ALBERT LUDWIGS UNIVERSITY FREIBURG

MASTER THESIS

Assessing Climate Impacts Against Groundwater Pumping Impacts on Stream Flow with Statistical Analysis

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Declaration of Authorship

I, Jonas PYSCHIK, declare that this thesis titled, "Assessing Climate Impacts Against Groundwater Pumping Impacts on Stream Flow with Statistical Analysis" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
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“The most exciting phrase to hear in science, the one that heralds the most discoveries, is not "Eureka!" (I found it!) but 'That's funny...'.”

Isaac Asimov

ALBERT LUDWIGS UNIVERSITY FREIBURG

Abstract

Faculty of Environment and Natural Resources

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Master of Science

Assessing Climate Impacts Against Groundwater Pumping Impacts on Stream Flow with Statistical Analysis

by Jonas PYSCHIK

Declining summer streamflow is observed in Pacific Northwest catchments, impacting endangered salmon species which need sufficient flow to reach their spawning grounds. Groundwater pumping for irrigation is generally considered to cause lower summer flow. However, it is unclear, how much water is lost due to water use or climatic factors, as there often is no data on pumping-volume. In this study we assess the lost amount of streamflow during summer low flows and quantify the shares attributable to climate change and agricultural water-consumption, only using streamflow data. As a case study we focused on the Scott River catchment, California, having 7% agricultural land use. We compared summer streamflow, snow water equivalent and precipitation betweenhistoric (pre-development: 1940-1976), intermediate (post-development: 1977-1999), and modern (potential mega-drought: 2000-2020) timeframes. Snow water equivalent showed negative significant trends at lower elevations (1600-1800 m). We also observed significant negative trends in mean and minimum streamflow as well as earlier starting and longer lasting low flow season. Using a paired-basin approach we were able to detect a mean 38.5% (37.5 +/- 3 Mm^3) streamflow decrease from historic to modern timeframe years, where 14.6% (14.25 +/- 1.4 Mm^3) were attributable to increased agricultural water consumption and 23.9% (23.2 +/- 1.4 Mm^3) to climate change. These results demonstrate that agriculture substantially impacts streamflow; however, the influence of climate change dominates. Therefore, base flow restoration during the critical dry period cannot be achieved by pumping curtailments alone. A possibility to ensure enough flow for endangered salmon could be artificial aquifer recharge during high flows to top of low flow season.

Keywords: Streamflow, Climate Change, Groundwater, Agriculture, Snow, California

Abstract German

In den Einzugsgebieten des pazifischen Nordwestens wird ein abnehmender Sommerabfluss beobachtet, der sich auf gefährdete Lachsarten auswirkt, welche genügend Abfluss benötigen, um ihre Laichgründe zu erreichen. Grundwasserpumpen zur Bewässerung werden als Ursache für niedrige Sommerabflüsse aufgeführt. Unklar ist allerdings, wie viel Wasser durch Wasserverbrauch oder klimatische Faktoren verloren geht, da es oft keine Daten zum Wasserverbrauch durch landwirtschaftliche Pumpen gibt. In dieser Studie ermitteln wir die verlorene Menge an Abfluss während sommerlicher Niedrigwassermengen und quantifizieren die Anteile, die auf den Klimawandel und den landwirtschaftlichen Wasserverbrauch zurückzuführen sind, nur unter Verwendung von Abflussdaten. Als Fallstudie konzentrierten wir uns auf das Scott River-Einzugsgebiet in Kalifornien, das 7% landwirtschaftliche Landnutzung aufweist. Wir haben Sommerabfluss, Schneewasseräquivalent und Niederschlag zwischen historischen (1940-1976), mittleren (1977-1999) und modernen (2000-2020) Zeiten verglichen. Das Schneewasseräquivalent zeigte negative signifikante Trends in niedrigeren Lagen (1600-1800 m). Wir beobachteten auch signifikante negative Trends beim mittleren und minimalen Abfluss sowie eine früher beginnende und länger anhaltende Niedrigwassersaison. Mit einem Paired Catchment Ansatz konnten wir einen durchschnittlichen Rückgang des Sommerabflusses um 38,5% (37,5 +/- 3 Mm^3) von historischen bis zu modernen Zeiträumen feststellen, wobei 14,6% (14,25 +/- 1,4 Mm^3) auf den landwirtschaftlichen Wasserverbrauch und 23,9% (23,2 +/- 1,4 Mm^3) auf den Klimawandel zurückzuführen waren. Diese Ergebnisse zeigen, dass die Landwirtschaft den Abfluss erheblich beeinflusst; der Einfluss des Klimawandels dominiert jedoch. Daher ist es nicht ausreichend, den Wasserverbrauch im Sommer zu stoppen, um niedrige Flüsse zu erhöhen. Eine Möglichkeit, einen ausreichenden Durchfluss für gefährdete Lachse zu gewährleisten, könnte die künstliche Grundwasserneubildung bei hohen Abflüssen bis zur Niedrigwassersaison sein.

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List of Abbreviations

BRT	**B**oosted **R**egression **T**ree
CART	**C**lassification **A**nd **R**egression **T**rees
DOY	**D**ay **Of** (the) **Y**ear
FDOY	**F**irst **D**ay **Of** (the) **Y**ear
FNS	**F**irst (day with) **N**o **S**now
LDOY	**L**ast **D**ay **Of** (the) **Y**ear
LOC	**L**ine (of) **O**rganic **C**orrelation
MEAN.A.T	**Mean A**fter **T**hreshold (is exceeded)
NRCS	**N**atural **R**esources **C**onservation **S**ervice
PDO	**P**acific **D**ecadal **O**scillation
SWE	**S**now **W**ater **E**quivalent
TF	**T**ime **F**rame
USGS	**U**nited **S**tates **G**eological **S**urvey
VPD	(maximum) **V**apor **P**ressure **D**eficit

1 Introduction

1.1 Introduction

Since the start of the industrial revolution in 1880 the climate warmed by 1.1°C, being on a warming trajectory of 0.15 to 0.2°C each decade since 1975 (NASA, 15.02.2022). This in turn has major hydrological influences. Studies suggest, that dry areas turn drier and wet areas become wetter. According to the Clausius-Clapeyron relationship, the warming trend also causes an enhanced water vapor uptake by air, increasing 7% every 1°C. This leads to more intense rainstorms, even though total precipitation may decrease (Trenberth, 2011; Rhoades, Ullrich, and Zarzycki, 2018).

Another effect of warming is the shift of snow to rain and earlier snowmelt, leading to increased discharge earlier in the spring and to lower summer baseflow (Trenberth, 2011; Ashfaq et al., 2013; Berghuijs, Woods, and Hrachowitz, 2014). Snowpack accumulates over the winter season when precipitation falls as snow and temperatures are below freezing. This water storage is released starting in spring when temperature rises over meltingpoint (Mote, 2006; Kapnick and Hall, 2012). As this increase happens gradually along elevation contour, lower altitudes melt earlier than higher, causing a steady meltwater supply. This water either feeds streams directly or infiltrates in the soil, recharging underlying groundwater (Godsey, Kirchner, and Tague, 2014). In Mediterranean climate regions, where precipitation is centered in winter and summers are rather dry, this meltwater substantially contributes to streamflow by increasing baseflow (Li et al., 2017). Due to climate change, increased winter temperatures, exceeding freezing-point, cause less precipitation to fall as snow but rather rain (Ashfaq et al., 2013; Rhoades, Ullrich, and Zarzycki, 2018). This leads to increased winter discharge, exacerbating floods (Kim and Jain, 2010; Yarnell et al., 2015). Even if snow accumulates in winter, warming either leads to snowmelt or the occurrence of "rain-on-snow" events earlier in the year, shifting runoff of meltwater towards spring start (Gleick and Chalecki, 1999; Stewart, Cayan, and Dettinger, 2005; Mote, 2006; Barnhart et al., 2016; Mote et al., 2018; Xiao, Udall, and Lettenmaier, 2018). Therefore, warming causes earlier discharges without contributing to summer baseflow, causing lower dry-season flows (Mote et al., 2005; Ashfaq et al., 2013; Berghuijs, Woods, and Hrachowitz, 2014; Vano, Nijssen, and Lettenmaier, 2015; Asarian and Walker, 2016).

Climate warming also increases evaporation, causing surface drying which leads to prolonged and intensified droughts (Trenberth, 2011). Droughts start as precipitation deficits (*metrological droughts*), which causes a soil moisture deficit (*agricultural drought*) over shorter, and runoff and groundwater deficits (*hydrologic drought*) over longer timespans (Cook, Mankin, and Anchukaitis, 2018; AghaKouchak et al., 2021). These stages however are influenced by anthropogenic factors like climate change, causing shifted precipitation regimes (Ashfaq et al., 2013; Pathak et al., 2018; Allen et al., 2020), increased evaporation decreasing soil moisture (Trenberth, 2011), and lower snowpack reducing summer runoff (Drake, Tate, and Carlson, 2000, Beguería et al., 2003, Mote et al., 2005, Mote, 2006, van Kirk and Naman, 2008, Luce and Holden, 2009, Berghuijs, Woods, and Hrachowitz, 2014, Vano, Nijssen, and Lettenmaier, 2015, Barnhart et al., 2016, Asarian and Walker, 2016, Li et al., 2017, Xiao, Udall, and Lettenmaier, 2018). AghaKouchak et al., 2021 also linked land use and land cover changes to both agricultural and hydrological drought by altering infiltration and runoff generation. Increased water consumption also heavily affects the hydrologic cycle with decreased streamflow caused by dams and reservoirs and lowered groundwater table due to pumping.

In many semi-arid and arid regions, people rely on groundwater for irrigation, especially during agricultural and hydrological drought, as aquifer storage provides perceived resilience (Thomas et al., 2017). Often, against scientific evidence, groundwater and streamwater are treated as different entities and not as a single, interconnected resource (Famiglietti, 2014). When pumps extract groundwater, the hydraulic head decreases and a cone of depression forms around the well, creating an hydraulic gradient in its direction (Barlow and Leake, 2012). This impacts river discharge by either lowering the watertable, causing streamflow to seep in the underlying aquifer, or by extracting water which would otherwise have fed the stream (Tabidian and Pederson, 1995; Fleckenstein et al., 2004; Jasechko et al., 2021). In both cases, discharge decreases relative to no groundwater outtake. The stream is still influenced by precipitation with rising and falling discharge, however flowrates are not as high as they would be (Barlow and Leake, 2012).

California has been affected by a drought starting in 2000 which is unprecedented in the reliable instrumental records period (Richman and Leslie, 2015), caused by a multi-year midtropospheric high pressure region (also coined the "Ridiculously Resilient Ridge") at the Pacific coast blocking cold, wet air from reaching California (Swain, 2015). The western United States have always been impacted by variable temperatures and precipitation (Meko, Woodhouse, and Touchan, 2014), however the recent drought is special due to its anthropogenic influence (Diffenbaugh, Swain, and Touma, 2015). Williams et al., 2020 used a 1200 year tree-ring soil moisture reconstruction (years 1200 - 2018) and hydrologic model of California to show that only a megadrought in 1500 was drier and persisted longer than the drought in 2000-2018. The model showed the drought would not be as severe as it was, if no anthropogenic warming occurred. However due to climate change, this drought is on a trajectory towards becoming the next megadrought. This is underlined by Williams, Cook, and Smerdon, 2022 recent study in which they find that 2000-2021 now evolved to be the driest 22 year drought. Their simulations also show, that with a probability of 75% the drought will outlast the 30 year mark due to anthropogenic climate warming.

Since the start of year 2000, multiple years were exceptionally dry and hot. Mann and Gleick, 2015 analyzed discharge and precipitation in Sacramento and San Joaquin river basin and found that 10 of the years 2000-2014 were below average with 2012-2014 being the hottest and driest since instrumental records started. In a similar study, Richman and Leslie, 2015 ranked the cool season precipitation from wettest to driest and coldest to hottest since 1895. Their analysis showed, that the hottest and driest 3 year lasting periods all happened after the turn of the millennium. This deficit in winter precipitation and higher winter temperatures caused lowered snow accumulation. As this snow storage however is the largest component of water storage in many Californian catchments (Mote, 2006), the decrease caused Californian residents to switch to groundwater as their watersource. In wet years, about one-third of water is supplied by aquifers, however in 2014, one of the driest years, groundwater accounted for nearly two-thirds (Harter and Dahlke, 2014). These amounts however far exceed natural recharge, overdrafting the aquifer (Gleick and Palaniappan, 2010). This results in watertable declines, causing land subsidence (Famiglietti, 2014) and wells to dry up at rates never seen before (Harter and Dahlke, 2014).

As deficits in precipitation, increased evaporation and lowered hydraulic head lead to declined streamflow, this also effected renewable hydropower generation. With steadily rising electric power demand, California therefore increased its natural gas power production. This combustion however produces more greenhouse gasses, further contributing to anthropogenic climate change (Christian-Smith, Levy, and Gleick, 2015).

The lower Klamath Basin in northern California and southern Oregon is also affected by changing climate. Warmer winters (Mote et al., 2018), less snowpack (Mote, 2006), hotter summers, decreased summer precipitation (Asarian and Walker, 2016) and increased evapotranspiration (Tang, Rosenberg, and Lettenmaier, 2009) lead to lowered summer streamflow. This is exacerbated by agricultural water use in some of its tributaries (van Kirk and Naman, 2008). Decreased summer discharge however heavily restrict species like Chinook (*Oncorhynchus tschawytscha*) and endangered Coho salmon (*Oncorhynchus kisutch*) (Coates, 2005). These anadromous fish migrate up the Klamath tributaries to reach their spawning grounds (Drake, Tate, and Carlson, 2000). After mating, the eggs develop in the streambed gravel during winter, hatching in spring and emerging as fry in next years summer (Kim and Jain, 2010). However, due to low streamflow induced by climate change and anthropogenic water use, some tributaries become disconnected. In some years Scott River, which is the most important spawning and rearing ground for coho salmon, only remains as warm, stagnant pools in the riverbed (van Kirk and Naman, 2008). These conditions are insufficient for the endangered salmons, causing declines of their population (CDFW, 18.02.2022).

To counteract low summer streamflow in Scott River, the California Water Board set Curtailment Orders in place, which limits agricultural water use to a minimum once river discharge falls below a certain, monthly defined, threshold. Based on a water-right hierarchy, farmers are prohibited to extract water until the stream exceeds the threshold flow (Nolan, 2021).

1.2 Related Work

The influence of climate change and anthropogenic factors on lower Klamath tributaries, especially Scott river was studied by a few researchers:

Drake, Tate, and Carlson, 2000 analyzed Scott river streamflow, snow and precipitation with the first two showing negative trends. By formulating an equation of snow course and precipitation data predicting total September discharge, they concluded, that nearly 80% of the variance in streamflow can be explained by the climatic factors of snow water content and precipitation during the prior 12 months.

van Kirk and Naman, 2008 also studied streamflow and snow trends in five lower Klamath basins. They used permutation tests for hypothesis trend testing, splitting their data into two periods, defining a historic (1940s-1976) and modern (1977-2005) period. To attribute flowdeclines to groundwater pumping and climate change, they chose a paired approach, estimating flow in Scott River based on unimpaired flow in Salmon River. They found decreasing April 1 snow storage at lower altitudes and increasing at higher. Summer low flow also showed negative trends, however none of these were significant. Attributing the flowdecline, they concluded, that from historic to modern times, summer discharge decreased by 10 Mm^3. Roughly halve of the decline was associated with climate change or agricultural water use respectively. Their flow-attribution methodology, with some modifications, will also be used in our study, futher described later in this thesis.

Asarian and Walker, 2016 focused on multiple catchments in northern California and southern Oregon, also including the lower Klamath basins. Analyzing precipitation and streamflow, they mostly found decreases. Annual precipitation showed no trends, whereas September precipitation significantly declined in most catchments. This was also true for discharge in catchments without reservoirs and dams. In catchments without reservoirs and anthropogenic water use they found no trends. Therefore their analysis concluded, that flowdeclines originate from human water use rather than the climatic factor precipitation.

1.3 Research Approach & Objectives

The goal of this study is to analyze climatic trends and assess groundwater pumping impacts by agriculture on streamflow to provide insight in the declines of summer discharge in anthropogenic-influenced, snow reliant catchments. Thus we seek to differentiate between flow-declines caused by larger climatic factors and regional agricultural influences. This should help water agencies and decision makers in finding appropriate, effective measures against low summer discharges. As a case study we focus on the lower Klamath basin, concentrating on the Scott River watershed and its surrounding basins.

