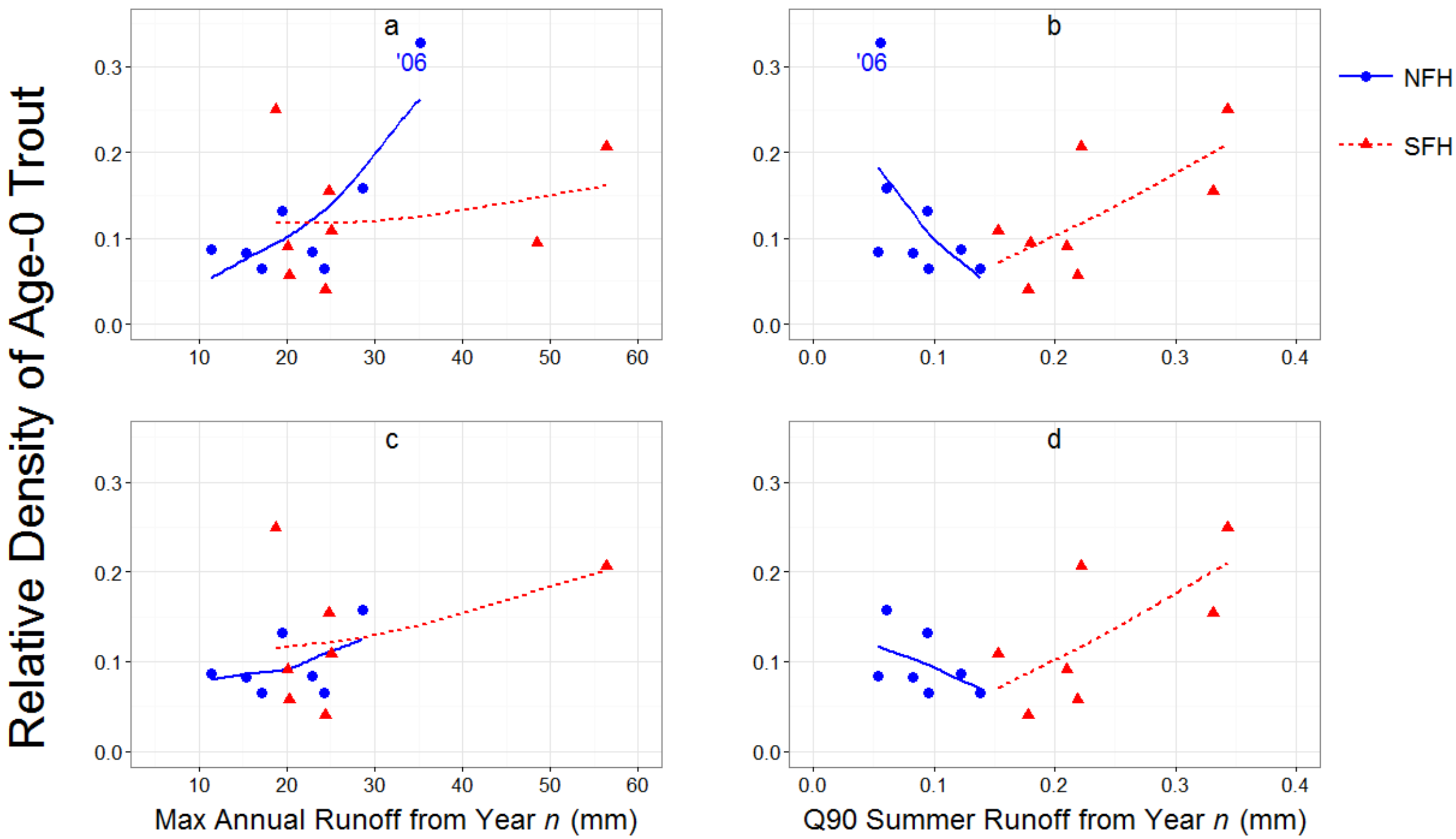


Figure 5-2 Peak annual discharge (mm) from the North Umpqua River at Winchester, Oregon (nearby USGS station 14319500). Black filled circles indicate the 2003–2011 study period. Red text labels mark years with the top two instantaneous storm values on record at Winchester and Hinkle Creek. Dark red dashed line indicates the storm

magnitude (in mm) with a return interval of 2.3 years and was calculated using a partial duration series from the NFHC gaging station.



a
b
c
d
'06
'06
NFH
SFH
0.0
0.1
0.2
0.3
10
20
30
40
50
60
0.0
0.1
0.2
0.3
0.4
Relative Density of Age-0 Trout
Max Annual Runoff from Year *n* (mm)
Q90 Summer Runoff from Year *n* (mm)

Figure 5-3 Comparison of age-0 RD and ecologically relevant indices in NFH and SFH with and without the 2006 value for NFH. Plots a and c demonstrate the relationships between ***age-0 RD*** and ***MaxAN*** in the same year, a) with outlier and c) without outlier. Plots b and d demonstrate the relationships between ***age-0 RD*** and ***Q10SP*** in the same year b) with outlier and d) without outlier. Solid and dashed lines indicate nonparametric smoothing lines to show trends in NFH and SFH, respectively.

Age-1+

Previous studies identified relationships between the abundance of age-1+ trout and hydrologic indices during drought (Hakala and Hartman 2004) or large storms (Elwood and Waters 1969; Seegrist and Gard 1972). There is no evidence for a relationship between ***age-1+ RD*** and ecologically relevant hydrologic indices in either watershed for this study. This absence of a correlation between hydrologic indices and ***age-1+ RD*** is consistent with many studies that found an absence of a relationship between discharge and age-1+ trout abundance in the absence of an extreme drought or storm (Erman et al. 1988; Jensen and Johnsen 1999; Seegrist and Gard 1972).

Stock-Recruitment & Cohort Strength

For many stream systems, the recruitment of the age-0 cohort determines the size of the overall population in subsequent years (Cattaneo et al. 2002; Latterell et al. 1998b; Lobon-Cervia 2007; Nelson 1986). The persistence of the age-0 cohort through time could provide an explanation for the inter-annual variability in age-1+ trout in the absence of a correlation with any hydrologic index. The persistence of the age-0 cohort was not directly measured in this study because it was not possible to separate age classes beyond one year and the sampling efficiency for age-0 trout was lower than for age-1+ trout. The presence of age-0 steelhead trout could also confound measures of the persistence of age-0 trout. Nonetheless, because the age-1+ age class is likely dominated by the age-1 cohort, the correlation between age-1+ RD and previous year age-0 RD is a simplified estimate of the persistence of the age-0 cohort.

This correlation provides a partial explanation for inter-annual variability of age-1+ trout in SFH (r = 0.768), but not in NFH (r = -0.299). In which case, the effect of hydrologic indices on age-0 RD may indirectly influence population fluctuations of age-1+ trout in SFH.

The correlation between age-1+ RD and the previous year age-1+ RD is a simplified measure of age-1+ persistence, though it is hindered by a lack of differentiation between age-1 and age-2+ classes. A weak estimate of age-1+ cohort persistence (r = 0.660) may provide a partial explanation for inter-annual variability of age-1+ trout in NFH. In NFH, a strong correlation with age-0 RD and ***MaxAN*** and a lack of strong correlation between age-1+ RD and any hydrologic index or estimate of age-0 or age-1+ cohort persistence suggests that survival to age-1+ trout after summer sampling of age-0 abundance is limited in NFH.

Results from this study do not preclude that discharge influences inter-annual variability in age-1+ trout density or that density-dependent factors do not influence the inter-annual variability in age-0 trout density. This study sought to identify relationships where hydrologic indices were contributors to population fluctuations of resident cutthroat trout density. ***Q90SM*** and ***MaxAN*** were identified as ecologically relevant indices for ***age-0 RD***. The lack of results for inter-annual variability of age-1+ trout density is likely a result of multiple biotic and abiotic factors.

All Trout

It is uncommon to test the effects of discharge on all trout, as opposed to individual age classes. This analysis was carried out to identify the hydrologic processes that might affect the whole population. The results for all trout were similar to the result from the age-0 analysis because the same indices were identified as weakly or strongly correlated with relative density for both age classes (***Q90SM*** and ***Q10SP*** in SFH and ***MaxAN*** and ***Q90SM*** in NFH; Table 4-2). The result is not explained by the percent of the age-0 trout in all trout, which ranged from 38.5–81.2% and 31.6–68.9% in NFH and SFH, respectively across the eight study years (Figure 5-4). See *Appendix B-Abundance Data* for values of total catch and relative density of age-0, age-1+, and all trout at the watershed level. The absence of a correlation in the age-1+ RD analysis may account for the strong similarity in the two age groups. These results suggest that in the absence of large storms, as occurred in this study, relationships between hydrologic indices and all trout density may be difficult to find. The strong influence of the age-0 population in these analyses supports the importance of analyzing age classes separately.

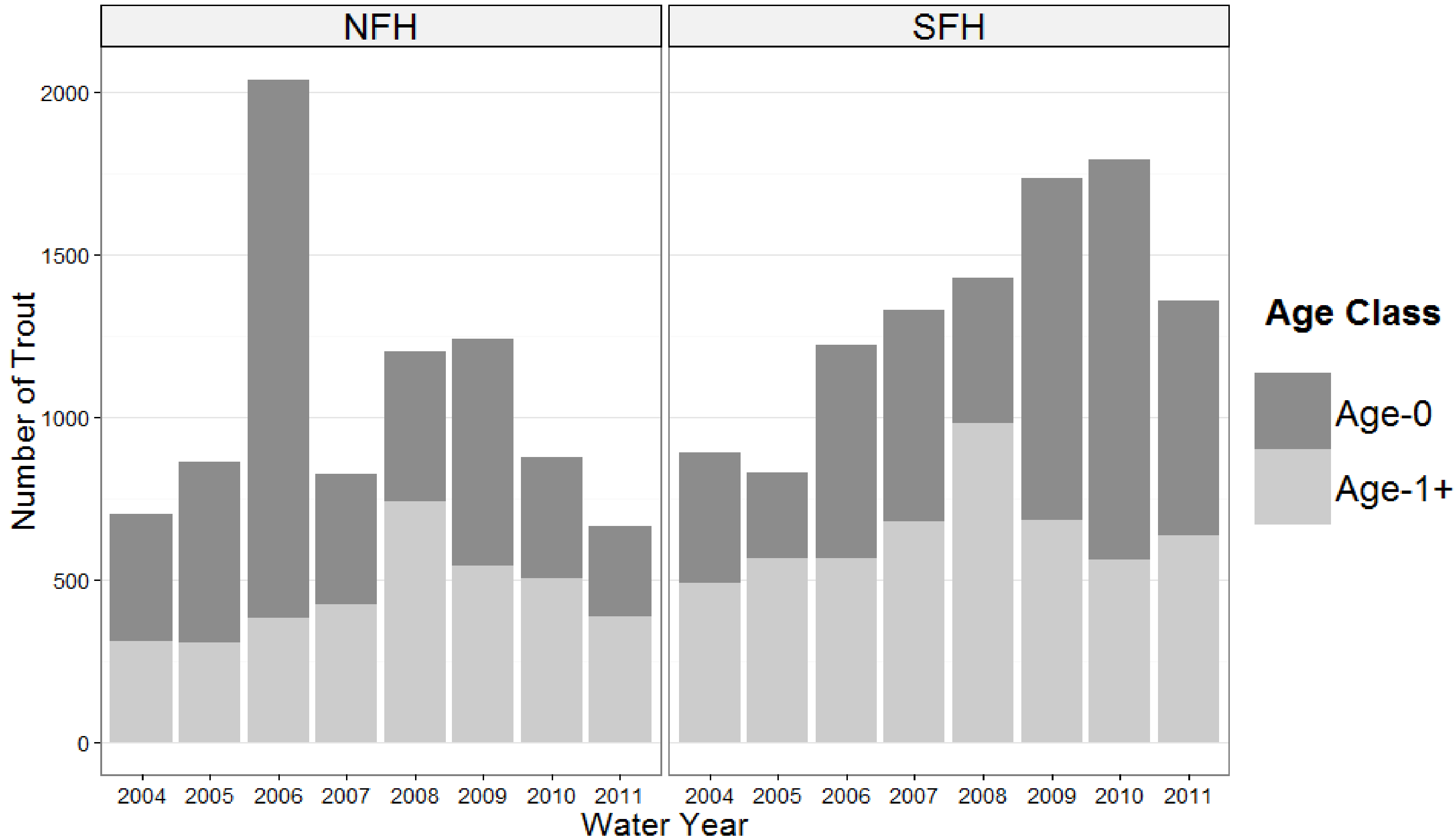


Figure 5-4 Composition of all trout by age class in NFH and SFH. Number of trout indicates the total number of trout counted during annual surveys in all fish-bearing streams within a watershed. See Appendix A for values of total catch and relative density of age-0, age-1+, and all trout.