The results from preceding studies lead us to the following hypotheses:

- Due to climate warming, April 1 SWE is declining in all catchments, but trends are different between altitudes. Also snowmelt occurs earlier each year, especially in lower elevations.
- As the catchments lie in a region where only shifts in center of precipitation is predicted, there is no trend in annual, wateryear precipitation.
- Resulting from higher temperatures due to climate change, evaporation increased in the more recent years.
- Due to all the climatic factors which alter the hydrologic circle and change the water balance of a catchment, mean summer discharge is trending lower with longer lasting low-flow season.
- According to the findings of van Kirk and Naman, 2008 we hypothesize that due to increased warming relative to their analysis, streamflow-declines have further exacerbated. However, due to higher temperatures which lead to increased evaporation, resulting in higher irrigational water use, the share of decreases attributable to agriculture and climate change stayed the same.

Our objectives therefore are to (1) analyze local trends in precipitation, vapor pressure, snow storage and streamflow for catchments in the lower Klamath basin, (2) quantify summer streamflow declines in Scott River basin, associated with climate change or agricultural water consumption, (3) get qualitative estimates of relative influences from climatic factors on summer streamflow, and (4) investigate yearly snowmelt occurrence in each catchment. We will also discuss our results against those of the three previously described papers and further review current management practices and their benefits to endangered fish species.

2 Study Area

2.1 Study Area

Our study area is located in Northern California and Southern Oregon in the western United States. The catchments are predominantly mountainous with steep slopes and heights from 1700 to 4300 meters. The highest point is Mount Shasta (4300 meters). Climate is Mediterranean with dry summers and wet winters (Asarian and Walker, 2016). The annual precipitation sum is 500 to 2000 mm, predominately in winter and spring. Over 1500 m, precipitation falls almost exclusively as snow, which stores the water until melting season in spring. Consequently flow regime is dominated by snow/rain with winter peak flows, spring recession, summer baseflow and fall flush flows (Yarnell et al., 2015). Lane et al., 2018 classified the catchments as "Low Snowmelt and Rain" with variable winter and spring flows. This high variability results from rapid runoff due to the steep slopes and impermeable bedrock.

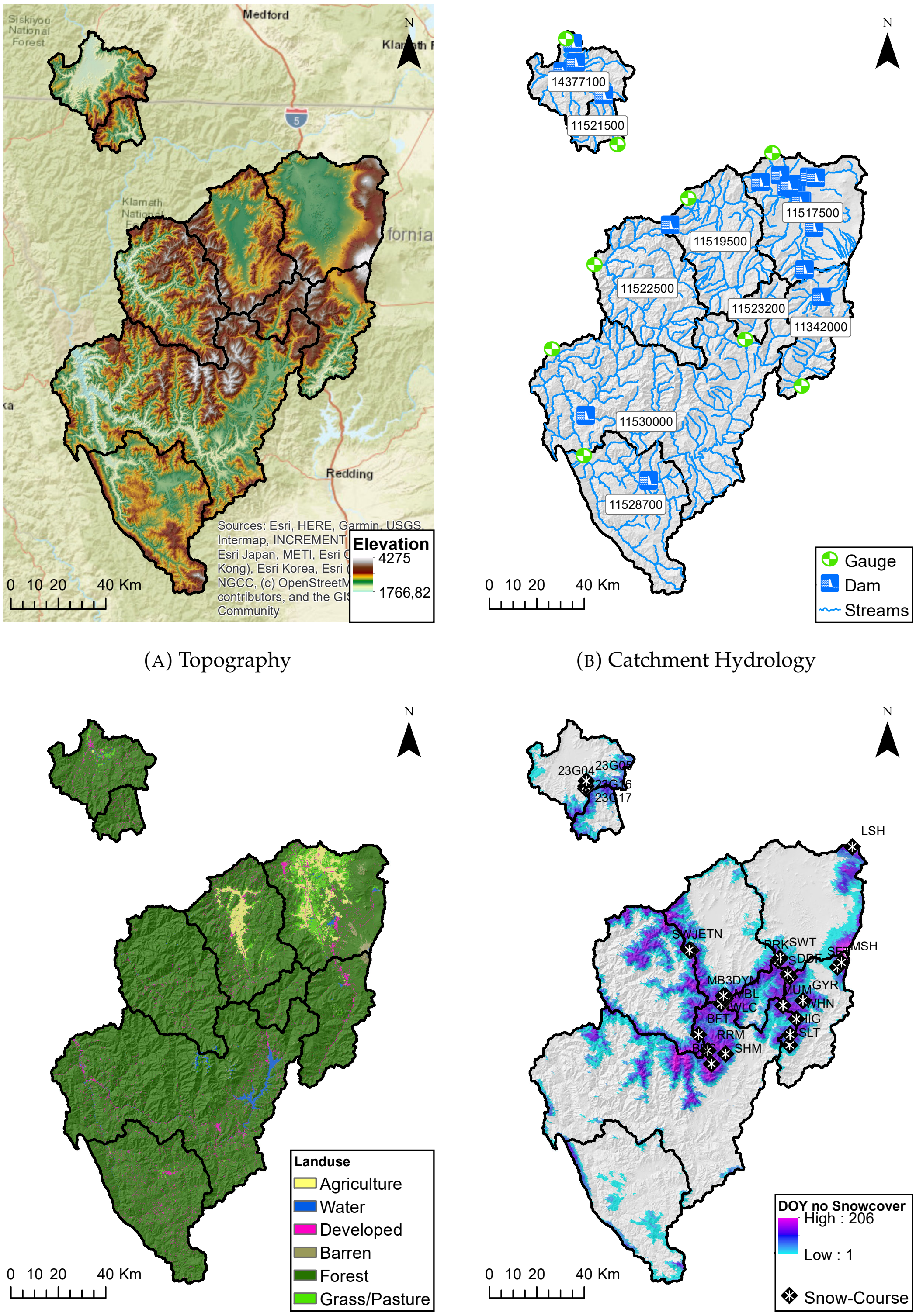
Subsequently to our objective to test for climate change impacts, only catchments in the lower Klamath basin area with gauging longer than 60 Years were selected. Gauges which meet these requirements are shown in a table 2.1 with their respective catchment information.

All watersheds are sparsely populated, the major vegetation is coniferous forest. The area is very fire-prone with major parts of Salmon (USGS ID: 115122500) being burned in the last century. Sacramento headwaters (USGS ID: 11342000) and Shasta (USGS ID: 11517500) have large reservoir storage, altering streamflow (data obtained from DWR[1] and Oregon State[2]). In Scott (USGS ID: 11519500) and Shasta Catchment, valley plains with shallow alluvial aquifers near the rivers are used for agriculture and pasture (van Kirk and Naman, 2008).

Succeeding the California Gold Rush in the 1850s, agriculture developed in Scott Valley, mostly focussing on cattle ranching and crop production (Grain and Alfalfa). Irrigated area increased from 29.000 acres in 1959 to 34.000 acres today. Prior to 1960s, about halve of the cultivation area were flood irrigated by diverting discharge from Scott river; only little groundwater pumping for irrigation occurred. In the 1960s-1970s, irrigation sprinklers became popular in Scot Valley. These required high

[1] https://gis.data.ca.gov/datasets/DWR::california-jurisdictional-dams/about
[2] https://spatialdata.oregonexplorer.info/geoportal/details;id=523fed781b444e278e86fd0c63fd7c53

water pressure, which was provided by groundwater pumps. This led to increased water use, as acreage could now be irrigated at times when prior flood irrigation was no possible as the Scott River did not carry enough water (Siskiyou County Flood Control and Water District Groundwater Sustainability Agency, 2021).



(A) Topography (B) Catchment Hydrology

(C) Landuse (D) Snow

FIGURE 2.1: Study area overview with (A) elevation, (B) rivers, gauges and reservoir locations, (C) landuse and (D) snow course locations and first day in year with all snow melted. (*Maps generated by the authors with data from USGS, DWR, NCRS, NASA*)

TABLE 2.1: Catchment Overview

Basin Name	Basin ID	Reservoir Capacity	Area	Mean Elevation	First Measuring Year	Percentage of Agriculture	Number of snow courses
		[aft]	[km2]	[m a.s.l.]			
Sacramento (Delta)	11342000	26000	1099.32	1,263	1944	0.1%	6
Shasta (Yreka)	11517500	57110	2047.28	1,228	1933	11.4%	3
Scott (Fort Jones)	11519500	350	1713.7	1,321	1941	7.3%	5
Trinity (Hyampom)	11528700	887	1980.61	1,123	1965	0.0%	0
Trinity (Hoopa)	11530000	945	1683.77	958	1911	0.0%	8
Illinois (Kerby)	14377100	233	985.2	881	1961	0.1%	4
Indian (Happy Camp)	11521500	0	309.5	1,128	1956	0.0%	0
Salmon (Somes Bar)	11522500	0	1944.28	1,299	1911	0.0%	0

3 Methods

3.1 Data Overview and Seperation into Timeframes

All statistical and geographical analyses were computed in *R* (R Core Team, 2021) using the packages *tidyverse* (Wickham et al., 2019) for data-wrangling, *sf* (Pebesma, 2018) and *RPyGeo* (Brenning, Polakowski, and Becker, 2018) for geographical analyses and *ggplot2* (Wickham, 2016) for visualizing data. Streamflow, snow-water-equivalent (SWE), precipitation, maximum vapor pressure deficit and snow cover data was analyzed (Table 3.1). To quantify the influencing factors such as climate change and agricultural water use, the data time series were divided into 3 timeframes (TF) and defined as:

- "Historic" timeframe (synonymously referred to as "TF 1") starting in 1940 unless data acquisition began later, ending in 1976. In the Scott Valley, almost no groundwater pumping occurred during this period.
- "Intermediate" timeframe (synonymously referred to as "TF 2") beginning in 1977 with the PDO change from a cold to a warm phase and ending in 1999. The start of this period coincides with the switch in Scott River from agricultural surface water to groundwater use due to changed irrigation practices (flood to sprinkler irrigation)
- "Modern" timeframe (synonymously referred to as "TF 3") starting in 2000 with the beginning of severe drought (Williams et al., 2020; Williams, Cook, and Smerdon, 2022) and ending depending on data availability in 2020 or 2021

TABLE 3.1: Data Overview

Data Type	Unit	Interval	Source Agency	Available Year Range
Streamflow	m^3/s	day	USGS	1940s - 2021
Snow	SWE	month	NRCS	1940s - 2021
Precipitation	mm	month	PRISM	1940 - 2021
Max. Vapor Pressure Deficit	hPa	month	PRISM	1940 - 2021
MODIS NDSI Snow Cover	DOY	year	NASA	2000 – 2021

3.2 Precipitation and Vapor Pressure Deficit

Precipitation and maximum vapor pressure deficit (VPD) was retrieved from the PRISM datasets. PRISM calculates climate variables by combining measurement station observations with a so called "expert algorithm" which extrapolates measurements to a grid based on elevation effects (Daly and Bryant, 2013; Asarian and Walker, 2016). Monthly means for the whole period of interest of this study were available as raster with 4 km grid-resolution for the whole continental United States. They were cropped and averaged to each catchment (shapes obtained from USGS [1]). Next, data was transformed to water year means.

3.3 Snow

To asses our snowpack hypothesis, we used NRCS snow-course data which was obtained using the *RNRCS* R-Package by Lee and Roberti, 2018. Snow-courses are fixed sites where snow water equivalent (SWE) and snowdepth are manually measured monthly from January to June. SWE is a measurement for water-content of snowpack and is therefore a proxy for snow-storage. We evaluated April 1 SWE at all snow courses inside the catchments (Figure 2.1d). Elevations of included stations ranged from 1200 m to 2100 m (Table 3.2).

[1] https://water.usgs.gov/GIS/metadata/usgswrd/XML/streamgagebasins.xml

TABLE 3.2: Snow course

Basin Name	USGS Catchment ID	NRCS Snow course ID	Elevation in m	Mean SWE Historic	Mean SWE Intermediate	Mean SWE Modern
Sacramento (Delta)	11342000	SLT	1737	29.57	28.18	20.03
		HIG	1838	34.00	35.05	26.39
		GYR	1890	44.68	47.90	41.15
		SFT	2073	42.87	41.80	38.71
		NFS	2103	24.56	25.15	21.61
Shasta11517500 (Yreka)	SWT	1783	14.81	11.27	12.79	
		LSH	1890	21.10	16.44	14.05
		PRK	2042	37.29	34.61	28.93
Scott 11519500 (Fort Jones)	SWJ	1676	41.30	27.80	22.40	
		DYM	1737	19.45	17.17	14.58
		ETN	1798	37.62	20.86	20.27
		MB3	1890	28.00	28.14	24.67
		MBL	2012	31.82	31.87	26.61
Trinity (Hoopa)	11530000	BFT	1554	15.86	10.53	8.86
		WHN	1646	21.96	18.75	14.76
		MUM	1722	26.52	20.19	14.21
		WLC	1875	35.64	36.10	29.12
		SHM	1951	50.88	49.00	40.77
		BBS	1981	37.91	38.63	30.40
		RRM	2042	43.74	43.43	35.41
		DDF	2195	33.07	33.73	26.77
Illinois (Kerby)	14377100	23G05	1234	4.00	0.92	0.65
		23G04	1393	7.55	3.24	5.09
		23G16	1500		14.04	13.47

3.4 Streamflow

Daily mean discharge of all 9 selected catchmments was downloaded from USGS using the *dataRetrieval* R-Package by Cicco et al., 2018. The data was then separated into the three timeframes (Figure 3.1) and the summer low flow season was evaluated. Unlike van Kirk and Naman, 2008, who analyzed a set period of days, we defined the low flow summer period by a runoff limit. As a threshold, we used the 0.15 percentile of flows in the Historic timeframe. The threshold ranged from 1.1 m^3/s in Shasta River to 16.0 m^3/s in the large Trinity catchment (USGS ID 11530000). For all timeframes, the summer phase was defined by falling below and exceeding this value for 7 consecutive days and will further be referred to as "Summer Flows". Subsequently, we determined the following metrics for this phase:

- Mean discharge (MEAN [m3/s])
- Minimum discharge (MIN [m3/s])
- Start-Datum (FDOY [DOY])
- End-Datum (LDOY [DOY])
- Duration of Summer Flows (DURATION [days])
- Mean discharge after exceeding the 0.15 percentile until the end of the year (MEAN. A.T [m3/s])

3.5 Trend Hypothesis Analysis

To quantify differences between the timeframes of all data, we used the non-parametric Kruskal-Wallis test. This test examines whether the three groups correspond to the same data population or whether their mean range is significantly different (significance level $\alpha = 0.05$). The advantage of the Kruskal-Wallis test is that the data do not have to correspond to a certain distribution (Helsel and Hirsch, 2002). For example an ANOVA test requires normally distributed data, but a Shapiro-Wilk-Normality test showed that some of the data used in this study did not meet this criterion. Since the Kruskal Wallis test only indicates whether there are significant differences between the groups, a non-parametric Dunn-Bonferoni post-hoc test was added. This test produces differentiated results of group differences (Helsel and Hirsch, 2002).