Similarities and differences across NFH and SFH

Results from this study allowed comparisons of relationships between hydrologic indices and cutthroat trout abundance across the two contiguous study watersheds and possible explanations for the those differences. Patterns in relative density over time are well synchronized between the two watersheds for age-1+ trout until 2008 but these patterns are poorly synchronized for age-0 trout (Figures 5-5 & 5-6). This clarifies consistent findings across watersheds in the analysis of ***age-1+ RD*** and the inconsistent findings in the analysis of ***age-0 RD*** and also points to the lack of a recruitment effect on adult trout populations. Figure 5-1 shows that patterns in discharge were similar between NFH and SFH throughout the study period, although SFH had a slightly a higher unit area discharge than NFH for most peak flows. In both watersheds the two largest storm events occurred in 2006 and 2009, but the largest storm on record occurred in the 2009 water year in SFH and 2006 in NFH. Infilling of missing storm peak data by the United States Geological Survey may account for differences in storm magnitude between the NFHC and SFHC gaging stations because gaging instrumentation failed at SFHC during both storms.

NFH and SFH were selected for comparison in the HCPWS due to strong similarity in geologic and physical attributes. Both watersheds share the same geology, soils, vegetation cover, and elevation ranges. Each watershed has a main stem and 3 fish-bearing tributaries and stream lengths are similar (Table 3-1). Fish habitat characteristics and large wood loading during the study period was also similar (unpublished data from HCPWS). However, any two watersheds within a geomorphic province will vary in physical attributes to some degree. The two watersheds differ in drainage area and aspect and slight variability in the rates of runoff and groundwater flow are expected. Variability in storm behavior and physical features across the ~7.7 square-mile study area generates variability in microclimatology, storm cell intensity, and the form of precipitation as rain or snow. This natural spatial heterogeneity is one source of variance across the two watersheds.

The 2009 storm is a source of additional variation between the two watersheds due to a disturbance in the SFH watershed. A dam break flood, the consequence of a debris flow, occurred in the upper non-fish-bearing reach of ST3. The dam break flood deposited woody debris in the fish-bearing reaches of ST3. The dam break flood in non-fish-bearing reaches left the stream devoid of canopy or debris cover.

Timber harvest is an additional source of variation between the two watersheds. The ***Q90SM*** and ***MaxAN***, both ecologically relevant indices, are thought to be affected by timber harvest in SFH (Figure 5-7). The literature supports the idea that timber harvest will result in increases summer low flows (Hicks et al. 1991; Keppeler and Ziemer 1990) and certainly increases in peak flows for storms with a recurrence interval less than the mean annual flood (Beschta et al. 2000; Hewlett and Helvey 1970; Wright et al. 1990). Timber harvest in SFH caused an increase in August low flows of 45% after the first harvest entry and up to 106% after the second harvest entry (Surfleet and Skaugset 2013). Zegre N.P. (2008) reported increases in water yield and peak flows after the first harvest entry (2005–2008) and preliminary results from the HCPWS indicate that increased water yield and peak flows are a consequence of the second harvest entry also (2009–2011).

Increases in streamflow during summer caused by timber harvest could facilitate the strong positive relationship between summer discharge and the relative density of age-0 trout observed in SFH and not in NFH. Timber harvest also affects factors that influence abundance (e.g. solar radiation, water temperature, and primary productivity) (Aho 1976; Gregory et al. 1987; Murphy and Hall 1981; Murphy et al. 1986). The analysis carried out for this study did not differentiate between the effects of timber harvest on discharge and other factors that influence abundance. Timber harvest may further influence the lack of consistency between NFH and SFH by affecting the observed relationship between ***age-0 RD*** and ***MaxAN*** in SFH.

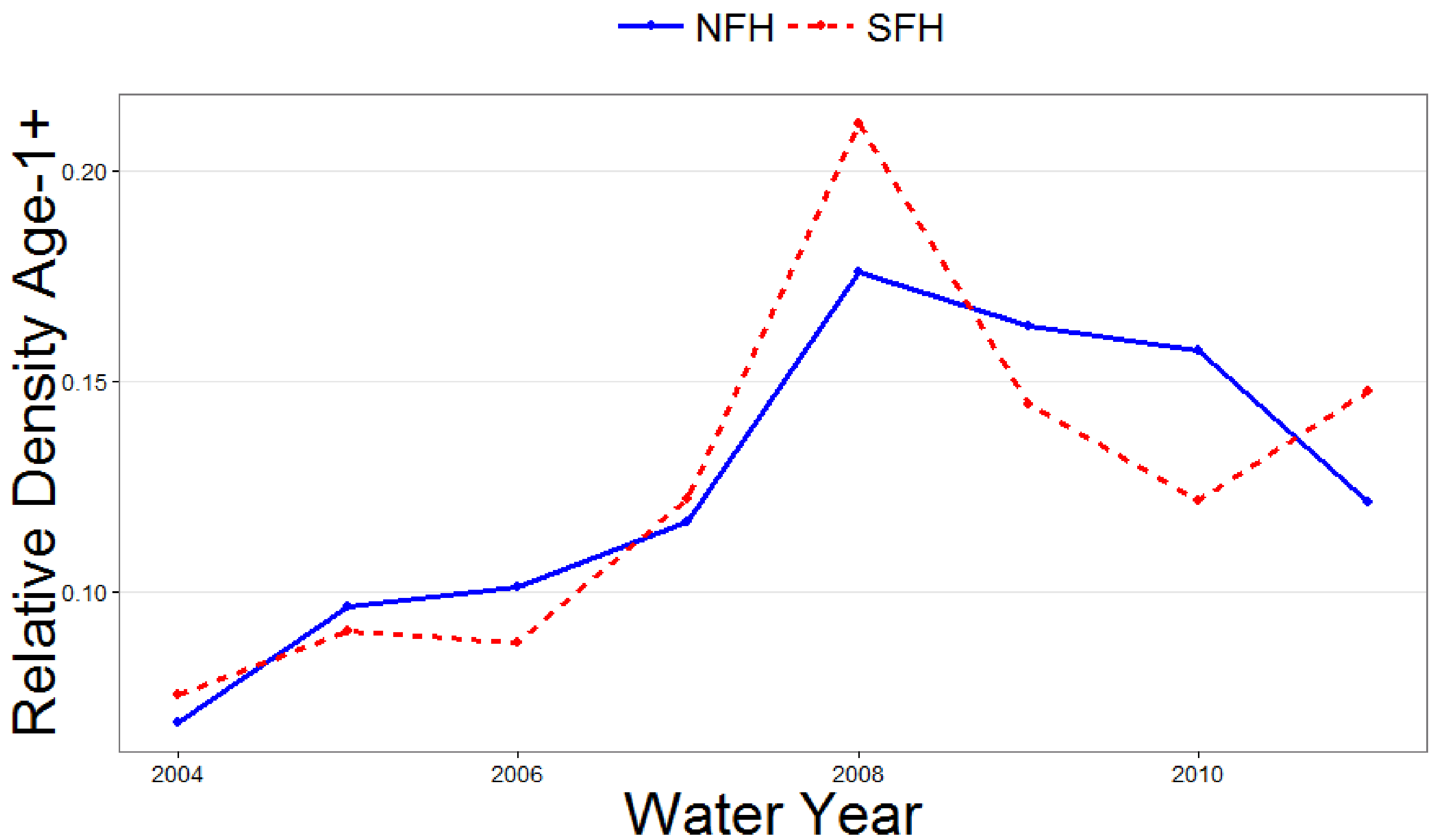


Figure 5-5 Fluctuations in relative density of age-1+ trout over time. Relative density is calculated for all fish-bearing streams within in the NFH and SFH watersheds. Temporal trends in relative density are moderately synchronous between the two watersheds early in the study period and deviate after 2008.

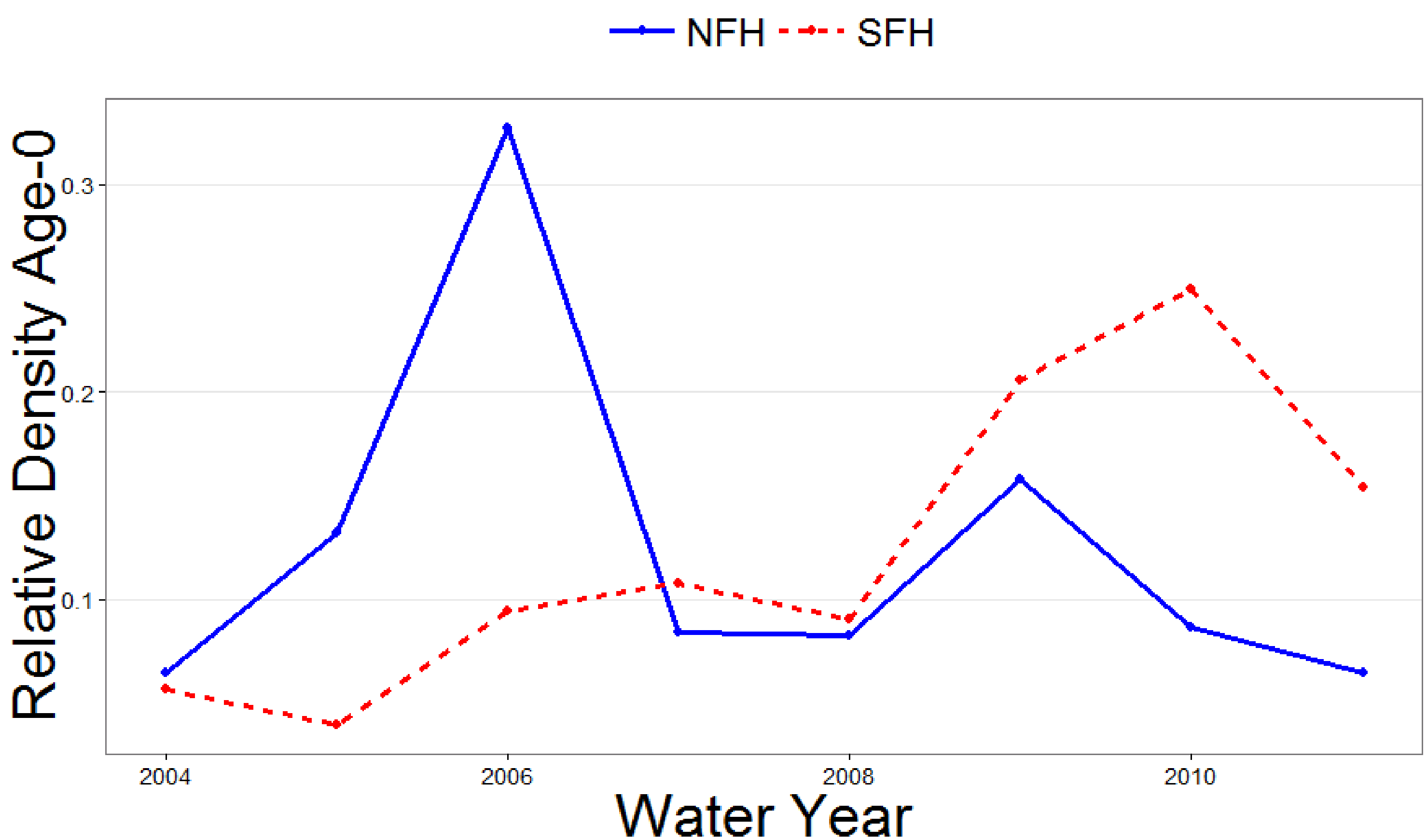


Figure 5-6 Fluctuations in relative density of age-0 trout over time. Relative density is calculated for all fish-bearing streams within in the NFH and SFH watersheds. Temporal trends in relative density are not synchronous between the two watersheds for much of the study period.

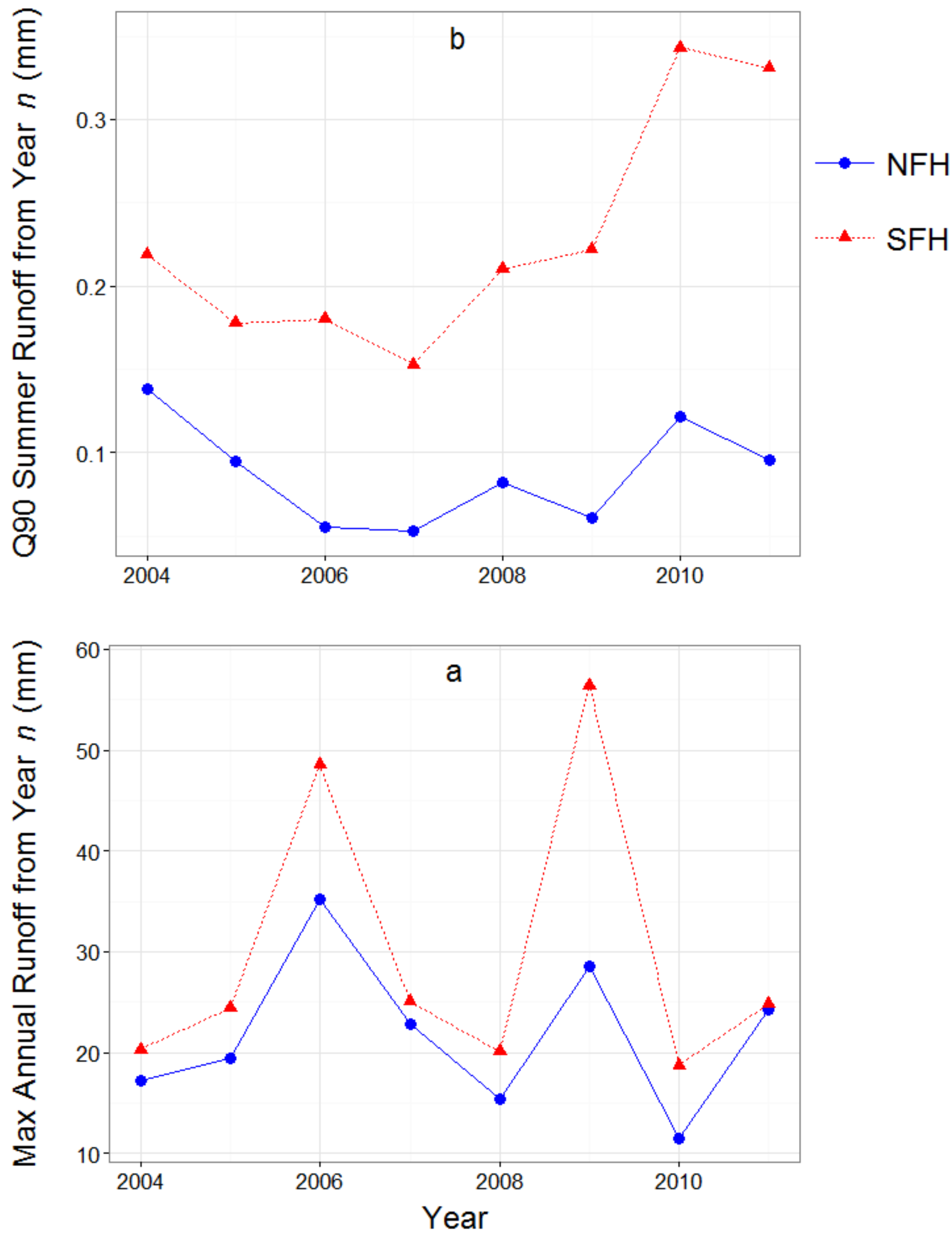


Figure 5-7 Ecologically relevant hydrologic indices over time in NFH and SFH. Plots show comparisons of a) ***MaxAN*** and b) ***Q90SM*** for a watershed without timber harvest (NFH) and with timber harvest (SFH). Timber harvest occurred alonside non-fish-bearing streams in 2005-2006 and alonside fish-bearing streams in 2009.

STREAM SEGMENT LEVEL ANALYSIS

The final objective of this study was to assess the role of spatial scale and network location on relationships between relative density of trout and hydrologic indices. This component of the study was an attempt to link and compare relationships at intermediate scales that management (watershed) and research (segment) are implemented and to highlight spatial context to hydro-ecological relationships.

The role of spatial scale on hydro-ecological relationships

Identifying the role of spatial scale on the detectability of relationships is an important step towards understanding processes that facilitate discharge-density relationships. Hydrologic indices were consistently not related to age-1+ relative density at all locations. Thus, the spatial scale that observations were made had no effect on the detectability of relationships with age-1+ trout, in the absence of large storms or severe droughts. The role of spatial scale on discharge-density relationships for age-0 trout was more complicated. Most indices had correlation consistently below the $r = |0.70|$ threshold at the watershed and stream segment level. Scale was not important to detect ecologically relevance for these indices. However, no hydrologic index that had a strong correlation with age-0 RD at the watershed level had consistent correlation across all stream segments. These findings indicate that scale was important to detect ecological relevance.

Conflicting results in consistency for ***age-0 trout*** may be explained by the patterns observed in similarity. The two ecologically relevant indices identified in this study, ***Q90SM*** and ***MaxAN***, had strong similarity at the watershed and stream segment scales. This suggests that the processes that drive these relationships are relevant at both spatial scales. Lack of consistency is driven by relationships at unique stream segments, which indicates that network location may be driving processes that facilitate the detectability of density-discharge relationships. Individual stream segments have different morphologies and may respond differently to hydrologic characteristics; stream segments with stronger correlations may indicate higher vulnerability to the effects of discharge on abundance than those than those with weaker correlations. Variability across the stream network may drive overall trends observed at the watershed scale. For example, in SFH a correlation of r = 0.697 between ***age-0 RD*** and ***Q90SM*** is likely influenced by a combination of strong relationships in ST1 and ST3 (r = 0.705 & r = 0.827, respectively), weak relationships in SM1, SM2, and SM3 (r = 0.503, r = 0.674, & r = 0.544, respectively) and the lack of a relationship in SM4 and ST2 (r = 0.409 & r = 0.390, respectively). A strong correlation in the NFH watershed between ***age-0 RD*** and ***MaxAN*** is likely influenced by strong and weak correlations at all segments. Thus, network location, driven by spatial variability across the landscape, appears to be an important factor to understand and detect relationships at the watershed scale.

The role of network location on hydro-ecological relationships

Spatial variation is not regularly considered in studies from aquatic ecology (Fausch et al. 2002). Results from stream segment-level comparisons in both watersheds suggest that location within the network can influence the magnitude and direction of relationships observed (Figure 4-3 & 4-4). The detection of a weak or strong correlation with age-0 RD in at least one stream segment for most hydrologic indices may be attributed to spatial heterogeneity across the stream network (Table 4-2 & 4-4) (Fausch et al. 2002; Townsend 1989). These findings compliment a body of literature that suggests results from individual stream reaches or segments should be applied to larger spatial extents or 'represent' multiple reaches across a landscape with caution (Fausch et al. 2002; Townsend et al. 2004).

Differences across segments based on the arbitrary threshold of $r = |0.70|$ indicate that if a study were to take place in any given stream segment independently, network location would determine the binary categorization of an index as either ecologically relevant or irrelevant. The advantage of the study design from the HCPWS is side-by-side comparisons of relationships across segments to provide a network perspective on observed relationships. While consistency across stream segments occurred only with ecologically irrelevant indices, similarity across stream segments was observed for ecologically relevant indices in both watersheds (***MaxAN*** in NFH and ***Q90SM*** in SFH). The presence of similarity suggests that despite spatial heterogeneity across the stream network, hydrologic indices may be functionally related to inter-annual variability throughout the watershed.

Overall trends in similarity, consistency, and network similarity were not different across the two watersheds. In both watersheds, hydrologic indices that were ecologically relevant at the watershed scale were similar but not consistently ecologically relevant across stream segments. NFH had a higher rate of similarity and network similarity than SFH. A mosaic of harvest units across the landscape present in the SFH and absent in NFH may contribute to more 'noise' in SFH. However, the presence of timber harvest does not appear to play a critical role in understanding the effects of scale and network location because patterns of similarity and consistency for ecologically relevant hydrologic indices were the same in both watersheds.

In this study, patterns in correlation across individual stream segments were not studied. Patterns in the strength of the correlations among stream segments were not placed into context with the habitat template of each unique stream segment. This was a first step in that direction. Future studies could identify commonalities in physical characteristics across stream segments, relate those to patterns of similarity, and identify how habitat characteristics can facilitate relationships between discharge and density.

CHAPTER 6- CONCLUSIONS

Discharge has been shown to influence resident trout abundance and/or survival in 1^{st}-4^{th} order streams from the United States and Europe. In this study, an existing dataset from the Hinkle Creek Paired Watershed Study was used to test relationships between the hydrology of managed, forested, headwater watersheds and resident cutthroat trout density in the western Cascades. The comparison of these relationships across many stream segments at two watershed scales to determine the role of spatial scale and network location on detectability of those relationships was novel in this study.

Hydrologic indices did not explain inter-annual variability in age-1+ trout density. This may be explained by the mild hydrologic conditions that characterized the 2003–2011 study period. It may also be explained by density-dependent factors such as cohort persistence that may be related to the inter-annual variability of age-1+ trout abundance but do not have a relationship with hydrologic indices. There are two hydrologic indices that could explain the inter-annual variability in age-0 relative density: the maximum annual flow in NFH (***MaxAN***) and the Q90 summer flow (***Q90SM***) in SFH. Differences in these two hydrologic indices across the two watersheds are best explained by the presence of timber harvest in SFH. High values of summer low flow corresponded with high densities of trout in SFH, which might be attributed to increased summer low flows due to timber harvest adjacent to fish-bearing stream segments. Additional factors affected by timber harvest that could influence abundance (temperature, solar irradiation, primary productivity, etc.) were not investigated but may also explain apparent increases in abundance after timber harvest. The propensity for large storms to redistribute sediment and improve spawning habitat was a proposed mechanism for the relationship observed in NFH. The effect of hydrologic indices on ***age-0 RD*** may indirectly influence population fluctuations of age-1+ trout, due to possible cohort persistence. In both watersheds, correlation analysis was used as a tool to identify potential drivers of inter-annual variability cutthroat trout. Correlation analysis is not able to identify synergistic or mutually exclusive relationships between hydrologic indices and other factors. These indices, and the mechanisms proposed to explain their influence on relative density were identified with an exploratory approach and should be considered as opportunities for future research.

In both watersheds, most hydrologic indices were consistently not related to the relative density of age-0 and age-1+ trout across a watershed and multiple stream segments. Ecologically relevant indices (***Q90SM*** and ***MaxAN***) were not consistent across locations (one watershed and multiple segments). Thus, for these important indices, the spatial extent of the analysis and location within the stream network can influence results. Network location had the strongest influence on the detectability of relationships. The similarity in the direction and magnitude of correlations across locations is suggestive of processes that act at both scales and that spatial heterogeneity across the network facilitates the degree that discharge influences abundance in stream segments. Researchers that identify relationships between discharge and abundance at the level of stream reaches should be mindful of these differences when conclusions are drawn to entire streams, watersheds, or geomorphic provinces.

During this study a method was developed to reduce incongruence in the spatial matching of abundance measurements and discharge gaging sites within the network. High leverage from the mainstem gaging stations resulted in strong influence of these data-points on the predicted values of hydrologic indices at non-gaged locations. Incorporation of additional gaging stations would have improved this method, but this would not have addressed issues regarding the utility of this method in watersheds where there is a low density of stream gaging stations. Observations of overall agreement between upper tributary and main stem gaging stations suggests that the assumption of spatial incongruence, that discharge measured at a gaging station that represents a downstream stream reach may be representative of the discharge at an non-gaged stream reach, may be acceptable for similar study areas.

The HCPWS is an impact assessment case study from the Hinkle Creek basin. The study site was not randomly selected and harvesting treatments were not randomly assigned. The stream network at Hinkle Creek is representative of small headwater watersheds in the foothills of the western cascades with similar elevation range, topography, geology, climate, legacy of forest management, and harvest techniques. However, because of watershed-specificity, the lack of replication, and the lack of randomization, the scope of inference is limited to resident cutthroat trout from resident populations at Hinkle Creek and nearby basins very similar to Hinkle Creek in physical attributes and management regimes. The study took place from 2003-2011, and inference beyond this time frame is also limited.