3.6 Attribute Summer Flow Decline to Climate Change and Agriculture

We determine how much water is lost in Scott River in summer months (May-October, DOY 150-300) due to climate change and agriculture by means of a paired-catchment approach. The paired catchment should not have agricultural land use or larger reservoirs and thus only be influenced by climate change. Flows in Scott and

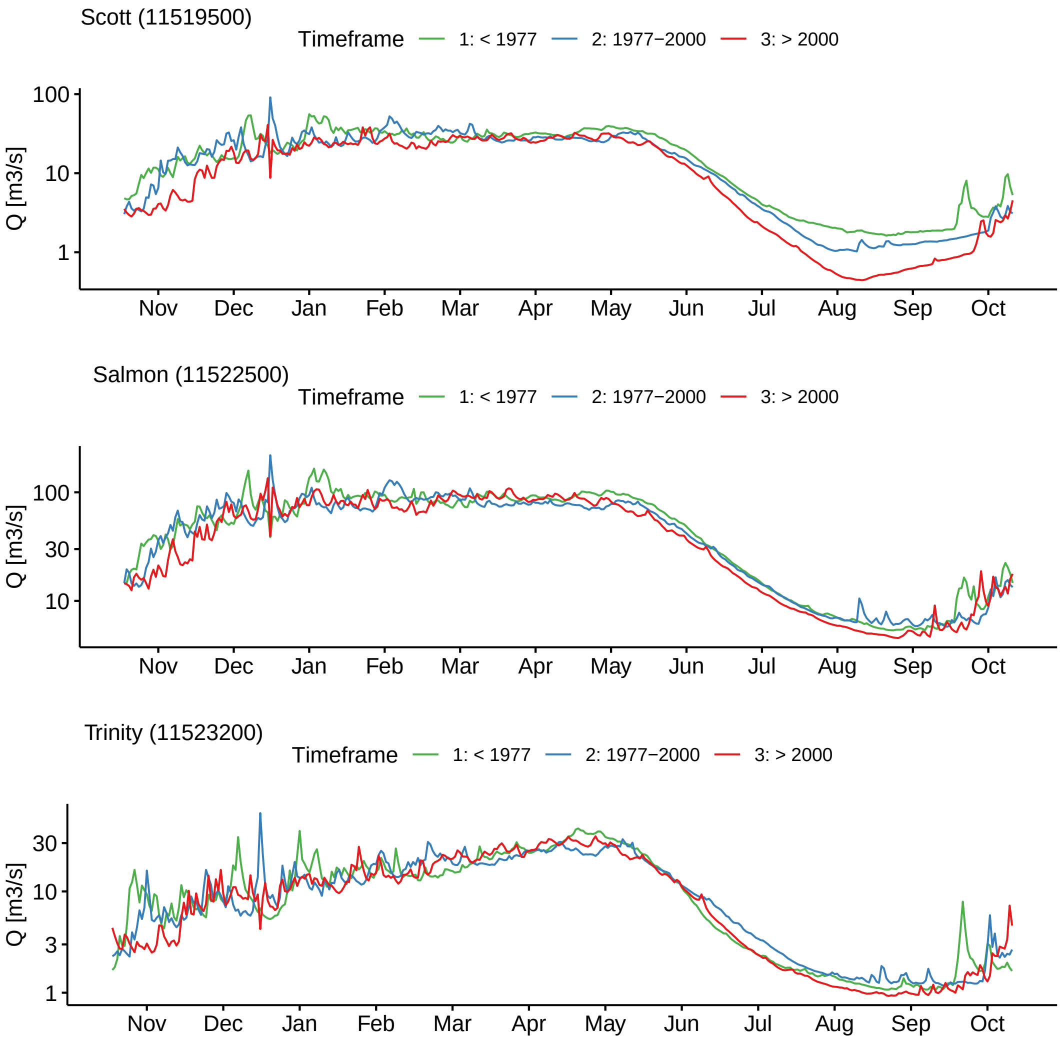


FIGURE 3.1: Mean daily discharge in Historic (TF 1), Intermediate (TF 2) and Modern period (TF 3) for the catchments Scott, Salmon and Trinity

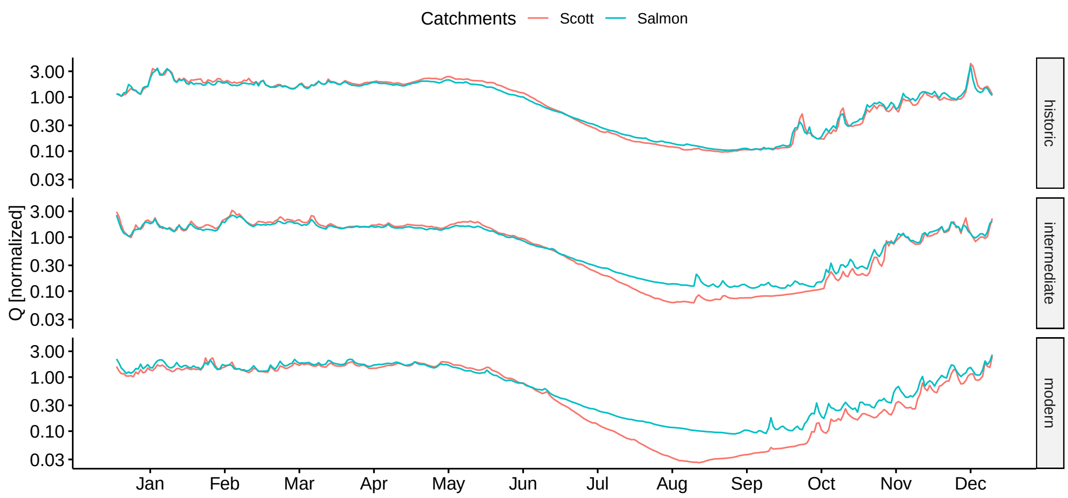


FIGURE 3.2: Normalized discharge in Scott and Salmon River compared by timeframe

suitable Study-Catchments were mean normalized (Formula 3.1). The flow of each summer day was divided by the mean of the total summer flows (DOY 150 -300).

$$Q_{norm} = Q_{obs} / mean(Q_{obs_{summer}}) \tag{3.1}$$

The Salmon River catchment adjacent to Scott in the west, which was also used in van Kirk and Naman, 2008 study, had the best fit (lowest total difference). Both Basins show lower flows in the Intermediate and Modern timeframe relative to Historic. We assume that the runoff in Salmon is only affected by climate change, but the decreases in Scott are due to a mix of climate change and agriculture. We also assume that both catchments are affected by climate change to a comparable extent. Thus, the proportion of runoff decrease due to climate should be the same in both areas.

In the first timeframe, where the agricultural influence in Scott had no substantial impact, the normalized flows of both rivers were very close to each other with the same peaks and general regime (Figure 3.2). However, since we see lower runoff in Scott relative to Salmon in Intermediate and Modern timeframes during the summer months, we can conclude that this deviation results solely from agricultural use.

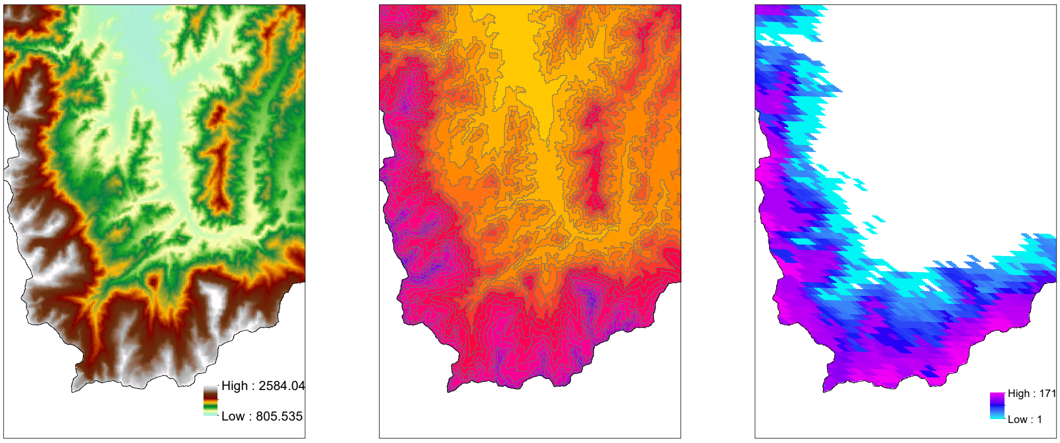
We established a relationship between flows in Salmon and those in Scott using a line of organic correlation (LOC) regression for each timeframe. LOC, also known as "reduced major axis" regression, is often used in hydrological data extension (Kruskal, 1953; Khalil and Adamowski, 2012; Helsel and Hirsch, 2002), as it better represents the variance of the data in contrast to conventional linear regression. This is achieved by minimizing the triangle-areas formed by horizontal and vertical extending lines in X and Y direction. The slope of LOC is determined by the ratio of both standard deviations (sy/sx) and is therefore identical for regression of X Y and Y X.

To receive a runoff-estimate for Scott without agricultural influence, we applied the Historic LOC relationship to the observed Intermediate and Modern flows of Salmon. Deviation of predicted and measured flows in Scott are therefore attributable to agricultural water consumption. Difference to the measured Historic flows is due to climate change.

3.7 Boosted Regression Trees

To qualitatively assess the relative importance of individual climatic factors we build boosted regression trees (BRT) for Scott and Salmon River summer flow. BRT is a machine learning algorithm which combines Regression/Classification Trees (CART) with the boosting technique (Hastie, Friedman, and Tibshirani, 2001; Elith, Leathwick, and Hastie, 2008; Ransom et al., 2017). In CART analysis, predictions are based on a decision tree. This tree is generated by partitioning the response variable into groups which behave similarly to the predictors. Predictors can be categorical or quantitative. Each tree-branch, symbolizing an response group, separates into two, based on a threshold value of the predictor variable which best explains the variance in this group. As each partition is based on the higher hierarchical split of another predictor, their interactions are automatically represented (Elith, Leathwick, and Hastie, 2008). Boosting is a technique which improves prediction accuracy by successively combining multiple models or trees as in BRT (Schapire, 2003; Elith, Leathwick, and Hastie, 2008). To conduct BRT to predict mean August and September flows in Scott and Salmon River we used the *gbm R-Package* by Greenwel, Boehmke, and Cunningham, 2020. Our explanatory variables were:

- Mean monthly Precipitation /Vapor Pressure Deficit in catchment (in each wateryear) (“P.Jan”, “V.Jan”)
- Wateryear Precipitation Mean (“P.YMEAN”, “V.YMEAN”)
- Winter Precipitation Mean (“P.WMEAN”, “V.WMEAN”)
- Summer Precipitation Mean (“P.SMEAN”, “V.SMEAN”)
- April 1 SWE at the Stations MBL, SWJ, ETN, MB3 (Give Timeframe and Elevation)
- Timeframe 1-3 ("TF")



(A) DEM (B) Elevation Zone Polygons (C) First Day no Snowcover

FIGURE 3.3: Routine for finding snowcover-free day of year in each catchment. First, a DEM (A) is reclassified and converted to 100 m elevation polygons (B). Next, the FNS raster (C) is intersected with the elevation polygons (B) to achieve mean melt day for each altitude zone

3.8 First Day No Snow

We calculated the first day a raster-pixel is no longer snow covered in a year using Modis snow cover satellite data [2] and data retrieval routine developed by Amanda Armstrong, 2020 (eg. Figure 3.3c shows FNS for Year 2020). Next, a digital-elevation-model (DEM raster obtained from USGS [3]) is cropped to each catchment (Figure 3.3a) and reclassified into 100 m elevation-zone polygons (Figure 3.3b). With these elevation-zones of each catchment, the FNS-Raster is masked, and mean values are extracted. This process was repeated for every available year and the resulting time-series was evaluated with a linear regression of each elevation zone FNS.

[2]https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD10A1
[3]https://developers.google.com/earth-engine/datasets/catalog/USGS_3DEP_10m

4 Results & Discussion

4.1 Precipitation Trends

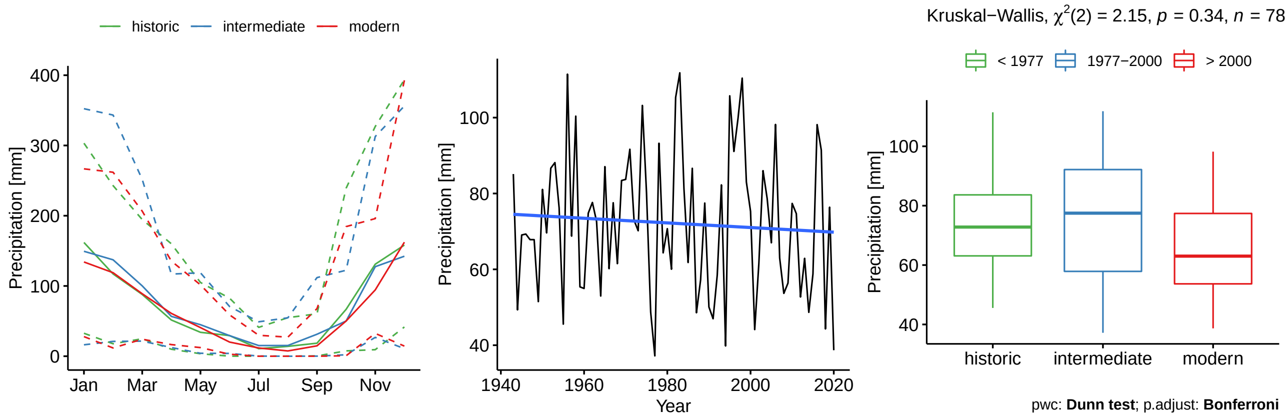
Yearly mean precipitation showed slight negative trends in all catchments between the timeframes, however none of them were significant. The Kruskal-Wallis Test indicated a slight mean precipitation increase between Historic and Intermediate with the later also having higher variance. Nevertheless, mean in Modern was lower compared to the previous timeframes in all catchments.

Drake, Tate, and Carlson, 2000 who analyzed year precipitation sum of a precipitation station in Scott Valley during our Historic and Intermediate timeframes, also observed no significant trends. A more recent study by Asarian and Walker, 2016 concerning long term trends in precipitation, which also included our Modern timeframe, found decreasing but non significant trend in our evaluated basins as well. Nonetheless, their analysis showed significantly lower mean precipitation in September in most of our catchments. These findings match simulations using climate models. Predicting future precipitation under warming scenarios, they forecast wetter winters and dryer summers for California, maintaining the prevalent Mediterranean climate (California Department of Water Resources, 2015, Mann and Gleick, 2015 Pathak et al., 2018, Allen et al., 2020).

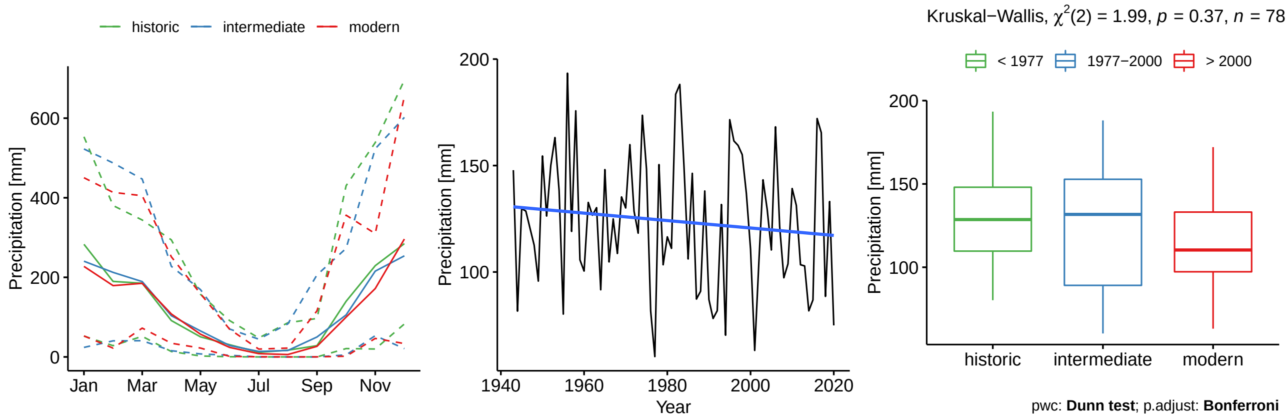
4.2 Vapor Pressure Deficit Trends

A trend towards a higher Maximum Vapor Pressure Deficit (VPD) was visible in all catchments (Figure 4.2), yet only Scott and Trinity showed significant increases. In the Intermediate timeframe, VPD variance was larger with a mean similar to Intermediate. This pattern was also visible in precipitation trend analysis (Figure 4.1). Therefore, the greater variability probably originates from wetter and drier than Historic-average years, resulting in a decrease or increase of water available for evaporation. This can also explain the significant difference between the Historic/Intermediate and Modern timeframe. In Modern, precipitation had lower means compared to the other timeframes, thus also limiting evaporation-water availability, increasing VPD.