Natural inter-annual variability of trout abundance can be confounding in studies that seek to identify the effects of contemporary forest management. Results of this study suggest that the inter-annual variability of trout abundance may be related to discharge, particularly the age-0 cohort. Researchers interested in the effects of contemporary forest management on trout populations should be mindful of 1) spatial and temporal variability in abundance, 2) the effect of discharge on the abundance of different age classes of trout, 3) the effect of timber harvest on hydrology, and 4) spatial heterogeneity across the stream network and the role of network location on detectability of those impacts.

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APPENDICES

APPENDIX A- GLOSSARY OF TERMS

Alevins- The hatchling form of the incubating embryo. The alevin is a stage of embryo development which remains in the intra-gravel space, nourished by a large external yolk-sac, until it is ready to swim out of the redd and feed on its own.

Carrying Capacity- The maximum population of a particular organism that a given environment can support without detrimental effects.

Collinearity- Collinearity reflects situations in which there is a linear association between two or more independent variables.

Cook's distance- In regression analysis, the cook's distance is a case statistic that measures overall influence of individual data points—the effect that omitting a case has on the estimated regression coefficients. The Cook's distance is based on values of leverage and the studentized residual of the data point in question.

Density-dependence- The regulation of the size of a population or age class by mechanisms that are controlled by the size of that population or age class. Density-dependence can be negative (as population increases, the growth rate of that population decreases) or positive (as population increases, the growth rate of that population increases).

Extent- Spatial extent encompasses the overall area included in an investigation or the area within the landscape boundary. Extent refers to both the physical area as well as the time period for which a landscape or population process occurs.

Grain- describes the size of the smallest homogeneous unit of study and determines the resolution at which a landscape is studied (spatial or temporal).

Hydro-ecology- The scientific overlap between the fields of hydrology and ecology; the impact of hydrology on ecosystems (and *vice versa*).

Leverage- In regression analysis, the leverage of an observation is a statistic that measures the ability of a point to ‘pull; the regression line towards itself. It is calculated as a function of the distance between its explanatory variable values and the average of the explanatory values in the entire dataset.

Influence- In regression analysis, the influence of an observation can be defined in terms of how much a statistic (e.g. the predicted scores for other observations) would differ if the observation in question were not used to compute the statistic.

PIT- stands for Passive Integrated Transponder. A small durable microchip implanted into trout to provide unique identification numbers to individual trout. Commonly used in movement and survival studies.

Pulse Disturbance- A disturbance that occurs as a relatively discrete event in time. A pulse disturbance can be caused by natural or anthropogenic causes. In stream studies a pulse disturbance typically refers to a large storm event, a drought, a debris flow, fire, etc.

Stream order- Stream order is a measure of the relative size of streams. Stream sizes range from the smallest, first-order, to the largest, the twelfth-order (the Amazon River).

Studentized Residual- a residual divided by its estimated standard deviation.

Young-of-the-Year- age-0 trout; fish born within the past year, which have not yet reached one year of age. At Hinkle Creek sampling takes place late summer and young-of-the-year are born in late spring early summer.

APPENDIX B- ABUNDANCE DATA

Table B-1 Watershed-level density data. *Count* indicates the number (#) of Age-0, Age-1+, and All trout for a given year. *Sampled Length* is the sum of the length of all pool and cascade habitat units sampled in a given watershed during electrofishing (in m) in a given year. *Density* is the *Count* of a given age class divided by the *Sampled Length* in (#/m)

Year	**Water-shed**	Count Age-0 **(#)**	Count Age-1+ **(#)**	Count All **(#)**	Sampled Length **(m)**	Density Age-0 **(#/m)**	Density Age-1+ **(#/m)**	Density All **(#/m)**
2004	**NFH**	389	311	700	2001	0.194	0.155	0.350
2005	**NFH**	558	305	863	1403	0.398	0.217	0.615
2006	**NFH**	1656	382	2038	1678	0.987	0.228	1.215
2007	**NFH**	405	421	826	1598	0.253	0.263	0.517
2008	**NFH**	462	738	1200	1859	0.248	0.397	0.645
2009	**NFH**	699	540	1239	1467	0.476	0.368	0.844
2010	**NFH**	372	503	875	1417	0.263	0.355	0.618
2011	**NFH**	278	387	665	1417	0.196	0.273	0.469
2004	**SFH**	401	491	892	2633	0.152	0.186	0.339
2005	**SFH**	267	564	831	2516	0.106	0.224	0.330
2006	**SFH**	656	564	1220	2596	0.253	0.217	0.470
2007	**SFH**	650	680	1330	2250	0.289	0.302	0.591
2008	**SFH**	452	978	1430	1871	0.242	0.523	0.764
2009	**SFH**	1053	684	1737	1913	0.550	0.358	0.908
2010	**SFH**	1235	558	1793	1855	0.666	0.301	0.966
2011	**SFH**	719	637	1356	1745	0.412	0.365	0.777

Table B-2 Stream segment-level density data. *Count* indicates the number (#) of Age-0 and Age-1+ trout for a given year. *Sampled Length* is the sum of the length of all pool and cascade habitat units sampled in a given stream segment during electrofishing (in m) in a given year. *Density* is the *Count* of a given age class divided by the *Sampled Length* in (#/m)

Year	**Water-shed**	**Segment**	Count Age-0 **(#)**	Count Age-1+ **(#)**	Sampled Length **(m)**	Density Age-0 **(#/m)**	Density Age-1+ **(#/m)**
2004	**SFH**	**SM1**	14	30	314	0.045	0.095
2005	**SFH**	**SM1**	4	43	286	0.014	0.150
2006	**SFH**	**SM1**	90	38	340	0.264	0.112
2007	**SFH**	**SM1**	104	104	252	0.413	0.413
2008	**SFH**	**SM1**	44	92	220	0.200	0.418
2009	**SFH**	**SM1**	286	109	292	0.978	0.373
2010	**SFH**	**SM1**	426	78	238	1.792	0.328
2011	**SFH**	**SM1**	18	81	266	0.068	0.305
2004	**SFH**	**SM2**	32	35	346	0.092	0.101
2005	**SFH**	**SM2**	26	71	272	0.096	0.261
2006	**SFH**	**SM2**	77	81	255	0.302	0.317
2007	**SFH**	**SM2**	49	125	231	0.212	0.540
2008	**SFH**	**SM2**	110	103	207	0.531	0.497
2009	**SFH**	**SM2**	225	72	228	0.988	0.316
2010	**SFH**	**SM2**	284	77	211	1.348	0.366
2011	**SFH**	**SM2**	98	43	196	0.500	0.220
2004	**SFH**	**SM3**	123	145	443	0.278	0.328
2005	**SFH**	**SM3**	99	187	513	0.193	0.364
2006	**SFH**	**SM3**	185	171	509	0.364	0.336
2007	**SFH**	**SM3**	185	173	428	0.433	0.404
2008	**SFH**	**SM3**	140	207	295	0.474	0.701
2009	**SFH**	**SM3**	313	133	370	0.846	0.360
2010	**SFH**	**SM3**	221	145	374	0.591	0.388
2011	**SFH**	**SM3**	220	133	315	0.699	0.423
2004	**SFH**	**SM4**	133	94	444	0.300	0.212
2005	**SFH**	**SM4**	45	104	481	0.093	0.216

Year	Water-shed	Segment	Count Age-0 (#)	Count Age-1+ (#)	Sampled Length (m)	Density Age-0 (#/m)	Density Age-1+ (#/m)
2006	**SFH**	**SM4**	158	110	516	0.306	0.213
2007	**SFH**	**SM4**	191	93	476	0.402	0.196
2008	**SFH**	**SM4**	47	178	269	0.175	0.661
2009	**SFH**	**SM4**	83	128	328	0.253	0.390
2010	**SFH**	**SM4**	100	96	319	0.314	0.301
2011	**SFH**	**SM4**	133	146	285	0.467	0.513
2004	**SFH**	**ST1**	14	27	491	0.028	0.055
2005	**SFH**	**ST1**	9	46	423	0.021	0.109
2006	**SFH**	**ST1**	19	35	417	0.046	0.084
2007	**SFH**	**ST1**	11	54	302	0.036	0.179
2008	**SFH**	**ST1**	26	57	231	0.113	0.247
2009	**SFH**	**ST1**	34	89	292	0.116	0.305
2010	**SFH**	**ST1**	22	39	241	0.091	0.162
2011	**SFH**	**ST1**	57	59	254	0.224	0.232
2004	**SFH**	**ST2**	68	105	380	0.179	0.276
2005	**SFH**	**ST2**	65	79	319	0.204	0.248
2006	**SFH**	**ST2**	88	93	388	0.227	0.240
2007	**SFH**	**ST2**	72	73	375	0.192	0.194
2008	**SFH**	**ST2**	74	208	451	0.164	0.461
2009	**SFH**	**ST2**	110	125	284	0.387	0.440
2010	**SFH**	**ST2**	89	102	340	0.262	0.300
2011	**SFH**	**ST2**	81	92	286	0.283	0.321
2004	**SFH**	**ST3**	17	55	215	0.079	0.256
2005	**SFH**	**ST3**	19	34	179	0.106	0.189
2006	**SFH**	**ST3**	39	35	145	0.269	0.241
2007	**SFH**	**ST3**	38	58	176	0.216	0.330
2008	**SFH**	**ST3**	11	133	193	0.057	0.689
2009	**SFH**	**ST3**	2	28	119	0.017	0.235
2010	**SFH**	**ST3**	93	21	133	0.701	0.158
2011	**SFH**	**ST3**	112	83	144	0.780	0.578
2004	**NFH**	**NM1**	173	59	359	0.482	0.164

Year	Water-shed	Segment	Count Age-0 (#)	Count Age-1+ (#)	Sampled Length (m)	Density Age-0 (#/m)	Density Age-1+ (#/m)
2005	**NFH**	**NM1**	157	49	201	0.781	0.244
2006	**NFH**	**NM1**	540	83	295	1.831	0.281
2007	**NFH**	**NM1**	107	59	280	0.382	0.211
2008	**NFH**	**NM1**	169	108	291	0.581	0.371
2009	**NFH**	**NM1**	211	87	291	0.726	0.299
2010	**NFH**	**NM1**	210	96	285	0.737	0.337
2011	**NFH**	**NM1**	86	58	266	0.323	0.218
2004	**NFH**	**NM2**	59	29	198	0.299	0.147
2005	**NFH**	**NM2**	156	44	141	1.107	0.312
2006	**NFH**	**NM2**	285	65	201	1.417	0.323
2007	**NFH**	**NM2**	67	58	197	0.340	0.295
2008	**NFH**	**NM2**	97	112	209	0.464	0.535
2009	**NFH**	**NM2**	230	72	232	0.991	0.310
2010	**NFH**	**NM2**	80	41	181	0.441	0.226
2011	**NFH**	**NM2**	48	60	175	0.274	0.343
2004	**NFH**	**NM34**	55	136	603	0.091	0.226
2005	**NFH**	**NM34**	96	105	475	0.202	0.221
2006	**NFH**	**NM34**	609	132	595	1.024	0.222
2007	**NFH**	**NM34**	190	221	610	0.312	0.362
2008	**NFH**	**NM34**	120	332	635	0.189	0.523
2009	**NFH**	**NM34**	180	258	492	0.366	0.525
2010	**NFH**	**NM34**	58	222	420	0.138	0.528
2011	**NFH**	**NM34**	82	156	447	0.184	0.349
2004	**NFH**	**NT1**	25	25	287	0.087	0.087
2005	**NFH**	**NT1**	19	50	177	0.108	0.283
2006	**NFH**	**NT1**	104	28	208	0.500	0.135
2007	**NFH**	**NT1**	14	31	198	0.071	0.157
2008	**NFH**	**NT1**	23	62	276	0.083	0.224
2009	**NFH**	**NT1**	14	39	169	0.083	0.231
2010	**NFH**	**NT1**	0	48	172	0.000	0.279
2011	**NFH**	**NT1**	11	24	146	0.075	0.164

Year	**Water-shed**	**Segment**	Count Age-0 **(#)**	Count Age-1+ **(#)**	Sampled Length **(m)**	Density Age-0 **(#/m)**	Density Age-1+ **(#/m)**
2004	**NFH**	**NT2**	72	51	337	0.213	0.151
2005	**NFH**	**NT2**	120	40	275	0.437	0.146
2006	**NFH**	**NT2**	84	62	245	0.342	0.253
2007	**NFH**	**NT2**	27	39	170	0.159	0.229
2008	**NFH**	**NT2**	42	117	283	0.148	0.413
2009	**NFH**	**NT2**	62	72	192	0.322	0.374
2010	**NFH**	**NT2**	23	86	246	0.093	0.349
2011	**NFH**	**NT2**	45	75	263	0.171	0.285
2004	**NFH**	**NT3**	5	11	217	0.023	0.051
2005	**NFH**	**NT3**	10	17	134	0.075	0.127
2006	**NFH**	**NT3**	34	12	134	0.255	0.090
2007	**NFH**	**NT3**	0	13	143	0.000	0.091
2008	**NFH**	**NT3**	11	7	165	0.067	0.043
2009	**NFH**	**NT3**	2	12	91	0.022	0.132
2010	**NFH**	**NT3**	1	10	113	0.009	0.089
2011	**NFH**	**NT3**	6	14	120	0.050	0.117

APPENDIX C- HYDROLOGIC DATA

Table C-1 Hydrologic indices from the NFHC and SFHC gaging stations expressed in mm (Min7FW, MaxAN, Q10SP, MaxEM, Q90SM) and # of storms (FreqEM). NFHC and SFHC gaging stations correspond to NFH and SFH watersheds, respectively. These data were used in correlation analysis at the watershed-level and stream-segment level.

Year	Watershed	Min7FW (mm)	MaxAN (mm)	Q10SP (mm)	MaxEM (mm)	FreqEM (# of storms)	Q90SM (mm)
2004	NFH	0.08	17.15	5.50	6.86	2	0.14
2005	NFH	0.16	19.44	4.22	13.72	2	0.09
2006	NFH	0.13	35.16	5.58	4.00	0	0.06
2007	NFH	0.06	22.87	8.29	1.66	0	0.05
2008	NFH	0.13	15.43	8.46	4.00	0	0.08
2009	NFH	0.04	28.58	6.86	7.72	1	0.06
2010	NFH	0.09	11.43	8.14	11.43	4	0.12
2011	NFH	0.15	24.29	9.65	6.00	2	0.10
2004	SFH	0.16	20.31	5.97	14.44	3	0.22
2005	SFH	0.37	24.38	4.18	11.96	1	0.18
2006	SFH	0.26	48.53	7.67	5.64	0	0.18
2007	SFH	0.17	25.05	8.95	2.05	0	0.15
2008	SFH	0.29	20.09	8.21	4.51	0	0.21
2009	SFH	0.20	56.42	7.00	11.96	1	0.22
2010	SFH	0.25	18.73	9.48	18.73	3	0.34
2011	SFH	0.44	24.83	12.47	6.09	0	0.33

APPENDIX D- SPATIAL INCONGRUENCE

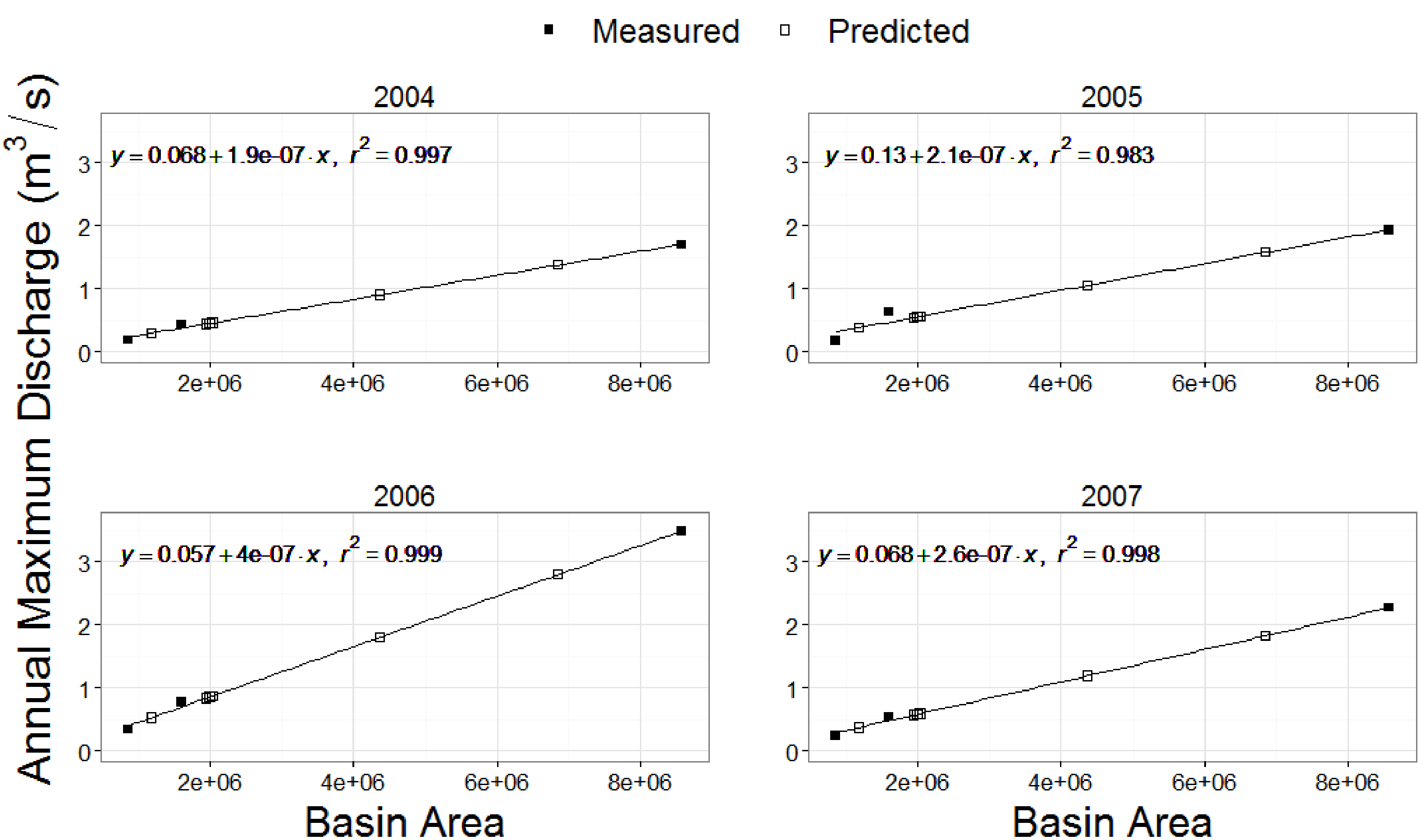

Figure A-1 Maximum annual runoff in NFH from 2004–2007 at measured and predicted sites with regression equation.

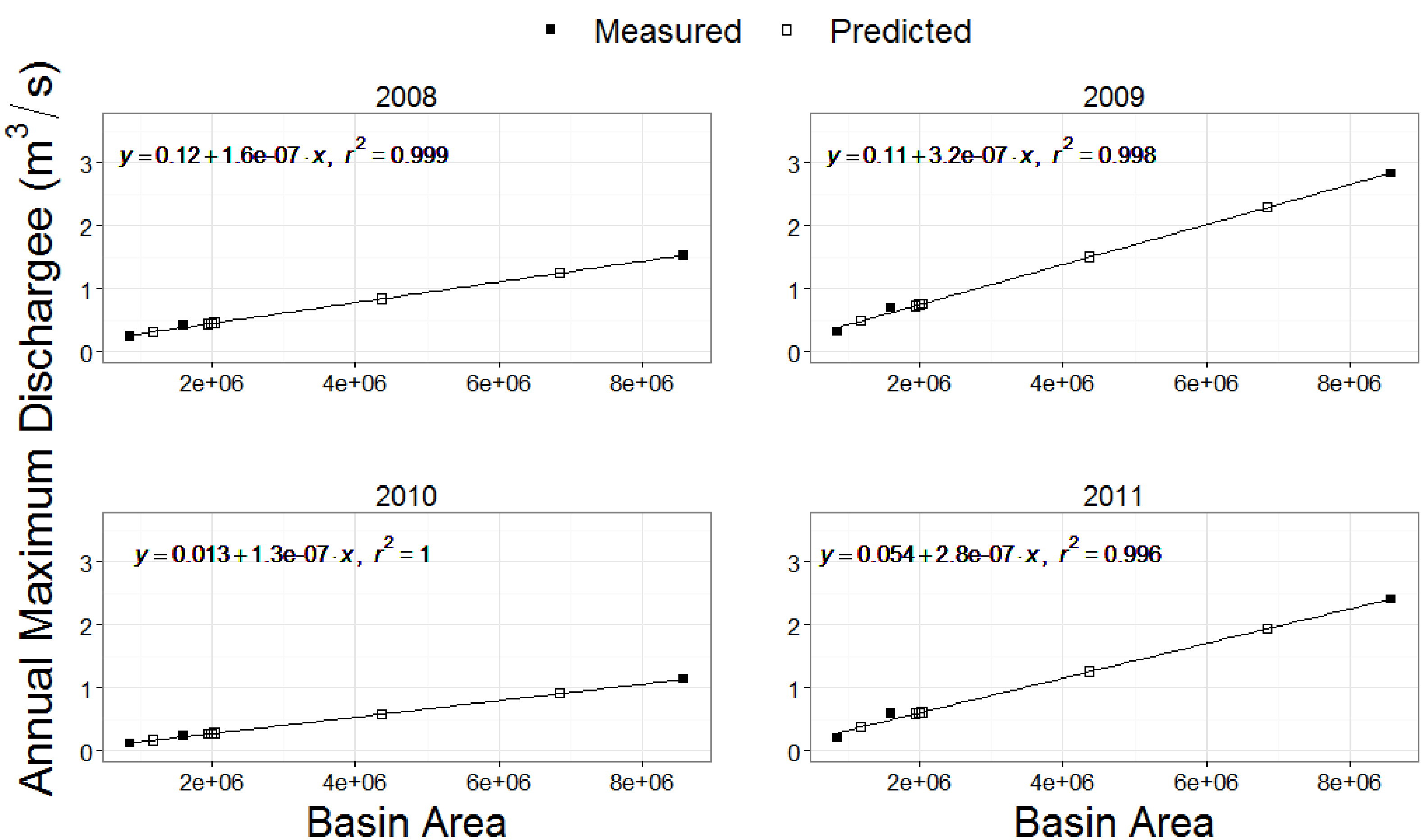

Figure A-2 Maximum annual runoff in NFH from 2008–2011 at measured and predicted sites with regression equation.

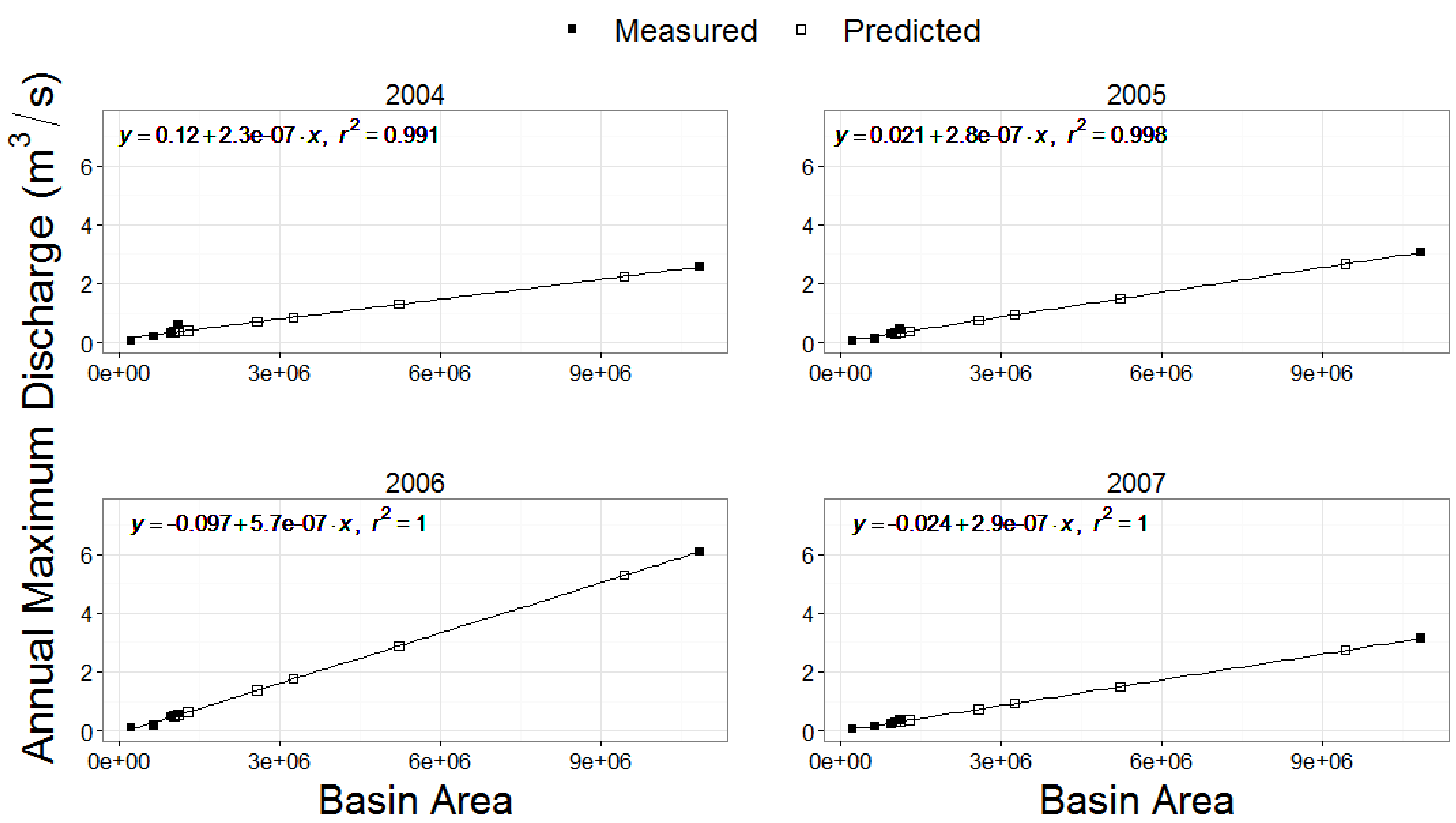

Figure A-3 Maximum annual runoff in SFH from 2004–2007 at measured and predicted sites with regression equation.