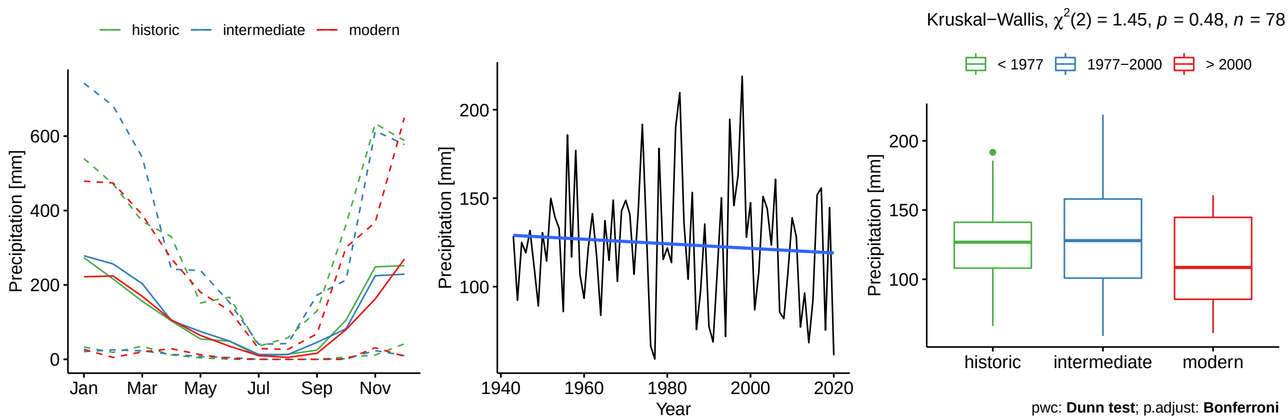
With climate warming, evaporation is predicted to increase. The main cause can be explained with the Clausius-Clapeyron relationship, in which every 1°C warmer



(A) Scott



(B) Salmon



(C) Trinity

FIGURE 4.1: *Left:* Comparison of mean monthly precipitation regime in each timeframe, dashed lines representing .975 and .025 quantile *Middle:* Mean yearly precipitation (black) and trend line (blue), *Right:* Kruskal-Wallis test of mean yearly precipitation between timeframes. *Top to bottom:* Scott, Salmon and Trinity catchment

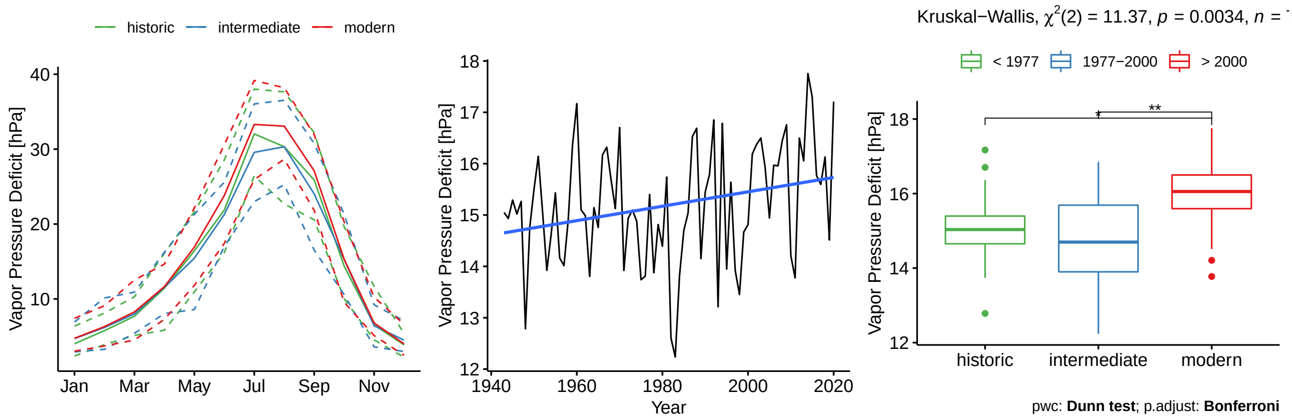
air can hold 7% more water, increasing atmospheric vapor uptake (Trenberth, 2011; Rhoades, Ullrich, and Zarzycki, 2018). Consequently, Cook, Mankin, and Anchukaitis, 2018 found that evaporative losses due to climate warming attributed to 5-27% of recent California drought anomaly. Additionally, a study by Zhang et al., 2016 forecasts rises in evaporation of intercepted water and higher transpiration by plants due to increased greening of vegetation. Furthermore, the study by Sorooshian, AghaKouchak, and Li, 2014 who investigated influence of irrigation on land hydrology concluded that irrigation causes increased evapotranspiration, additionally water-stressing agricultural basins. The described precipitation decrease in summer months (Figure 4.1) and more water leaving the basins as vapor, changes the catchments hydrological balance towards less water available for streamflow or groundwater recharge.

4.3 April 1 SWE Trends

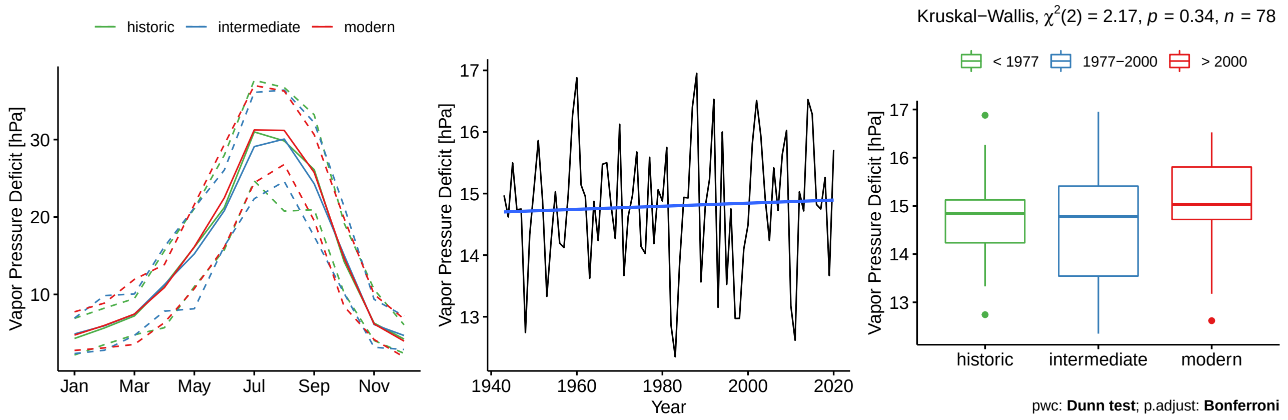
We observed that lower elevation snow courses had stronger negative trends compared to higher elevations, nevertheless all showed declines in April 1 SWE. Trends were only significant at some courses with altitudes lower 1900 m. SWJ and ETN (Figure 4.3c & 4.3b), situated on east-facing hillslopes in Scott Valley, declined significantly between Historic-Intermediate and Historic-Modern timeframes. At both sites, mean April 1 SWE decreased from about 35 to 25 to 20, from Historic to Intermediate to Modern times respectively.

The findings by Drake, Tate, and Carlson, 2000 and van Kirk and Naman, 2008, who analyzed the same Scott Valley snow courses until 2000 and 2005 respectively, seem to be superseded by climate change. Their analyses showed negative trends at lower elevations but positive trends at higher elevation snow courses. This was also observed by Mote et al., 2005 who reported large declines in snowpack in the western US by 50% up to 75% in lower altitudes. However in a more recent study, Mote et al., 2018 also found negative trends at nearly all snow courses analyzed, independent of altitude. Therefore our trend analysis results are consistent with those of other regional studies. van Kirk and Naman, 2008 discussed the possibility, that reduced snowpack at the significant courses SWJ and ETN might result from changes in adjacent vegetation. While a possibility, we would argue, that even if this effect might influence these snow courses, the generally observed declines at all stations is largely climate-related.

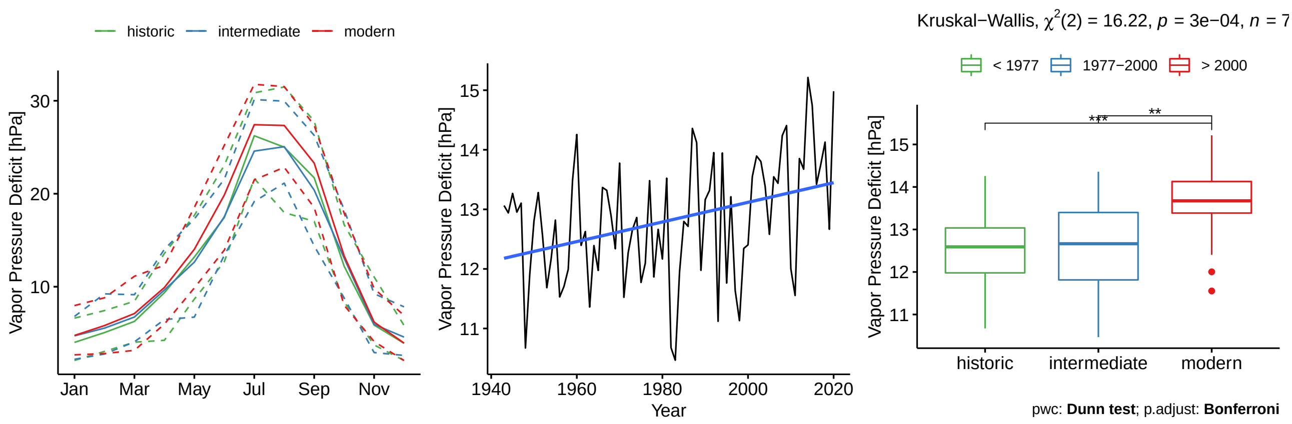
Kapnick and Hall, 2012 showed the decrease in April 1 SWE over the past few decades was due to higher temperatures in March-June. This decreased snow accumulation and provoked earlier snowmelt. At high elevation stations which showed a positive trend, this was only due to higher accumulation in December-February. Using a modeling approach, Mote et al., 2018 was also able to confirm that earlier snowmelt and lower snowpack are caused by higher winter temperature due



(A) Scott



(B) Salmon



(C) Trinity

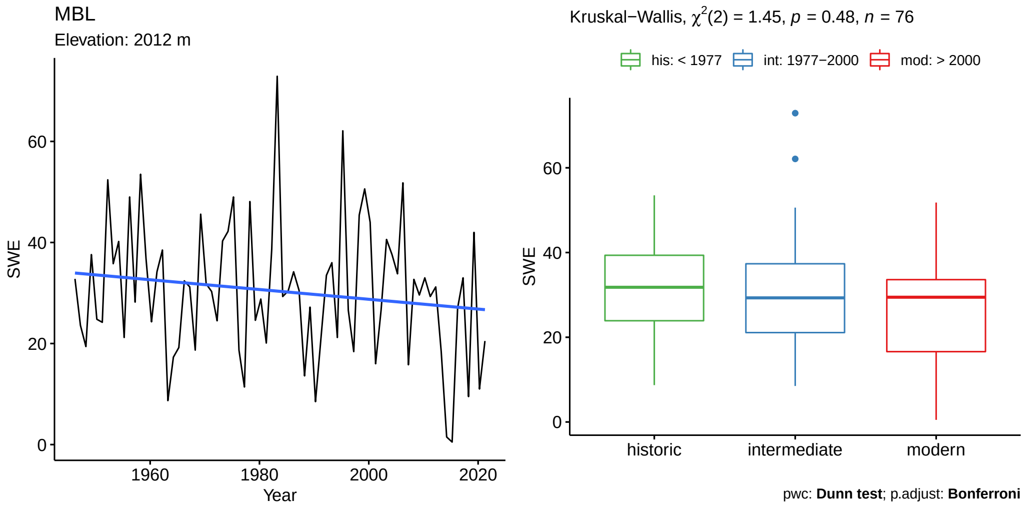
FIGURE 4.2: *Left:* Comparison of mean monthly maximum vapor pressure deficit regime in each timeframe, dashed lines representing .975 and .025 quantile*Middle:* Mean yearly maximum vapor pressure deficit (black) and trend line (blue), *Right:* Kruskal-Wallis test of mean yearly maximum vapor pressure deficit between timeframes. Significance indicated by connected lines between boxes with significance code (* = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = p < 0.0001) *Top to bottom:* Scott, Salmon and Trinity catchment

to climate warming. This shifts precipitation from snow to rain which prevents snow from accumulating. When they removed the warming trend in their simulation, the SWE trend reversed to more accumulation. This means snowpack declines are caused by changes in temperature and not by lower winter precipitation (see our Chapter 4.1). These findings were backed by Rhoades, Ullrich, and Zarzycki, 2018 whose simulations of SWE implementing the RCP8.5 scenario in multiple snow models indicated a snowpack decrease of up to 38% by 2065 in the western US. By the year 2100 their simulations predict a decrease of snowfall by -30%, snow cover by -44% and SWE by -69%. Rhoades, Ullrich, and Zarzycki, 2018 concluded, that due to 20-40% of snow in the western US falling just below freezing, small rises in temperature will further lead to substantially more precipitation falling as rain.

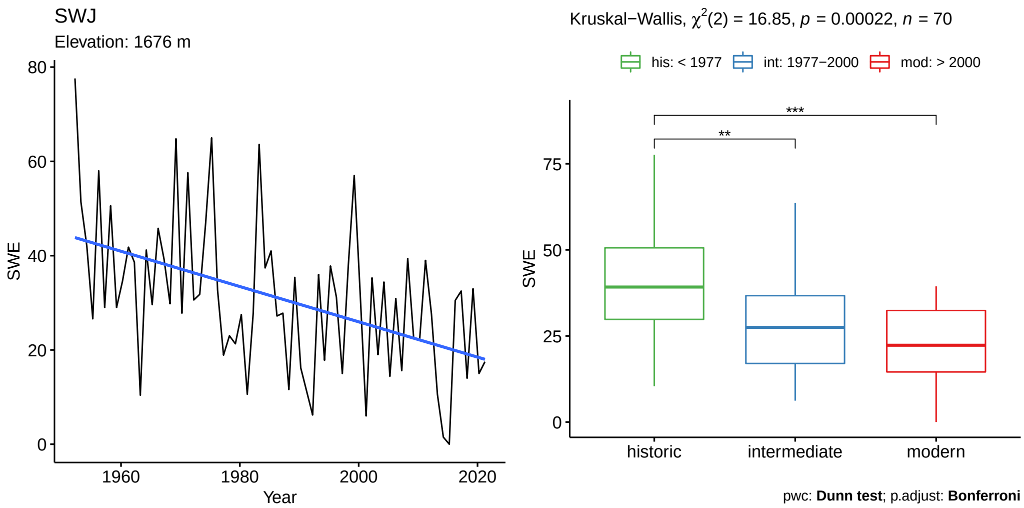
The declines in April 1 SWE due to higher winter temperatures show that even though winter precipitation is predicted to increase, its not stored in the catchment as snowpack but rather discharges more or less directly. Xiao, Udall, and Lettenmaier, 2018 were able to show that only a relatively small part of their study catchment, which accumulates snow in winter, is responsible for large amounts of summer discharge. With SWE trending lower in these subbasins, summer streamflow drastically deceased. These finidings are underlined by hydrological simulations of Li et al., 2017 who calculated that despite only 37% of precipitation falling as snow, 53% - 70% of total discharge in the western United States originates from snowmelt.

4.4 Streamflow Trends

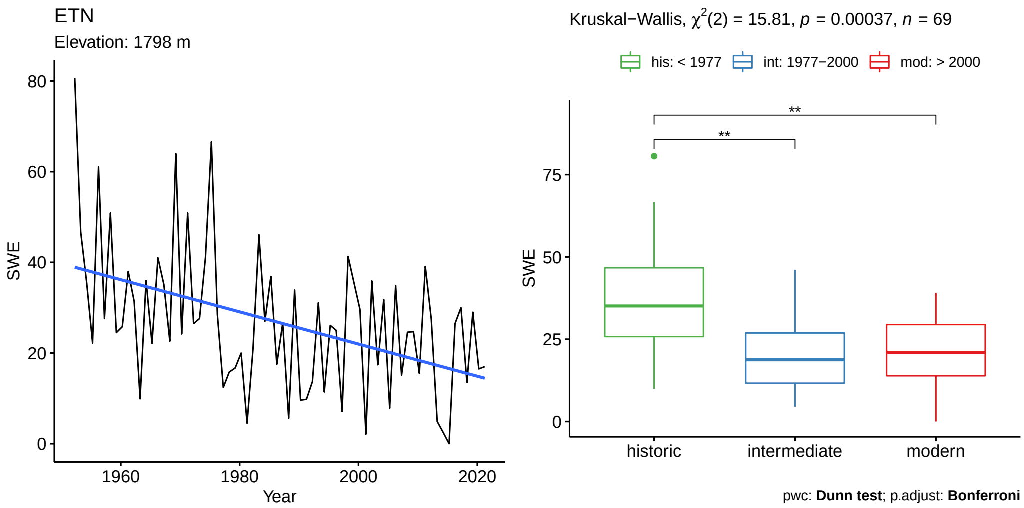
All Catchments (Appendix A) with less than 900 aft Reservoir Capacity (see Table 2.1) had negative trends for mean (MEAN) and minimum (MIN) discharge during Summer Flow season and mean flow after the threshold is crossed again (MEAN.A.T). We also observed positive trends in duration (DURATION) of Summer Flow season with earlier starting (FDOY) and later ending (LDOY) Days. Only in Scott trends were significant (Figure 4.4 & 4.5) for the mean ($p = <0.0001$), min ($p = <0.0001$), duration ($p = <0.00045$) and first day ($p = <0.0001$) between the Historic (1) and Intermediate (2) and Historic (1) and Modern (3) timeframe. There was no significant difference between Intermediate (2) and Modern (3) timeframe. The duration of Summer Flows in Scott increased by 50 days from 75 to 125 days between Historic and Modern, starting about 30 days earlier. Mean flows decreased from 1.5 m^3/s in timeframe 1 to 0.75 m^3/s in timeframe 2. Additionaly, in Scott minimum flows, a jump is visible in 1977, the first year with streamflow droping to nearly 0 m^3/s. Occuring multiple times in Intermediate and Modern times, this never happened during the Historic period. As this jump is not visible in the other catchments (A), a climatic origin like the shift of PDO can be excluded and is rather caused by the shift in irrigation-water-source.



(A) Snow course MBL



(B) Snow course SWJ



(C) Snow course ETN

FIGURE 4.3: *Left:* April 1 SWE (black) and trend line (blue), *Right:* Kruskal-Wallis test of April 1 SWE between timeframes. Significance indicated by connected lines between boxes with significance code (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$) *Top to Bottom:* snow courses MBL, SWJ and ETN all lying in Scott River catchment

A trend towards lower summer streamflow was also observed by Drake, Tate, and Carlson, 2000 and van Kirk and Naman, 2008, who only found a larger decrease in Scott River. Still, none of these trends were significant and their included data ended in 2005. van Kirk and Naman, 2008 also found a longer lasting low-flow period in Scott River. During their summer period (July 1 - October 22), discharge was less than 1 m^3/s on 4.3% in the Historic period (1940-1976) rising to 46.2% of these days in their Modern period (1977-2005).

Gleick and Chalecki, 1999; Drake, Tate, and Carlson, 2000; Beguería et al., 2003; Mote et al., 2005; Mote, 2006; van Kirk and Naman, 2008; Luce and Holden, 2009; van Vliet et al., 2013; Berghuijs, Woods, and Hrachowitz, 2014; Vano, Nijssen, and Lettenmaier, 2015; Barnhart et al., 2016; Asarian and Walker, 2016; Li et al., 2017; Xiao, Udall, and Lettenmaier, 2018; Mote et al., 2018; Cho, McCrary, and Jacobs, 2021 attribute the decline in summer streamflow to reduced snowpack by shifting precipitation from snow to rain and by earlier snowmelt which shifts meltseason runoff. These changes result in earlier occurring, higher peakflows (Stewart, Cayan, and Dettinger, 2005; Barnett et al., 2008; Kim and Jain, 2010; Trenberth, 2011; Georgakakos et al., 2014; Barnhart et al., 2016; Rhoades, Ullrich, and Zarzycki, 2018). Liu et al., 2021 simulated that climate change increases highflows by 0.5 to 4 times in central California with peak streamflow occuring 2-4 month earlier. Accordingly, in Scott River, where we observed significantly decreasing summer flows with significantly earlier setting in of lowflow season, we also observed significantly lower SWE at ETN and SWJ. Ashfaq et al., 2013 used an ensemble of climate and hydrologic models to show that increased climate warming will result in even less precipitation falling as snow, accelerating spring snowpack decrease.

4.5 Attribute Summer Flow Decline to Climate Change and Agriculture

Using the line of organic correlation (LOC regression) of Historic flows predicting Scott river discharge based on Salmon river discharge (Figure 4.6 *left*), we were able to predict discharges in Scott during Intermediate and Modern times if it had no enlarged agricultural water consumption. Figure 4.7 shows mean observed flows in red and mean predicted flows in blue (with grey uncertainty margins) of Intermediate and Modern timeframes respectively. In both plot facets, the green line represents mean flows observed in the Historic timeframe.

Predicted flows lie between the observed from each timeframe and the observed Historic. In July, the predicted flows lie close to the observed Historic flows, showing a minor climate and instead a higher agricultural influence. Nonetheless in September and October, the predicted flows match the observed flows of Intermediate and Modern more closely, indicating a stronger climate effect.

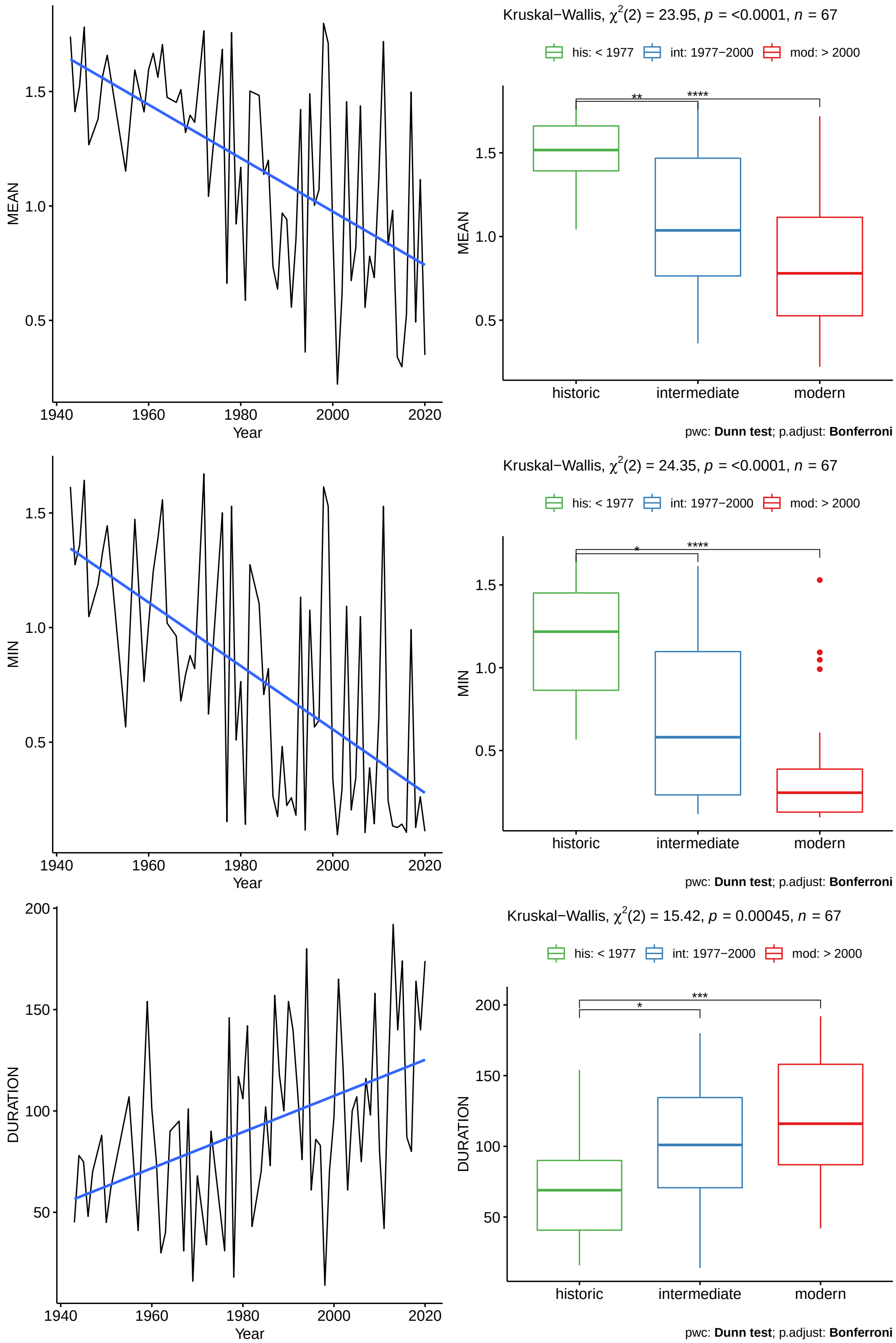


FIGURE 4.4: *Left:* summer low flow season metrics (black) and trend line (blue), *Right:* Kruskal-Wallis test of summer low flow season metrics between timeframes. Significance indicated by connected lines between boxes with significance code (* = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = p < 0.0001) *Top to bottom:* Scott River (USGS ID 11519500) Mean, Min and Duration of Summer flows

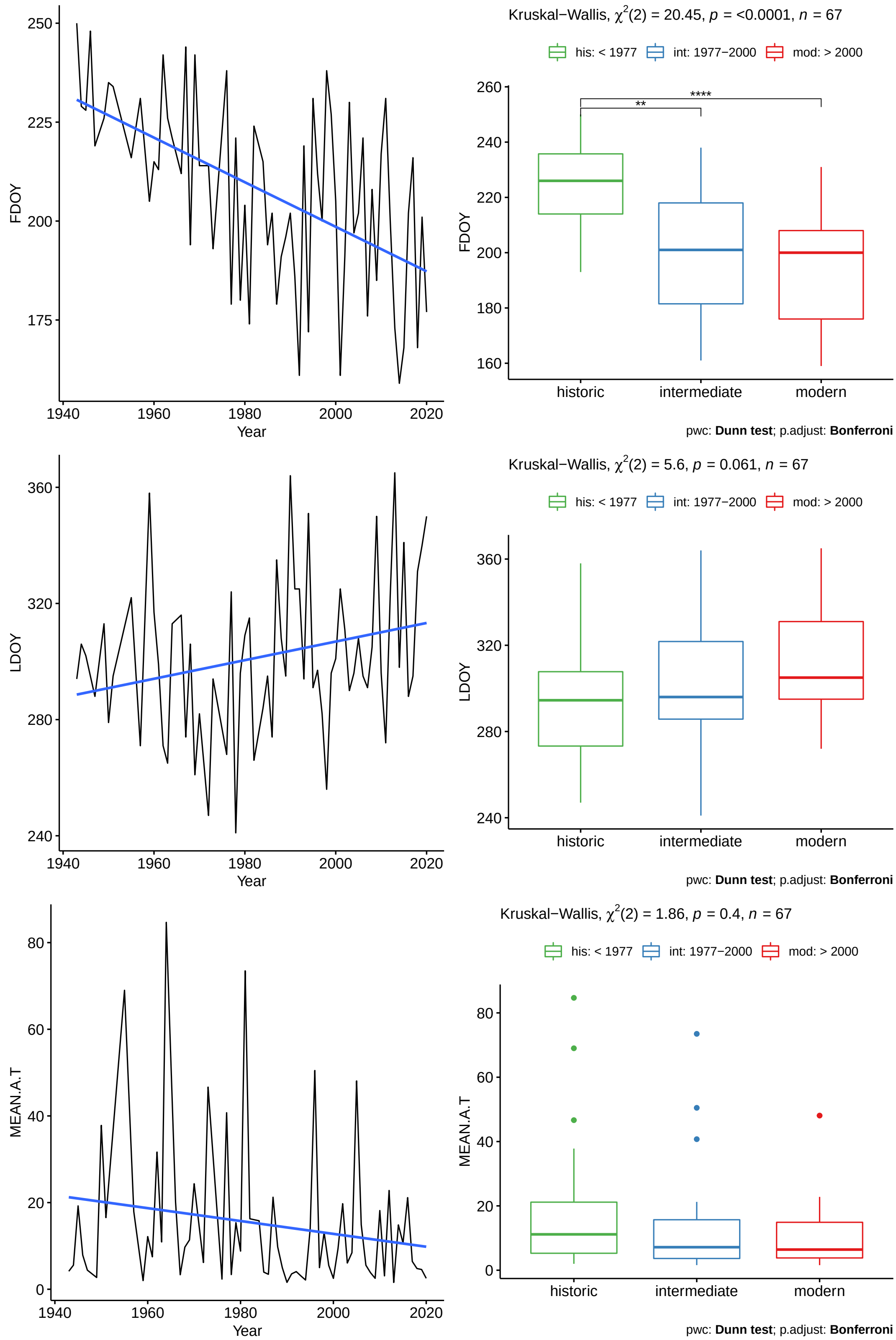


FIGURE 4.5: *Left:* summer low flow season metrics (black) and trend line (blue), *Right:* Kruskal-Wallis test of summer low flow season metrics between timeframes. Significance indicated by connected lines between boxes with significance code (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$) *Top to bottom:* Scott River (USGS ID 11519500) First Day (FDOY), Last Day (LDOY) and Mean Discharge after the summer flow threshold is crossed (MEAN.A.T.)

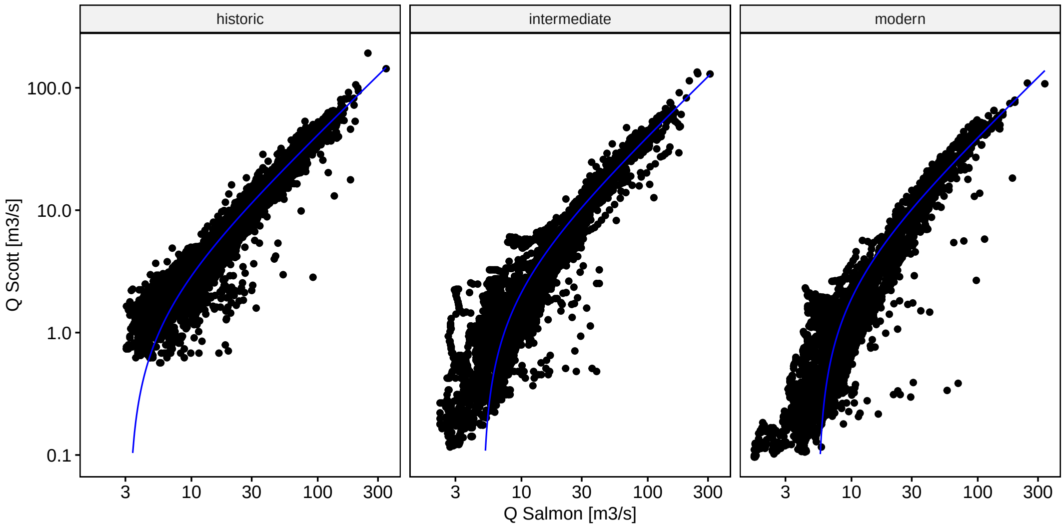


FIGURE 4.6: Regression of Salmon and Scott River summer discharge for each timeframe. Regression functions: Historic *y = 0.42x-1.35*; Intermediate *y = 0.42x-2.05*; Modern *y = 0.41x-2.24*

Table 4.1 shows that the day of year when a discharge threshold is crossed, happens earlier in more recent timeframes, underlining the trend analysis findings. As the climatic influence in the recession period is not as strong as in the later summer month, predominately agriculture is responsible for earlier, lower flows. This is especially visible in the Modern timeframe where the 10 m^3/s threshold is crossed 8 days earlier with 6 days due to agriculture. The lower flows are even more affected. The flow limit of 3 m^3/s occurs 17 days earlier in Modern timeframes compared to Historic with 13 days attributable to agriculture (Grey dashed lines in 4.7).

Comparing the predicted and observed discharges we were able to estimate the amount of streamflow lost due to climate change and agricultural water consumption (Figure 4.8). Comparing Historic and Intermediate timeframe (1 & 2), we calculated a decrease of about 20 Mm^3 over the course of June to October. Climate change and agricultural water use had about the same share in attributable loss. Analyzing Historic and Modern (1 & 3) the decline developed to 38 Mm^3, nearly doubling in just 20 years. Attributable agricultural amount increased by 50% while flow reduction associated with climatic factors rose by 250% over the summer month.

The increase in agricultural water consumption from Historic to Intermediate can be explained with an extended irrigation season due to the switch from surface to groundwater as irrigation source. This allowed growers to extend their alfalfa harvest from two cuttings to three cuttings per year, increasing the irrigation period by about one month. Consequently, this practice increased water use, thus leading to a higher evapotranspiration. DWR reported an Alfalfa cultivation area of roughly 5500 ha in Scott Valley in 2017 (Siskiyou County Flood Control and Water District Groundwater Sustainability Agency, 2021). For Alfalfa, local farmers reported an

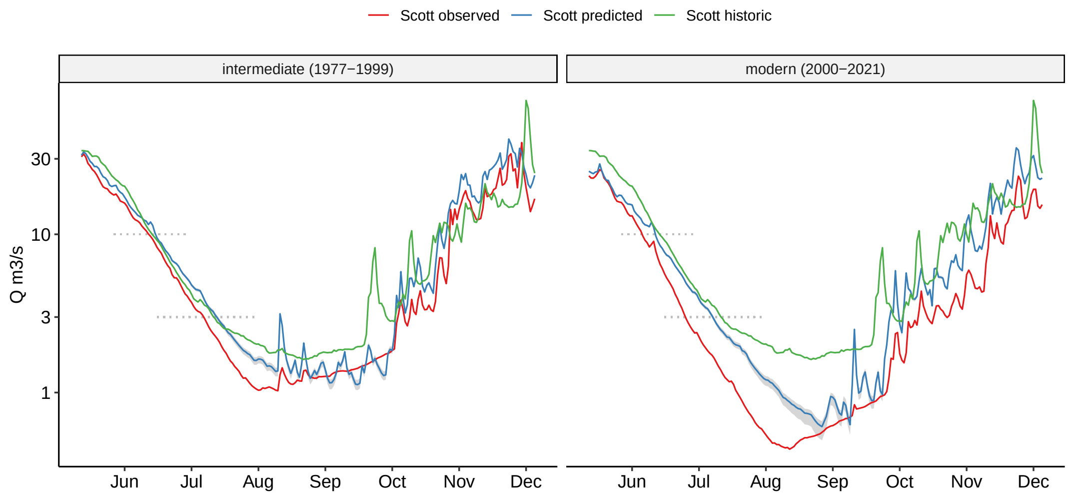


FIGURE 4.7: Predicted discharge of Scott in each timeframe based on the LOC Salmon regression. Grey horizontal dashed lines indicate 10 m^3/s and 3 m^3/s thresholds from table 4.1, grey band around predicted flow (blue) indicates error margins (.975 and .025 quantile)

average irrigation amount of 550 mm per year Foglia et al., 2018. Attibuting one third of the wateruse to the third cutting achieved by the switch to groundwater, this accounts for 180 mm * 5500 ha = 9.9 Mm^3 additional water use per year, closely matching our estimate in 4.8. Even though sprinkler irrigation used in Scott, has a higher irrigation efficiency relative to flood irrigation, some water still percolates and feeds groundwater. Thus not the complete irrigation amount is directly related to the summer flow decrease in Scott River, but a large part is.