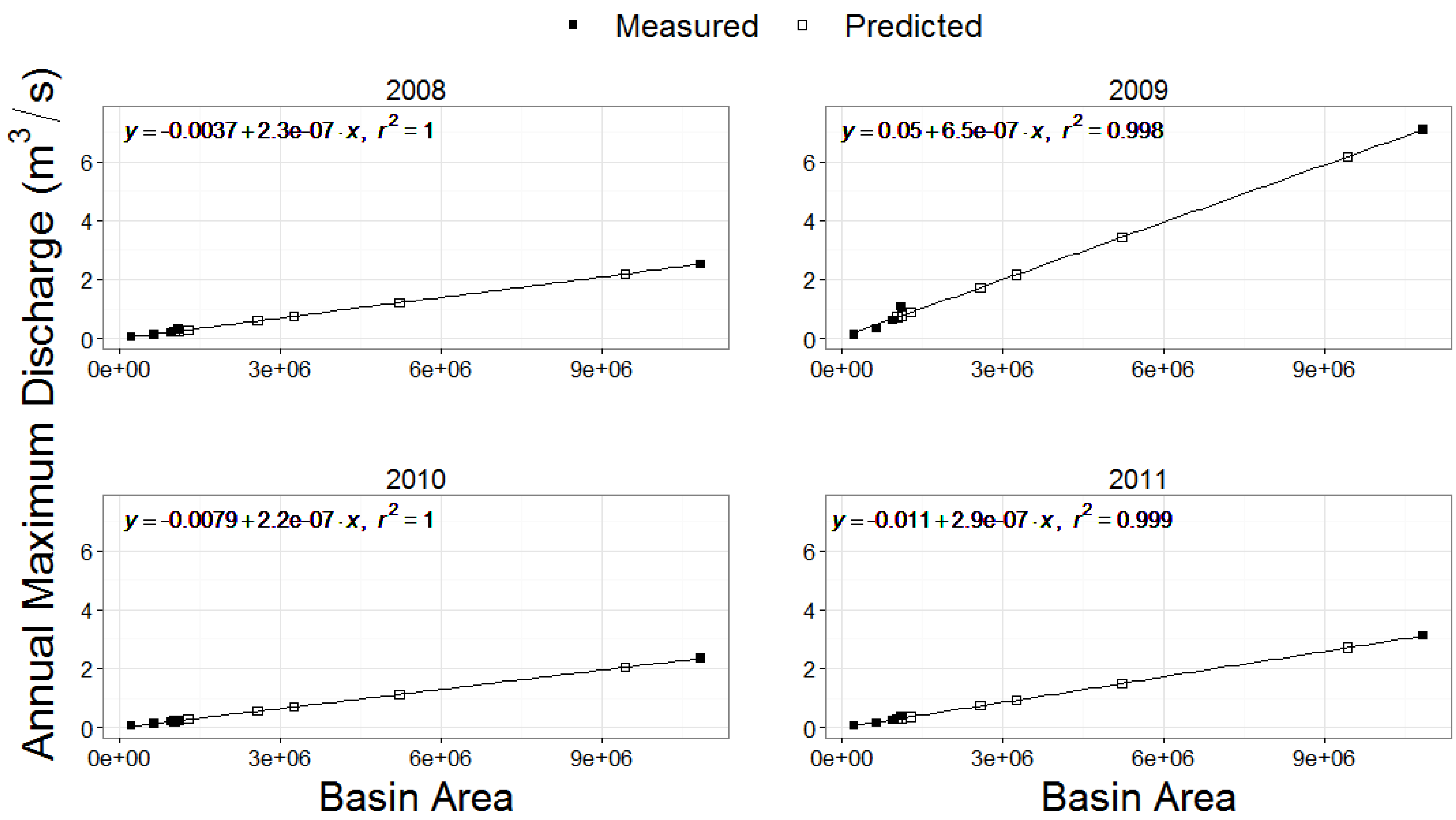

Figure A-4 Maximum annual runoff in SFH from 2004–2008 at measured and predicted sites with regression equation.

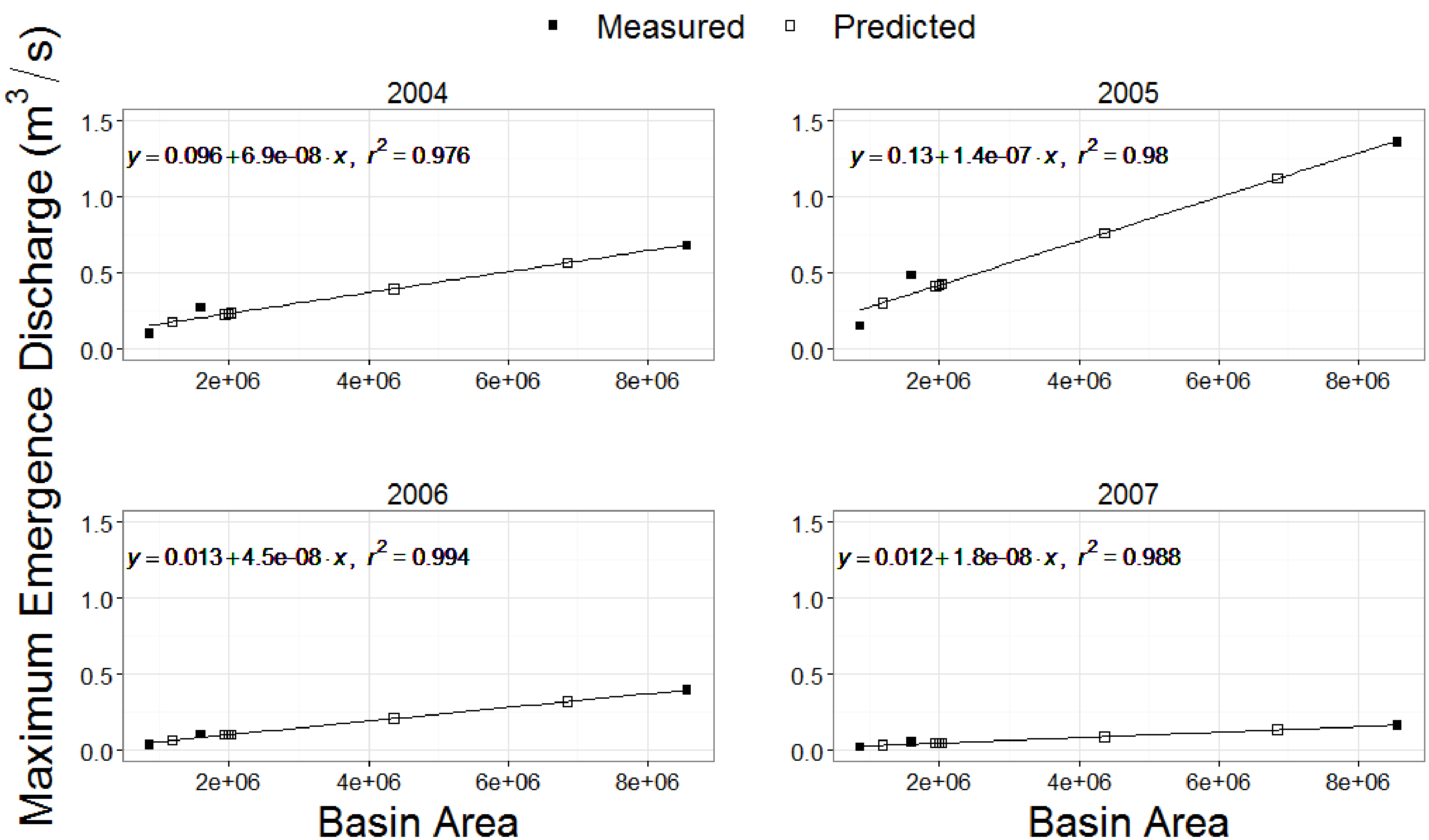

Figure A-5 Maximum emergence discharge in NFH from 2004–2007 at measured and predicted sites with regression equation.

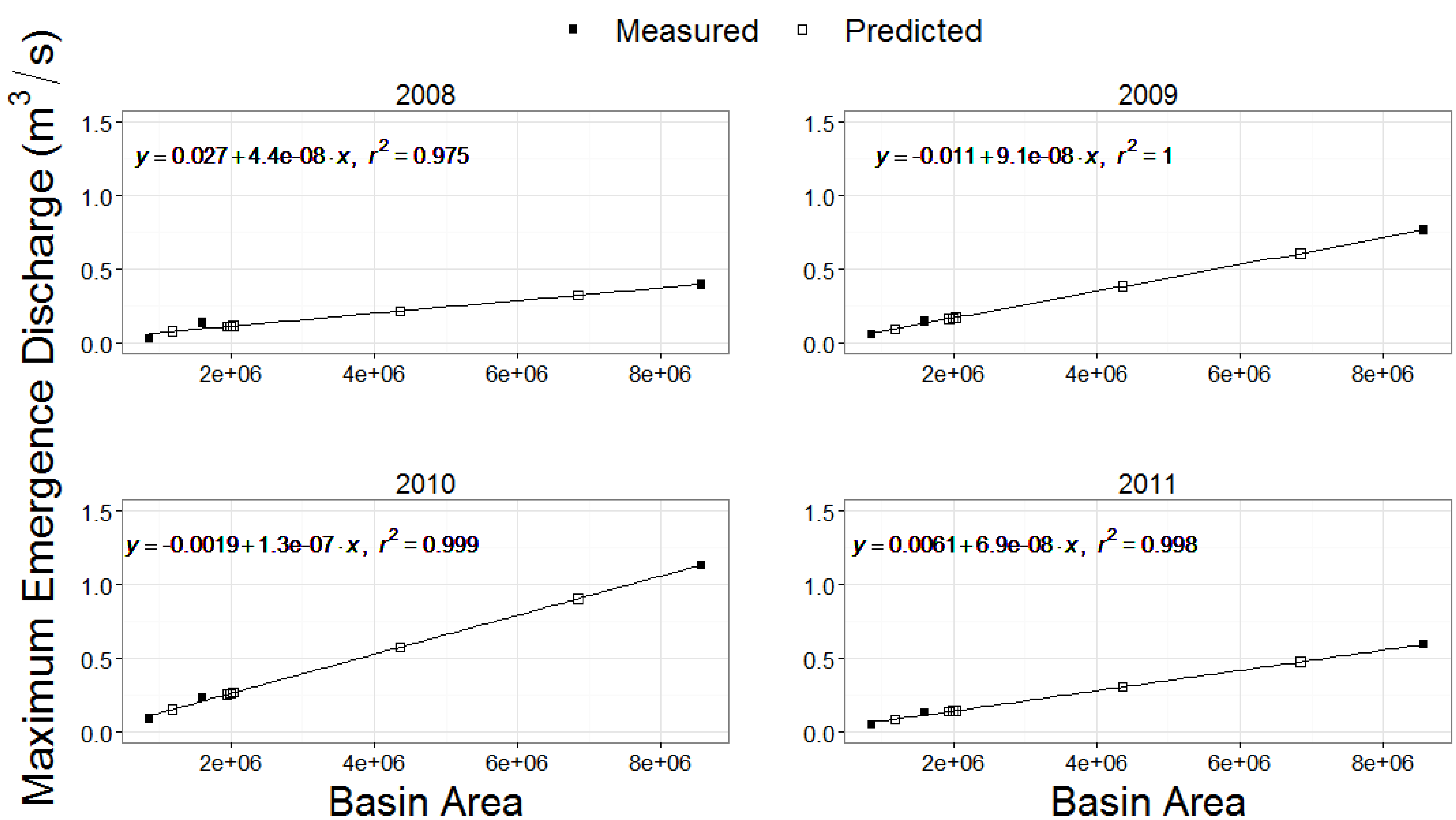

Figure A-6 Maximum emergence discharge in NFH from 2008–2011 at measured and predicted sites with regression equation.

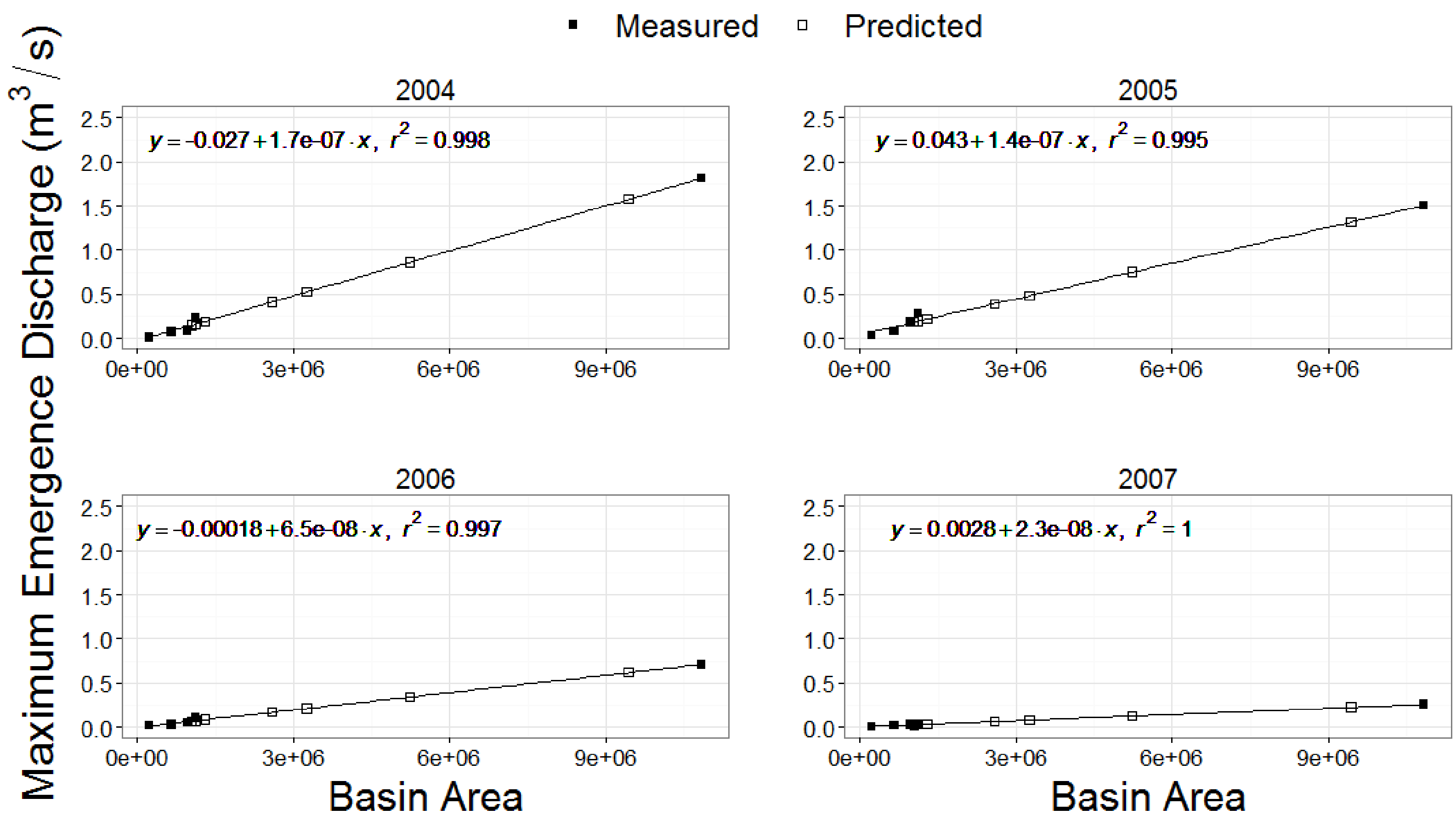

Figure A-7 Maximum emergence discharge in SFH from 2004–2007 at measured and predicted sites with regression equation.

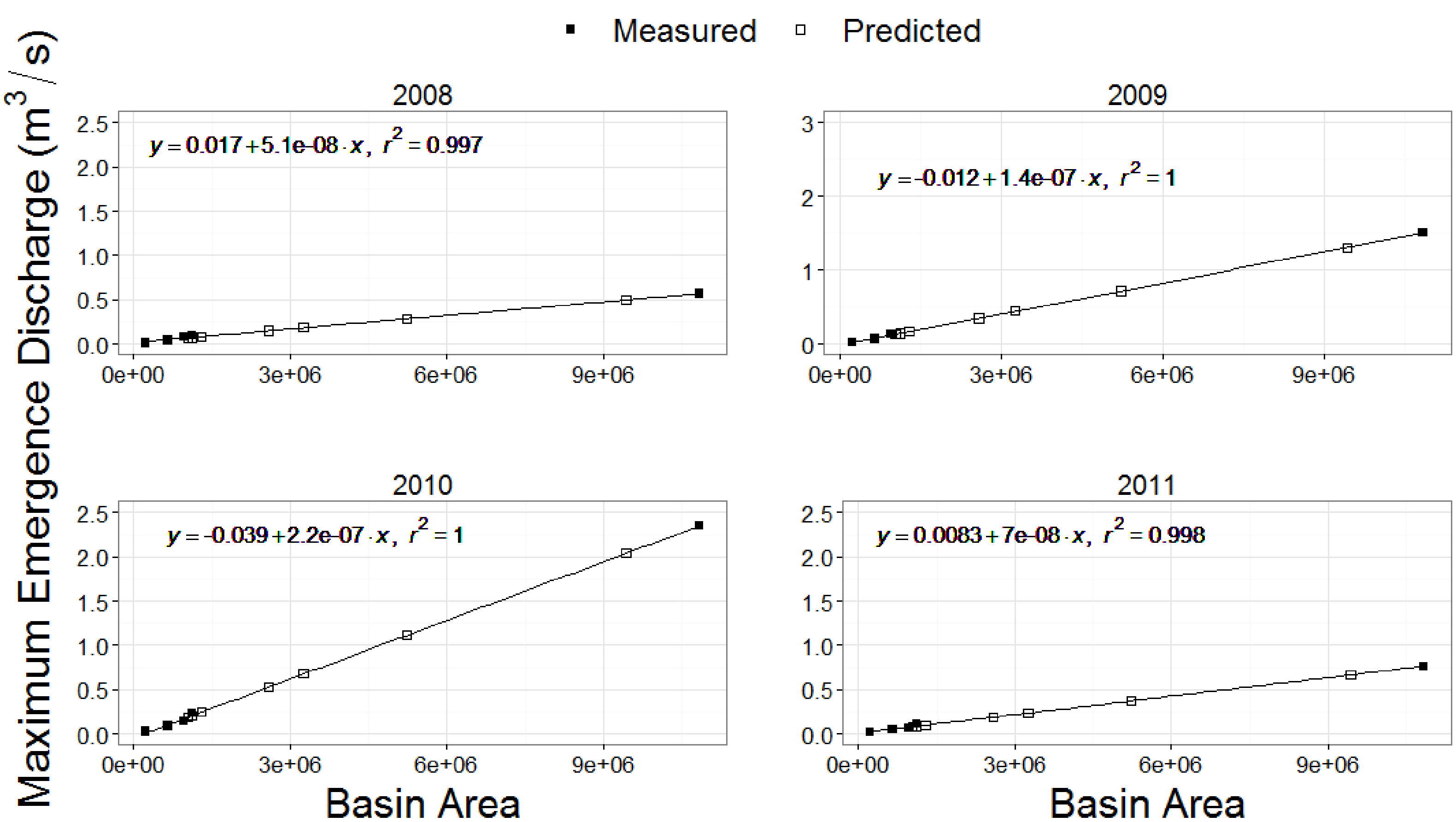

Figure A-8 Maximum emergence discharge in SFH from 2008–2011 at measured and predicted sites with regression equation.

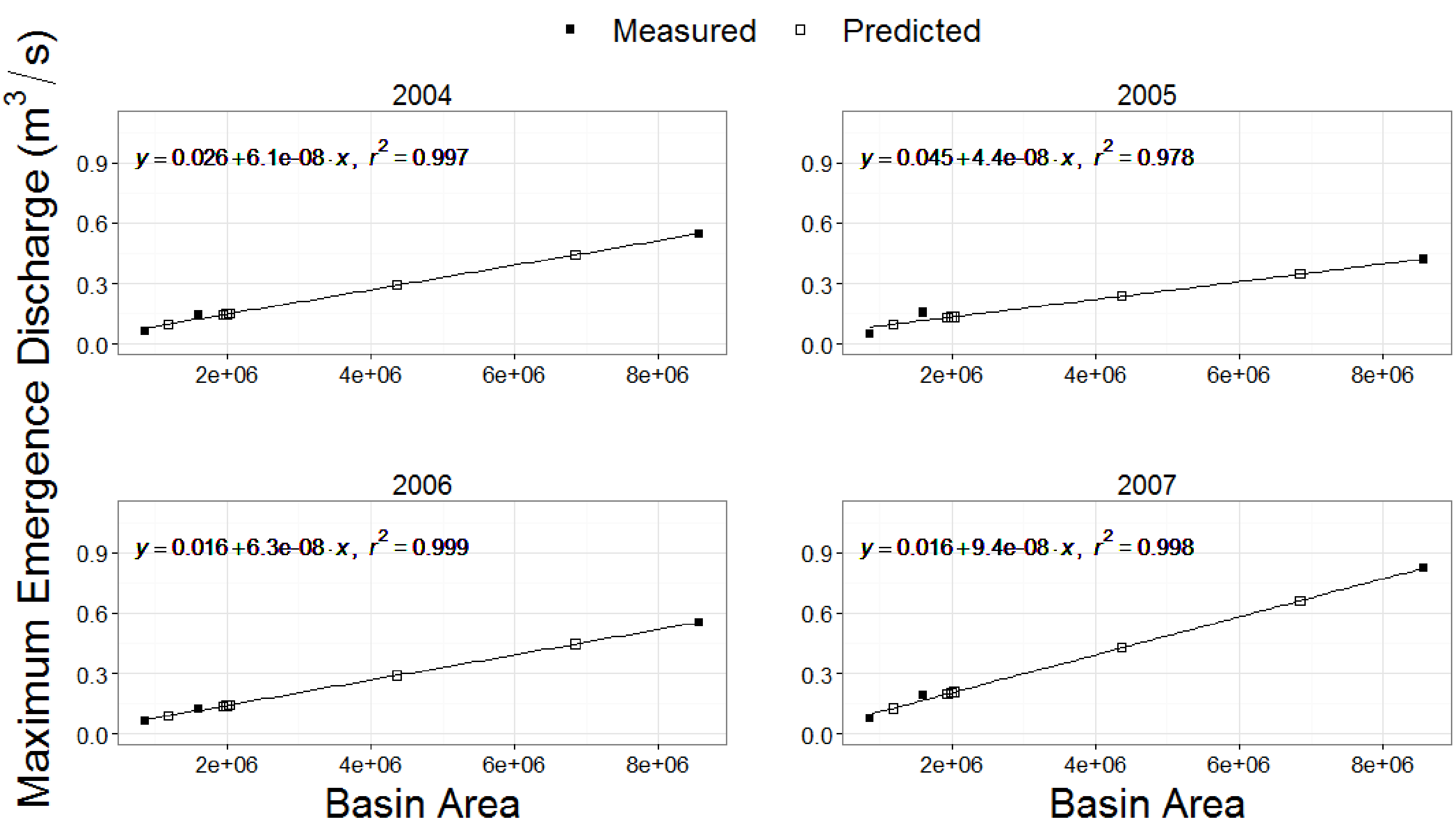

Figure A-9 Q10 Spawning discharge in NFH from 2004–2007 at measured and predicted sites with regression equation.