Our findings underline results by van Kirk and Naman, 2008 who found a 10 Mm^3 streamflow decline in 1977-2005 relative to 1943-1976 summer period. They only analyzed July-October but also attributed 39% decrease to climatic factors, a value within our uncertainty range in the Intermediate (TF 2) period (light grey in Figure 4.8). Our findings are similar to those of Vano, Nijssen, and Lettenmaier, 2015 whose simulations of basins in the pacific northwest predicted 31%, 21%, and 7% flow-decrease per 1°C warming for July, August, and September, respectively.

As shown by Williams et al., 2020, the current California megadrought is exacerbated by human induced climate change. However, it is only responsible for 47%, the remainder being explained by natural variability. The same goes for our findings on streamflow declines due to climate change. Where agricultural attribution is robust, as this is the main difference between the paired catchments, climate impact needs to be differentiated between human induced change and natural variability. Both human induced change and natural variability affect a regional scale, therefore all studied catchments. Yet it is save to say, that without human induced warming, the declines in streamflow would not be as severe as observed.

TABLE 4.1: Mean day of the year when a flow threshold is crossed

Timeframe	**10 m^3 Measured**	**10 m^3 Predicted**	**3 m^3 Measured**	**3 m^3 Predicted**
	[DOY]	**[DOY]**	**[DOY]**	**[DOY]**
Historic	183		212	
Intermediate	182	185	207	213
Modern	175	181	195	208

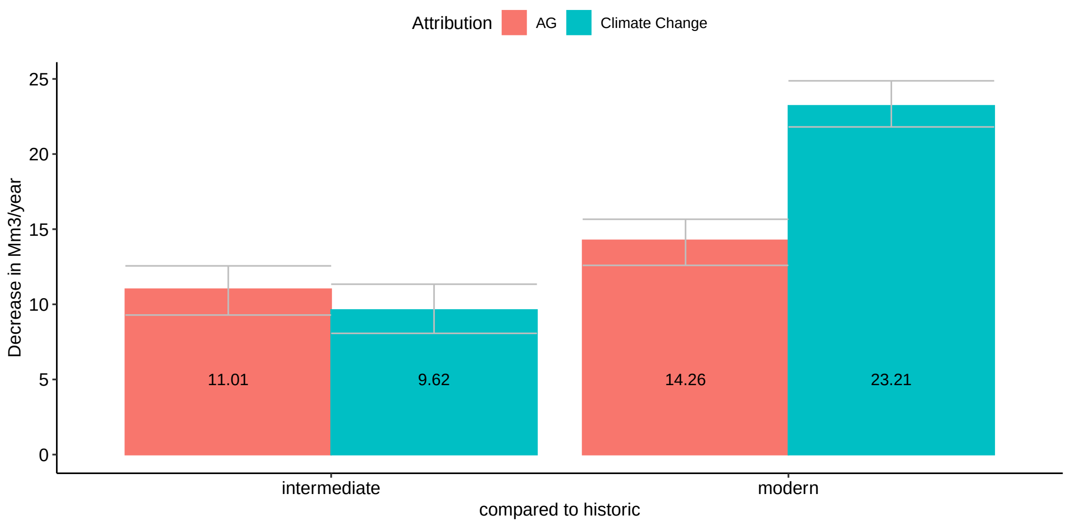


FIGURE 4.8: Streamflow loss by agriculture (red) or climate change (blue) within each timeframe in Scott River

Analyzing each individual month and relating its flow decrease to measured flows in the Historic timeframe, we were able to differentiate when each factor influences discharge (Figure 4.9). During August to October, declines seem quantitatively low compared to May and June. However, in proportion to Historic measured flows, this decrease constitutes to a decrease of 30-40% in August to October discharge. This is exacerbated when comparing Historic and Modern with declines of up to 70%.

In timeframe 2 we observed positive climatic influence increasing flow in November and December but also slightly in July. This is probably attributable to some wetter years in Intermediate times, also visible in the higher mean and greater variability of precipitation in our trend analysis (Figure 4.1a).

Also, agricultural influence seems to lag behind climatic factors. Even though irrigation withdrawals happen in the summer month, the largest decreases attributable to agriculture happen after the onset of fall flush flows (Figure 4.9). The response to the onset of fall precipitation is lower compared to flowrates which would be observed if no groundwater was withdrawn. This is due to either:

1. rainwater recharging the aquifer, which was depleted over summer month, without producing discharge. Groundwater and streamwater are at an equilibrium state where neither gains from or loses to the other until enough precipitation replenished the aquifer and it feeds the river again (Barlow and Leake, 2012).
2. more streamwater percolating to groundwater when available during fall flush flows, recharging the aquifer, which was depleted over summer month. This happens until the water table is sufficiently increased again that the hydraulic gradient is reversed (Tabidian and Pederson, 1995; Fleckenstein et al., 2004; Barlow and Leake, 2012) .

4.6 Boosted Regression Trees

We used a Boosted Regression Tree (BRT) to predict mean flows in August / September in Scott and Salmon River, implementing climatic variables as predictors. Our goal was to get a qualitative assessment of relative influence of each predictor on summer flows. Figure 4.10 shows both rivers are primarily influenced by precipitation, vapor pressure deficit is of minor importance.

Snow reflected by snow courses has a major effect on discharge in Scott River. Most influential stations are SWJ, ETN and MBL. SWJ and ETN also showed significant negative SWE decreases in our trend analysis (Figure 4.3b & 4.3c), underlining the importance of snowpack on streamflow as previously observed by Drake, Tate, and Carlson, 2000, Beguería et al., 2003, Mote et al., 2005, Mote, 2006, van Kirk and Naman, 2008, Luce and Holden, 2009, Ashfaq et al., 2013, Berghuijs, Woods, and Hrachowitz, 2014, Vano, Nijssen, and Lettenmaier, 2015, Barnhart et al., 2016, Asarian

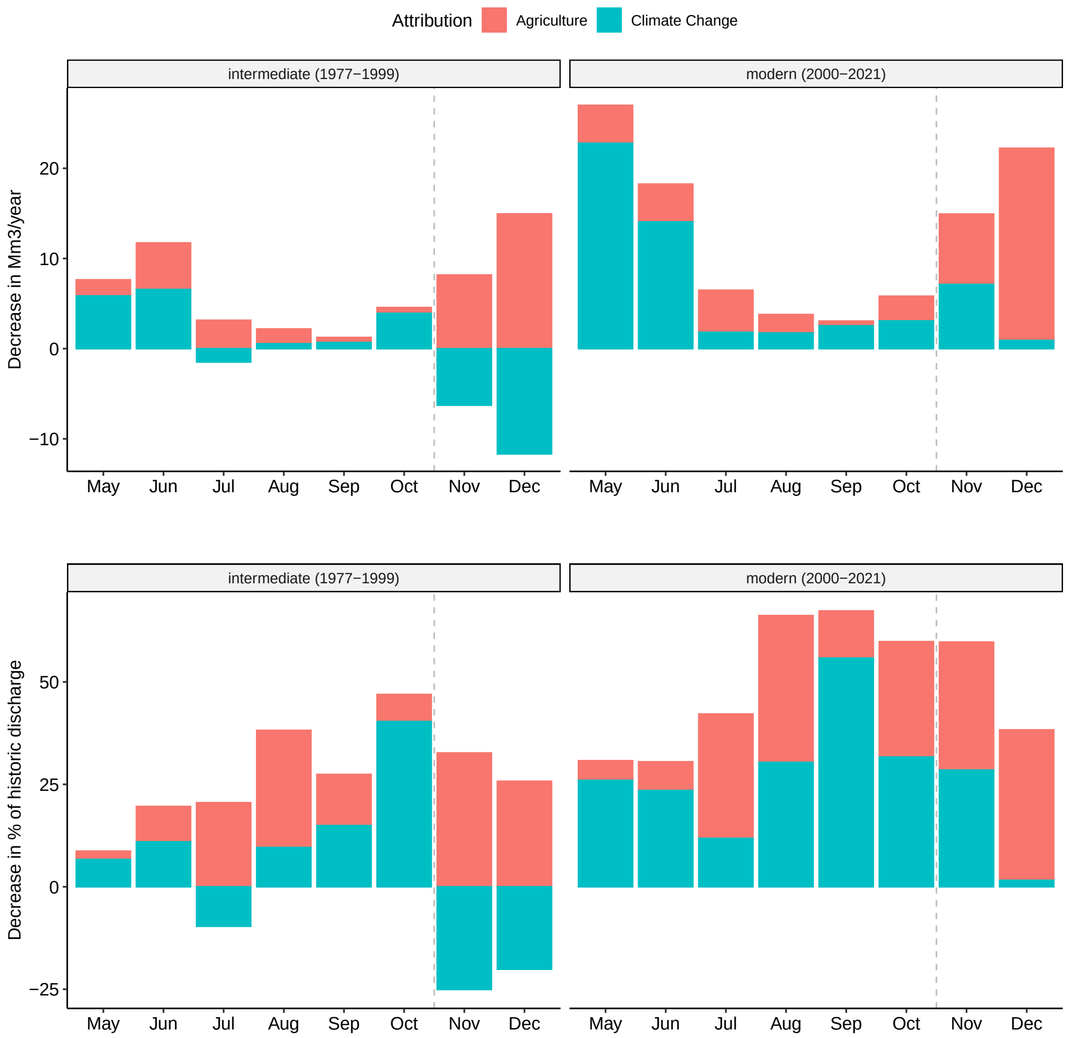


FIGURE 4.9: Streamflow loss by agriculture (red) or climate change (blue) within each timeframe and month in Scott River. *Top:* absolute change in $Mm^3/year$, *Bottom:* relative change in %. Grey dashed lines indicate month which went into the total losses in Figure 4.8

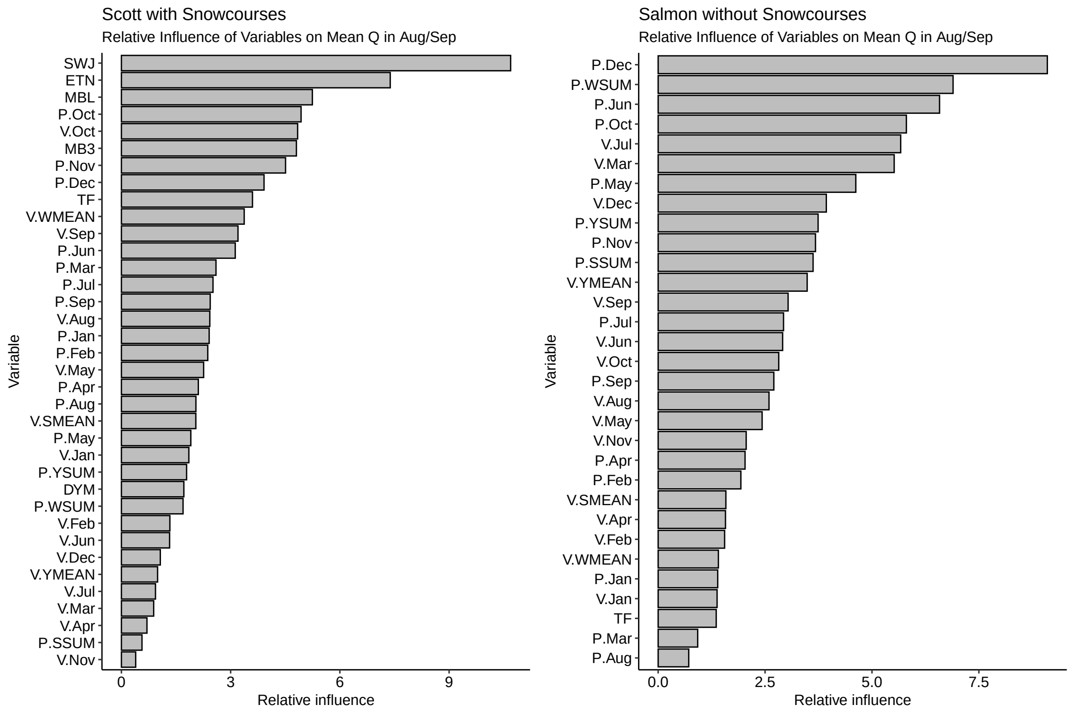


FIGURE 4.10: Boosted Regression Tree predicting mean August and September discharge in Scott (*left*) and Salmon River (*right*). For lables on y-axis see chapter 3.7

and Walker, 2016, Li et al., 2017, Xiao, Udall, and Lettenmaier, 2018. Since Salmon has no snow courses in its catchment, the highest ranking values were December and total winter precipitation, also reflecting snow and snow storage. However, their relative influence, indicating its explanatory power, is lower than that of snow courses in Scott, by only indirectly representing snowpack.

In Scott, timeframes have a relatively high influence, being ranked 9th, where in Salmon it is only ranked 29th. This matches our trend analysis with a significant difference in Scott between summer low flows at each timeframe which did not exist in Salmon.

4.7 First Day no Snow

Analyzing MODIS snow cover satellite data, we observed earlier snowmelt trends in all catchments at almost all elevations. Matching the observations of SWE stations with greater snow accumulation at higher snow courses, lower altitudes are earlier snow-cover-free than higher altitudes. Especially the elevation zones where the significant negative snow courses are stationed in Scott (SWJ 1700 m & ETN 1800 m) show a more rapid decline in snow cover compared to the lower and higher zones (Figure 4.11a).

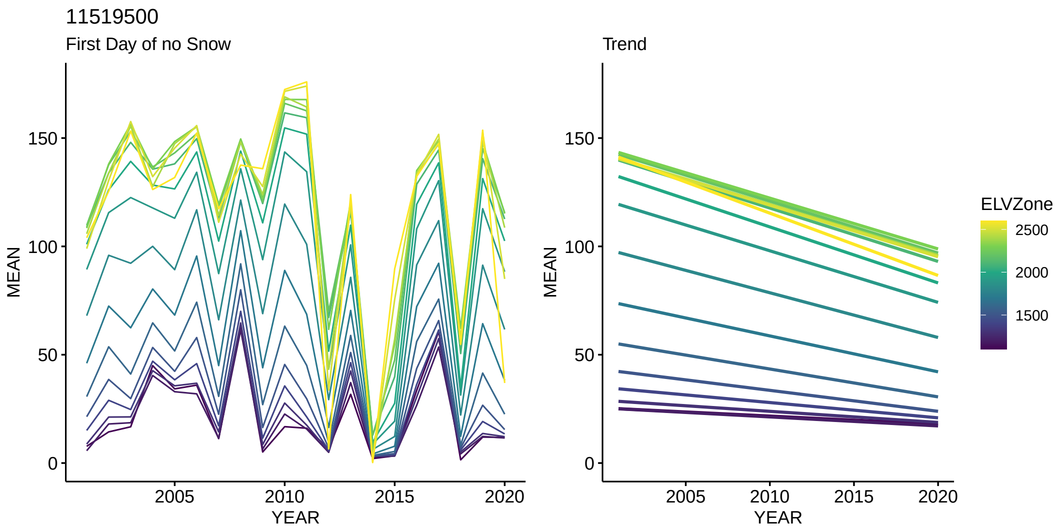
Earlier snowmelt shifts meltseason flows, discharging earlier in spring. First day in the year with no snow occurred by May - June at the start of the millennium, but until 2020 it decreased to March - April. Therefore, meltwater discharges during times of high precipitation (see Figure 4.1), increasing peakflows, not contributing to lowflow season anymore. This phenomenon was observed by Ashfaq et al., 2013 who investigated center of mass of discharge, onset of spring pulse flows and seasonal fractional flows in 302 catchments in the western US. Their trend analysis indicated earlier springtime snowmelt and streamflow, resulting in increased fractions of annual flow occurring 1–4 weeks earlier.

Data was only available from year 2000 on in our study, which coincides with the onset of the prolonged California drought. One could argue, that it therefore does not represent general future trends, as the data was recorded during specific circumstances. This is partially true if the drought ends, however this period gives a good estimate on how snowmelt and snow storage will behave if climate continues to warm and droughts occur more often.