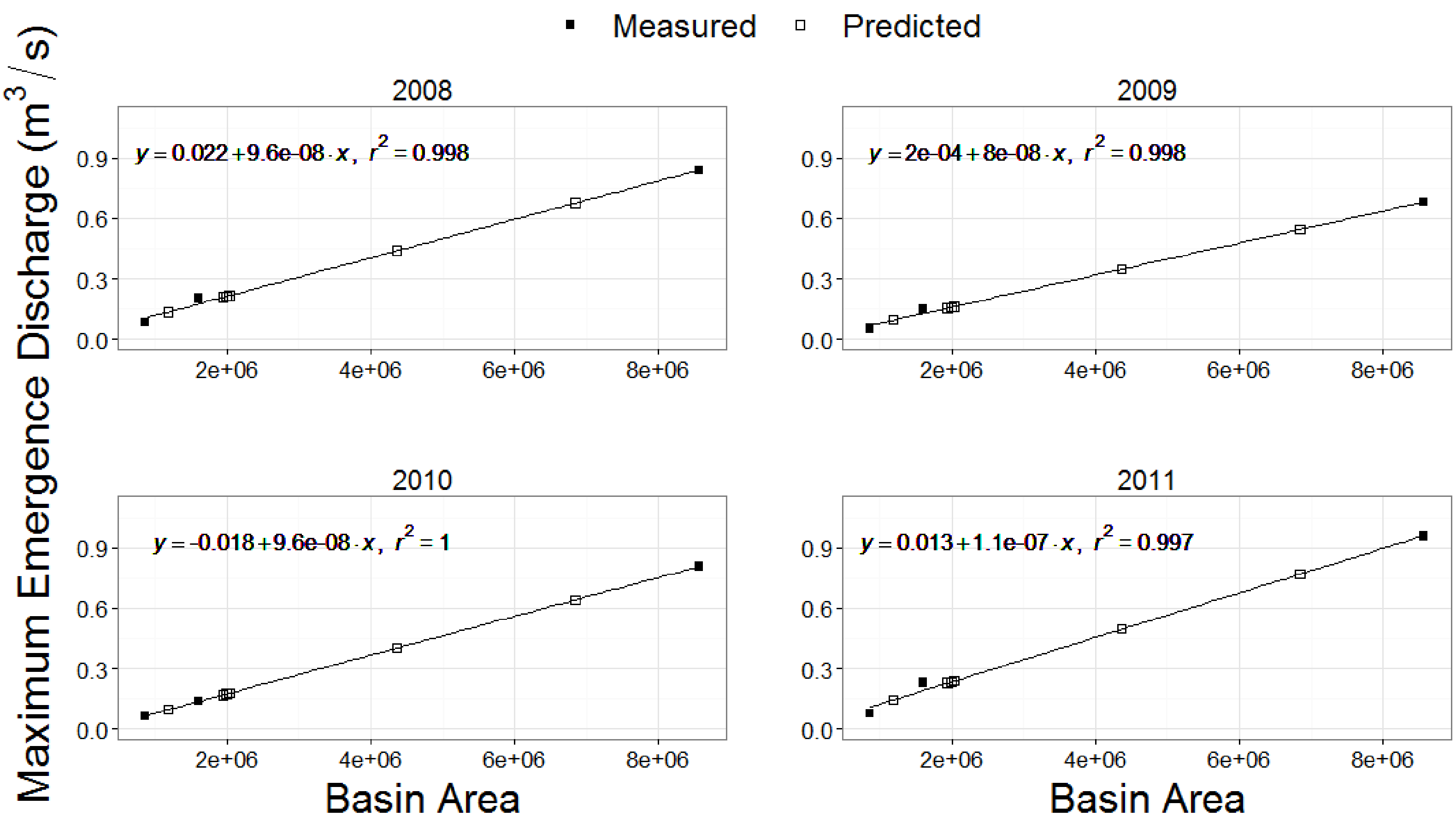

Figure A-10 Q10 Spawning discharge in NFH from 2008–2011 at measured and predicted sites with regression equation.

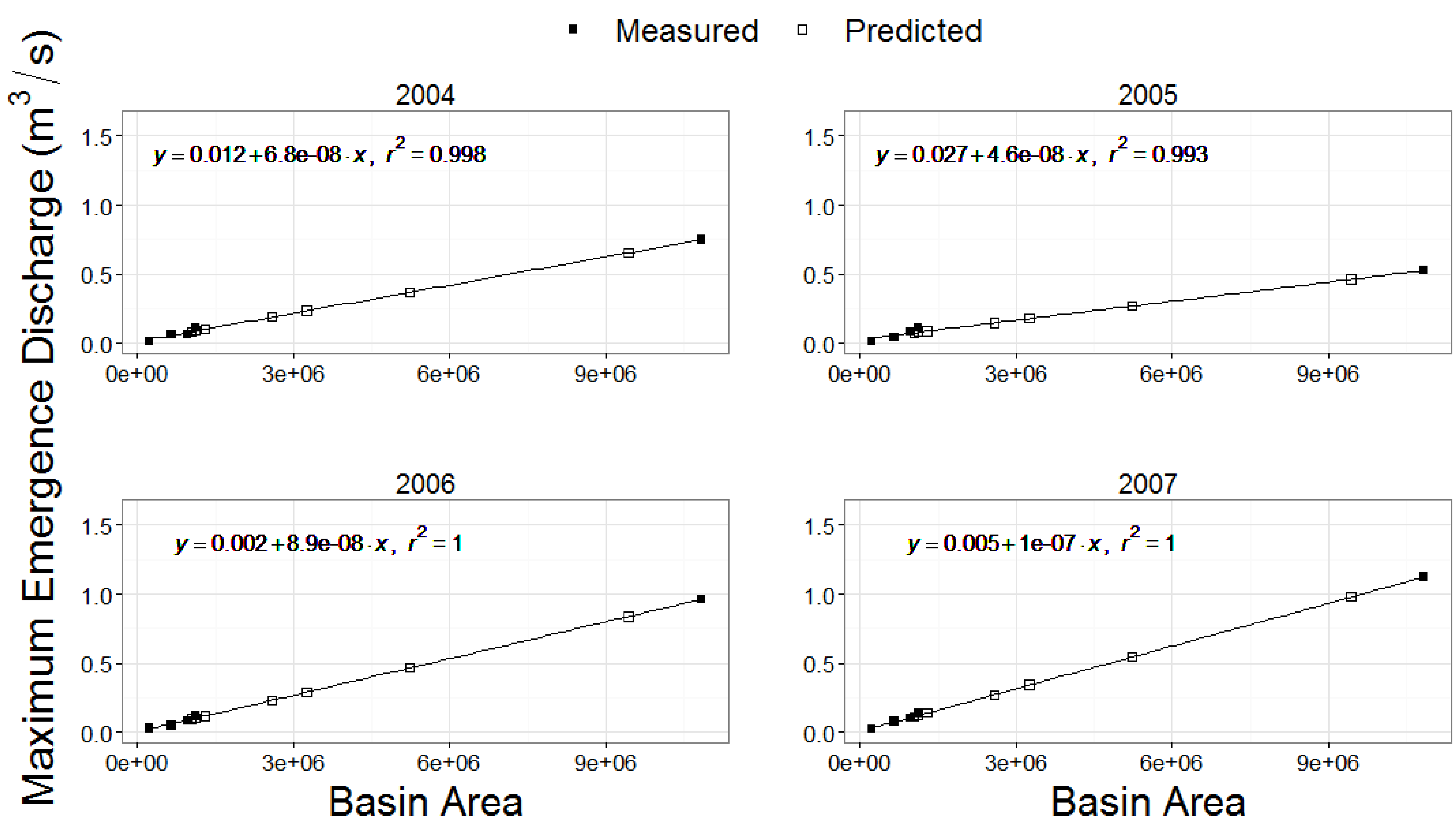

Figure A-11 Q10 Spawning discharge in SFH from 2004–2007 at measured and predicted sites with regression equation.

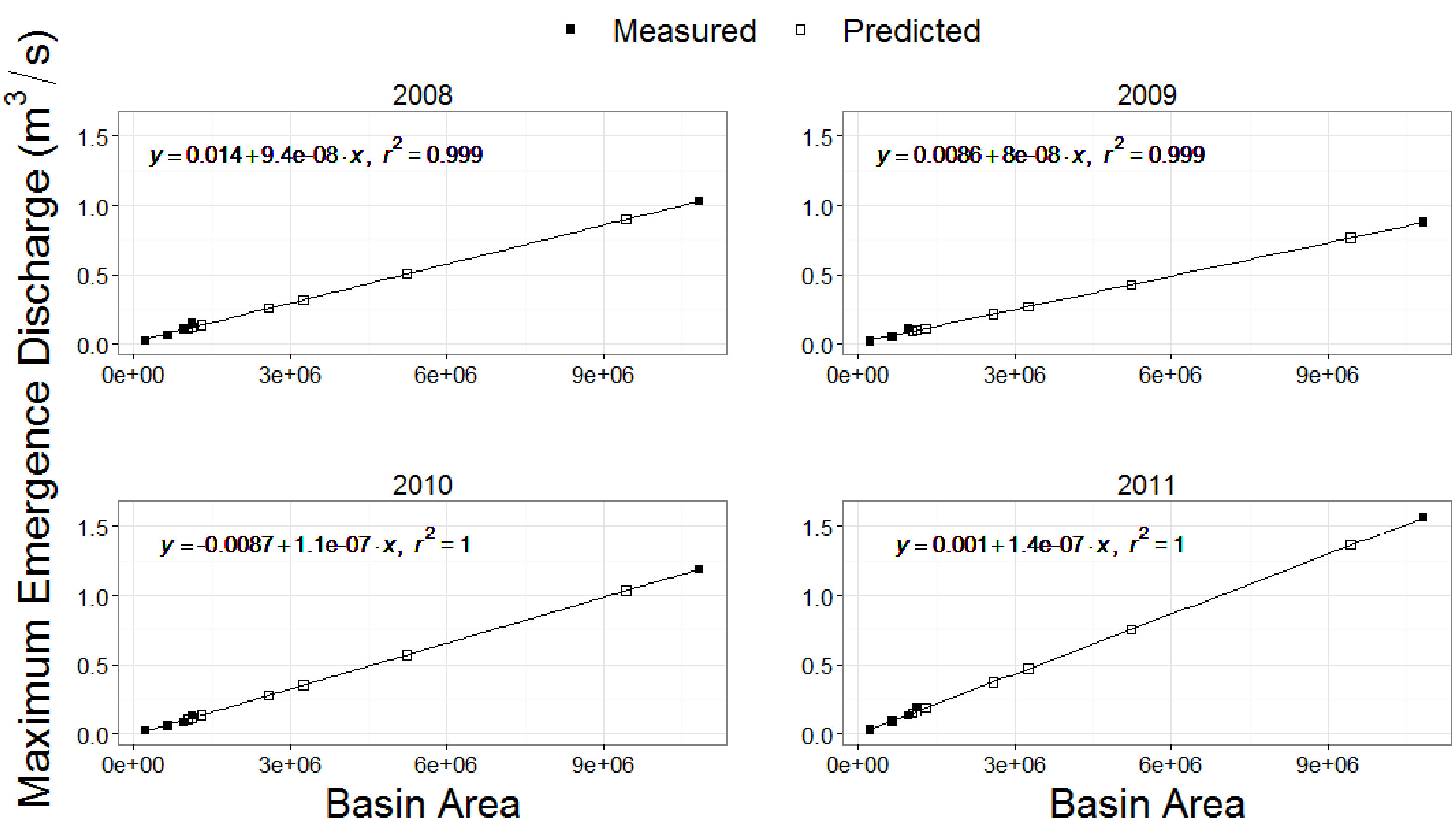

Figure A-12 Q10 Spawning discharge in SFH from 2008–2011 at measured and predicted sites with regression equations.