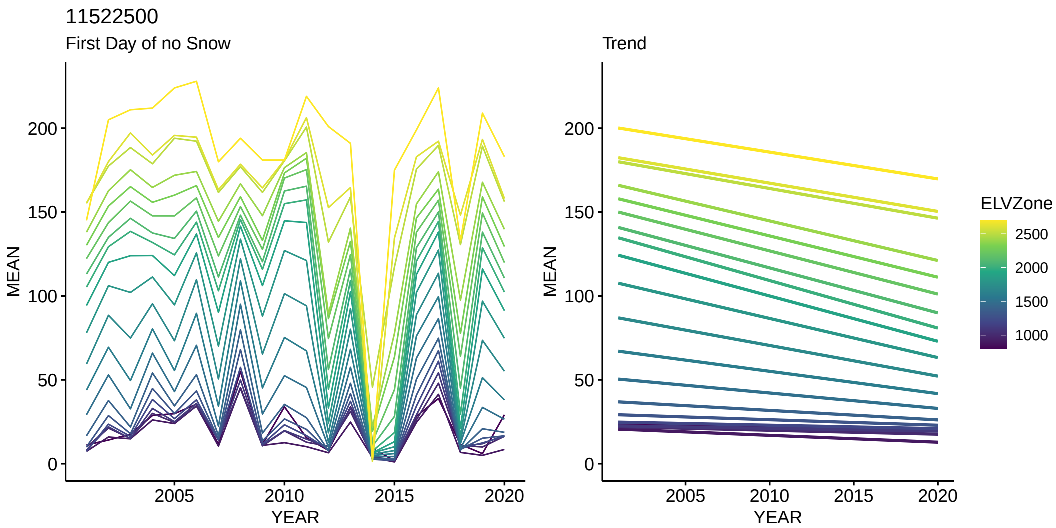
4.8 Implications for Fish

van Kirk and Naman, 2008 already reported that low streamflow causes some tributaries of Scott River to disconnect, leaving stagnant pools. This heavily disrupts the salmon live-cycle as adult fish cant reach their spawning grounds. Even if spawning is successful, the next years salmonids are also impacted by low discharge. Salmonids rely on cold water and can survive even in disconnected pools if enough cool water is supplied from groundwater (Power et al., 2015). However our analyses show, that stream-connectivity to groundwater is heavily impaired by agricutural water consumption. Therefore the pools become stagnant, with shallow, sun exposed ones continuously warming over summer. Additional to the problematic temperature and lentic water, this combination also provides ideal conditions for cyanobacteria to thrive. These harmful prokaryota rapidly multiply in warm river pools, excreting toxic substances, further decreasing salmonide survival (Power et al., 2015).

Warming conditions not only affect salmons but about all native fish species in California. A study by Moyle et al., 2013 showed, that increased temperature due to climate change over-proportionally impact native species, especially those requiring cold temperatures (< 22°C) or those already endangered. Neobiota on the other side are more robust to changes and often better adapted to a wider range of environmental conditions, therefore further repressing natives. Their study concluded, if climate change persists, multiple native fish species will become extinct.



(A) Scott



(B) Salmon

FIGURE 4.11: *Left:* Evolution of first snow cover-free day in each year and elevation, *Right:* Trend lines of first snow cover-free day in each year and elevation. *Top to bottom:* Scott and Salmon River

4.9 Management

To counteract these summer conditions, agricultural water use is limited by government curtailment (Nolan, 2021), if flows in Scott fall under a monthly defined threshold. The prohibition only allows for a minimal outtake, sufficient enough to water livestock. In 2021 curtailment regulations took effect during late August and September. Our analyses however show, the declines in this month relative to Historic is mostly (70%) attributable to climate causes, therefore being relatively inefficient. Even if all water which is lost, would directly return by inset of the curtailment, increases would only yield 20% more relative to flows observed in the Historic period. Yet such rapid flow-reaction is unrealistic, as agricultural irrigation water is rarely diverged riverwater but rather pumped groundwater. When the pumps are shut off by the curtailment, the hydraulic gradient towards the cone of depression, caused by pumping around each well, will first strive towards an equilibrium state. Therefore the water will still flow towards the well, not contributing to the streamflow, delaying discharge response. To assess the time needed to reach equilibrium, measurements of permeability and transmissivity of the aquifer would be needed to parametrize a hydrogeologic model (Tolley, Foglia, and Harter, 2019).

Even the goal to increase the probability of sufficient flows in the fall and an earlier onset of fall flows is hard to achieve with the current curtailment system. As shown in figure 4.7, the predicted streamflow (aka discharge if Scott was only affected by climate change) and observed streamflow in Modern have a similar flush start in the third quarter of September. Still, both onsets of fall flows are delayed by about 10 days relative to Historic. However, fall flush discharge only affected by climate change peaks substantially higher compared to observed flows. Therefore curtailments have the potential to increase the discharge amount of fall flows, yet the onset is mostly dictated by climate change.

With continued climate warming, the observed trends towards decreased SWE, earlier meltseason, lowered summer precipitation and higher evapotranspiration will lead to further declines in summer streamflow. Additionally, declines in summer precipitation and intensified evapotranspiration will also cause higher agricultural water demands. This was already visible in our analysis, showing the enhanced discharge-decrease due to agriculture from Intermediate to Modern timeframes (Figure 4.8). Therefore the curtailment can effect summer streamflow to a certain degree, nevertheless, as most water is lost due to climatic factors, gaining enough flows only due to stopped pumping is unrealistic.

5 Conclusion

5.1 Conclusion

Our study found negative trends in snowpack and summer streamflow and longer lasting lowflow seasons due to increased climate warming, underlines findings of prior research. We were also able to attribute streamflow decline amounts directly to agricultural consumption and climate change using a paired catchment approach. This further validates the method by van Kirk and Naman, 2008 for estimating agricultural influence on streamflow when no data on extracted irrigational water is available. With the presented workflow we were able to show that climate change has become responsible for the largest portion of declines in late summer discharges in our case study catchment. Additionally our analyses revealed, that agricultural water consumption influences streamflow even after pumping stops and precipitation increases in early fall. We attribute this lag time to groundwater transit times, slowing its reaction to external influences. In consequence, we conclude, that the current curtailment regulatory system in our case study basin is ineffective for directly returning summer flows when only applied in critical low discharge month. As the streamflow exhibits a strong interaction with groundwater, further research could focus on artificial aquifer recharge during high flow winter month. This could increase the groundwater-table enough to potentially buffer declines due to summer pumping, thereby increasing summer flow. However, our study showed, that effects of human induced warming heavily and increasingly influence hydrologic systems. Therefore, regional scale management efforts have limited effectiveness and should be enhanced by national and global efforts in mitigation and adaptation to climate change.

A Appendix Streamflow Trend Graphics

A.1 Streamflow

For information on how to read these figures see caption of Figures 4.4 and 4.4

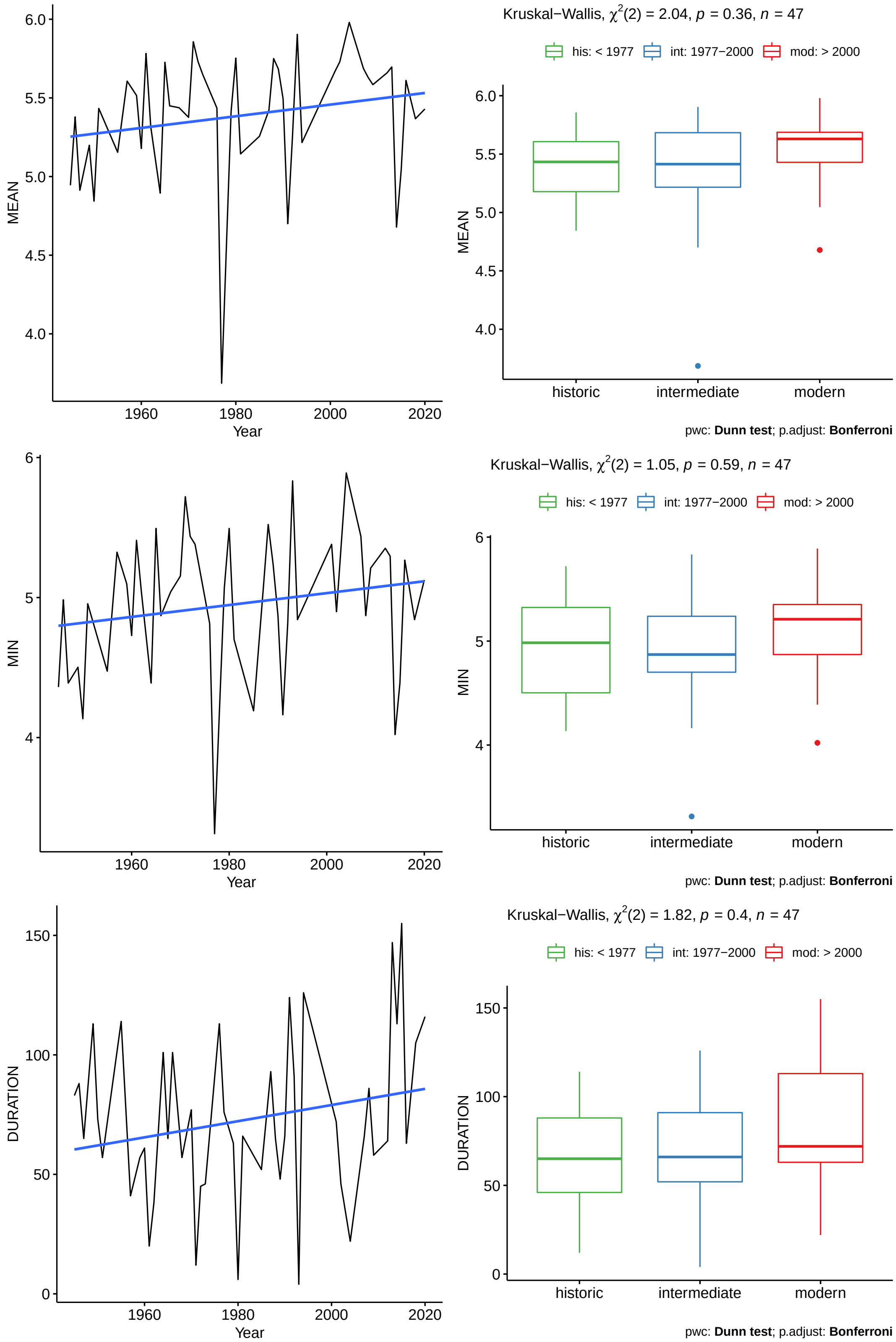


FIGURE A.1: Sacramento (Delta) Catchment (11342000) Mean, Min, Duration

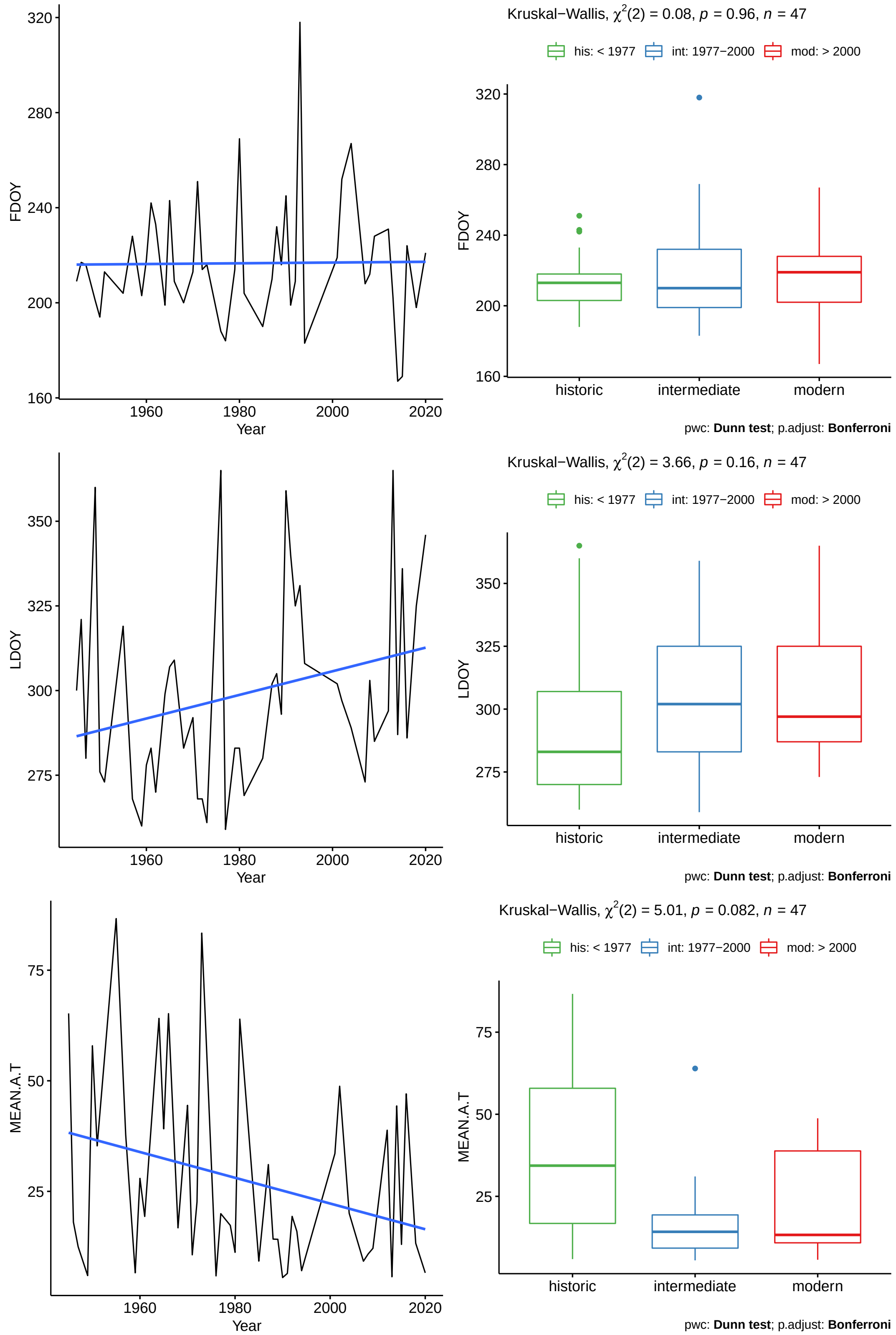


FIGURE A.2: Sacramento (Delta) Catchment (11342000) LDOY, FDOY, MEAN.A.T.

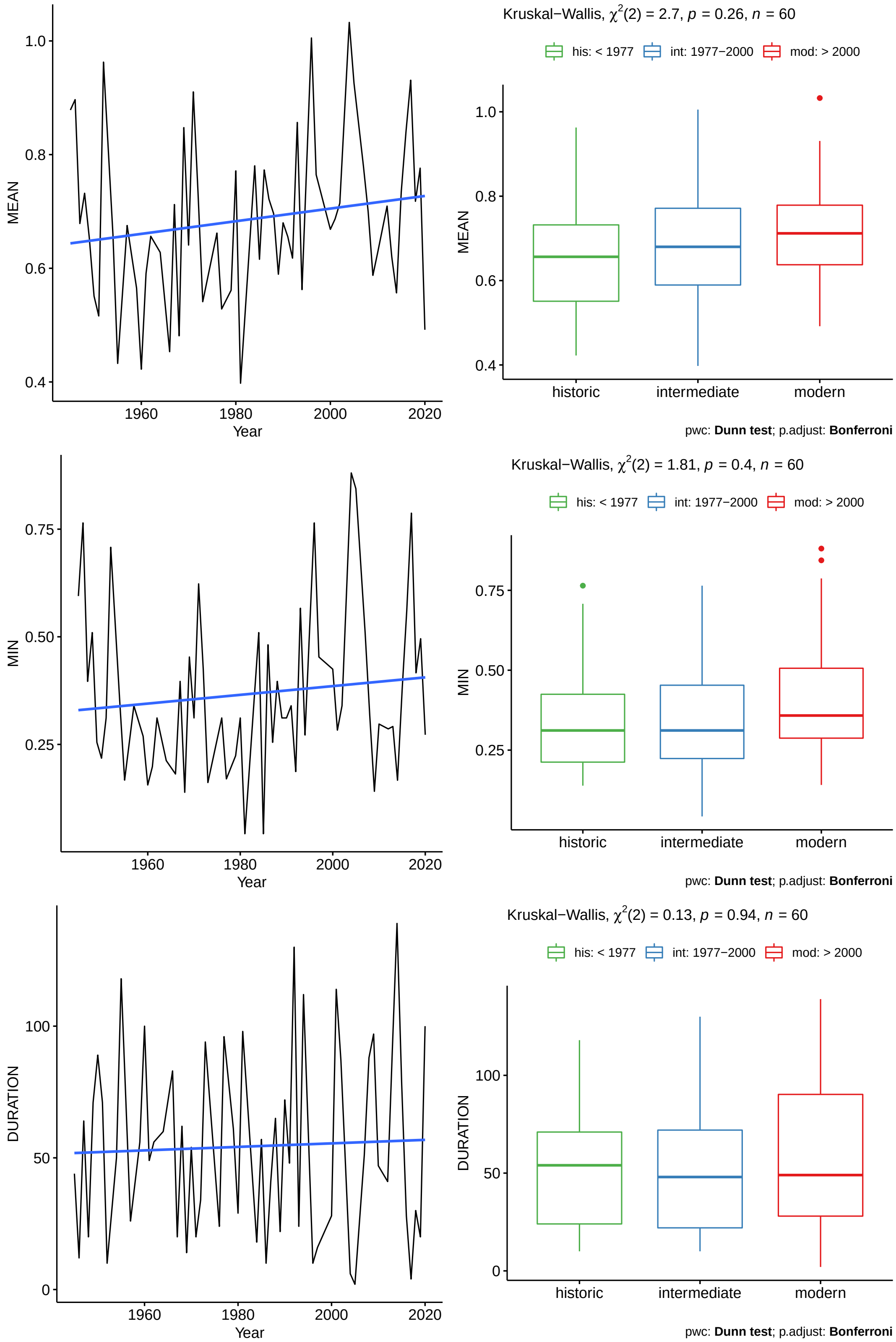


FIGURE A.3: Shasta (Yreka) Cacthment (11517500) Mean, Min, Duration

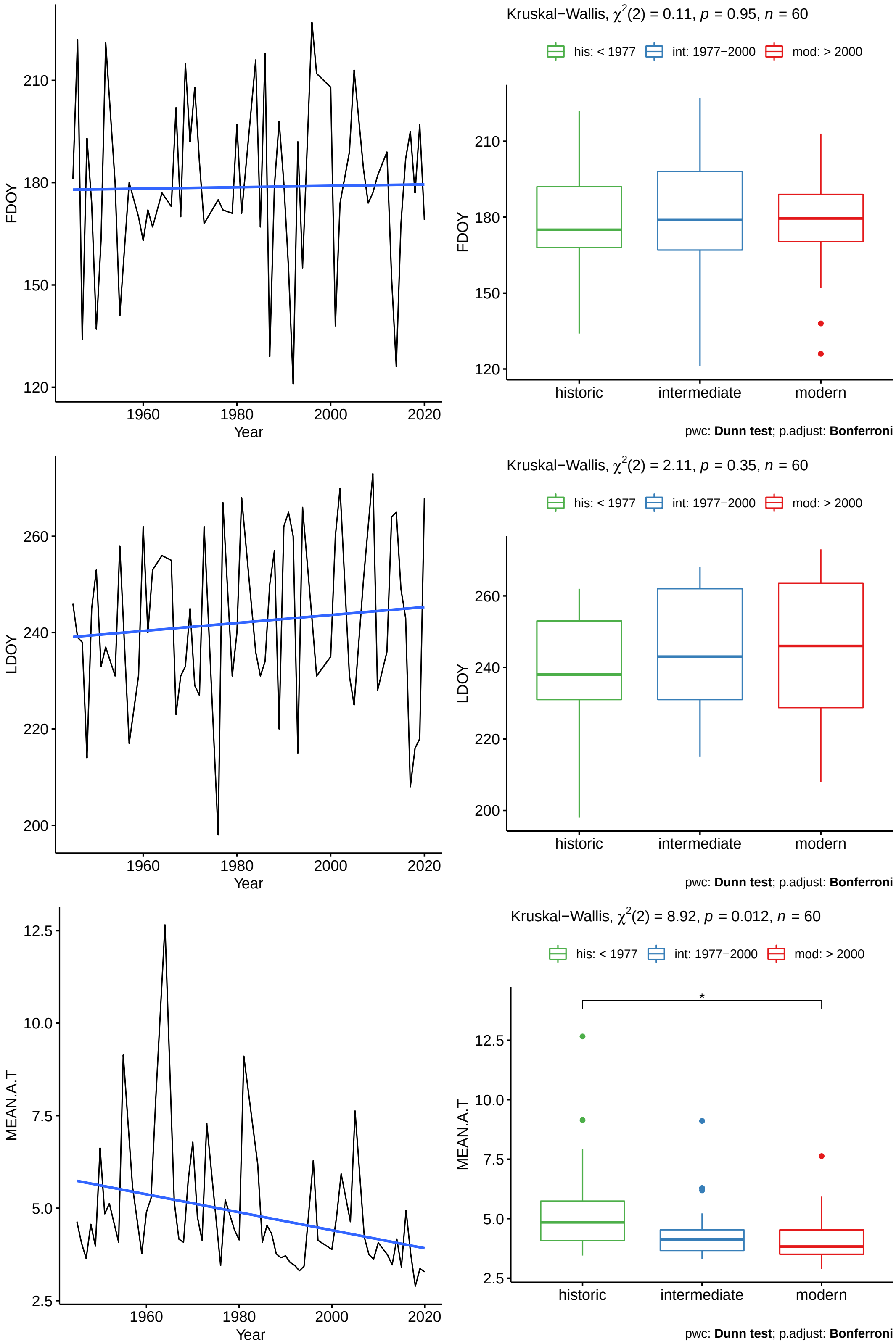


FIGURE A.4: Shasta (Yreka) Cacthment (11517500) LDOY, FDOY, MEAN.A.T.

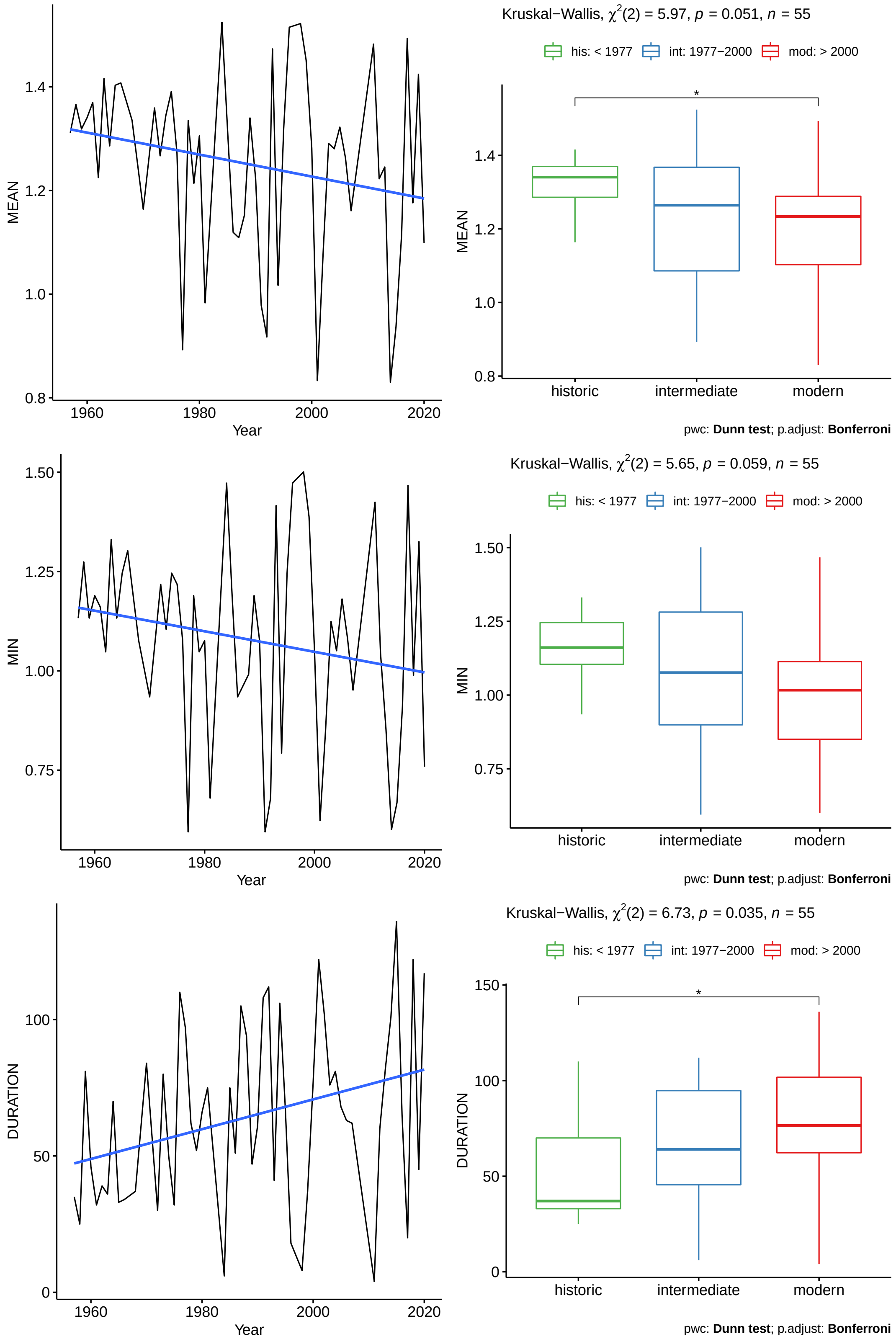


FIGURE A.5: Indian (Happy Camp) Catchment (11521500) Mean, Min, Duration

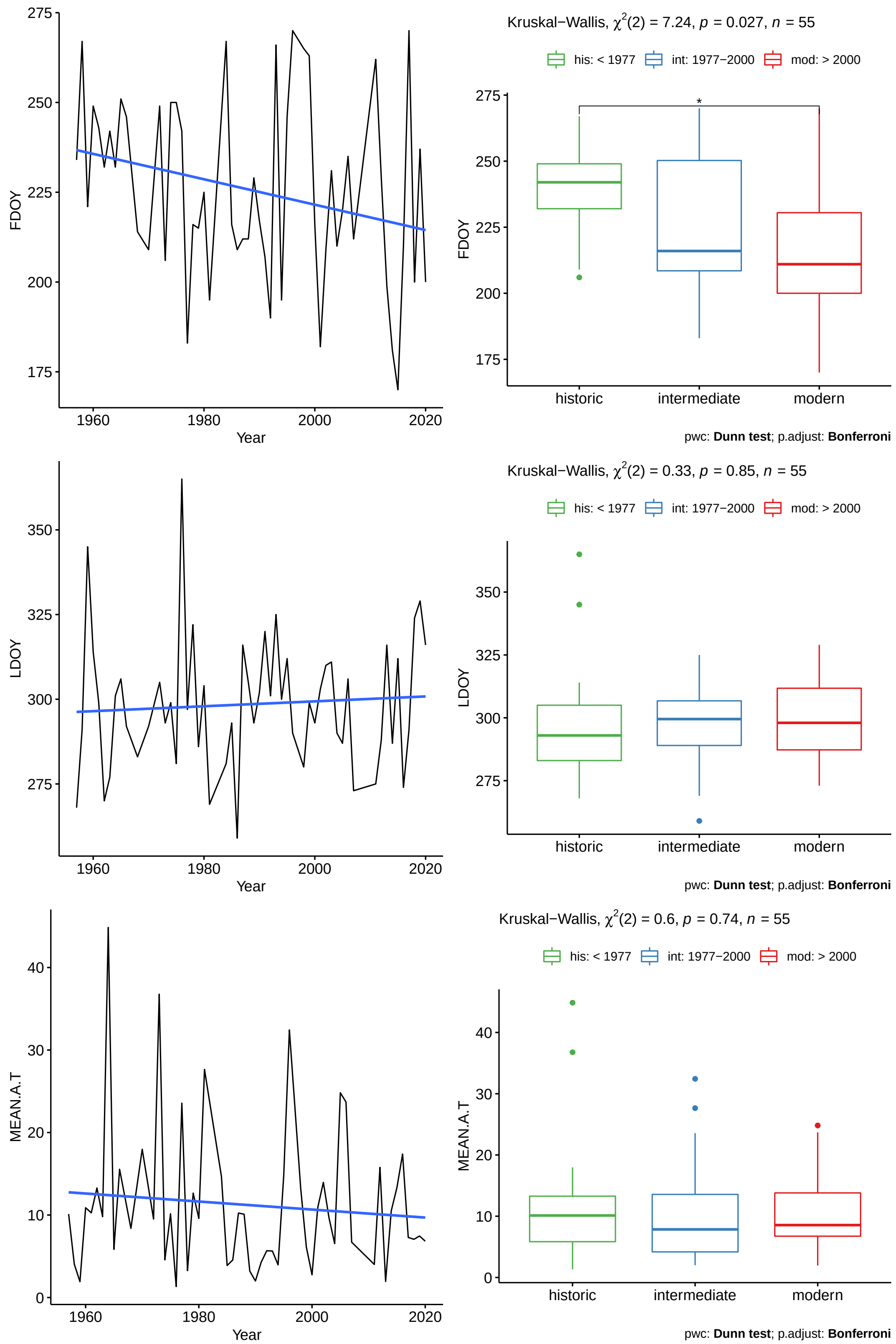


FIGURE A.6: Indian (Happy Camp) Catchment (11521500) LDOY, FDOY, MEAN.A.T.

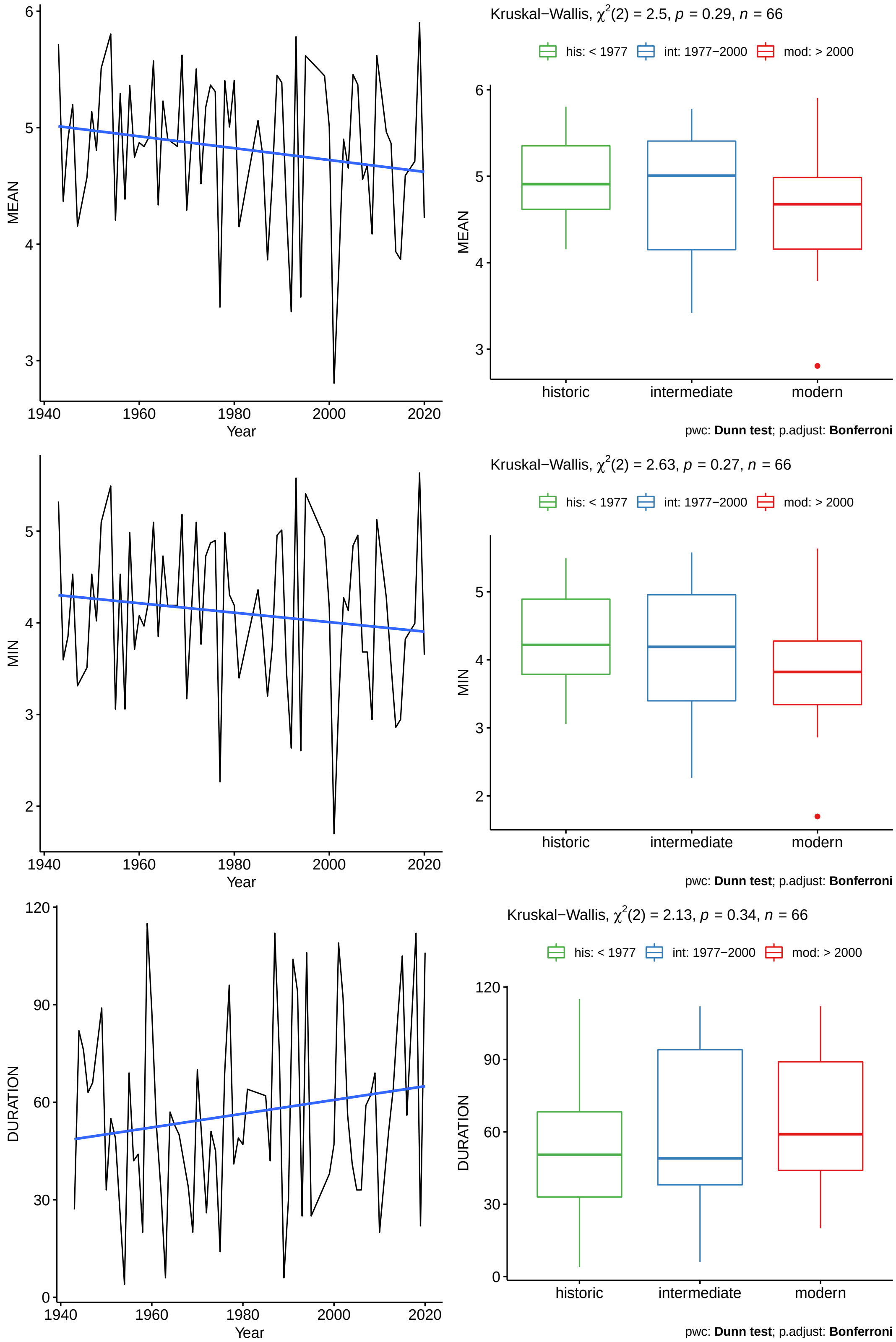


FIGURE A.7: Salmon (Somes Bar) Catchment (11522500) Mean, Min, Duration

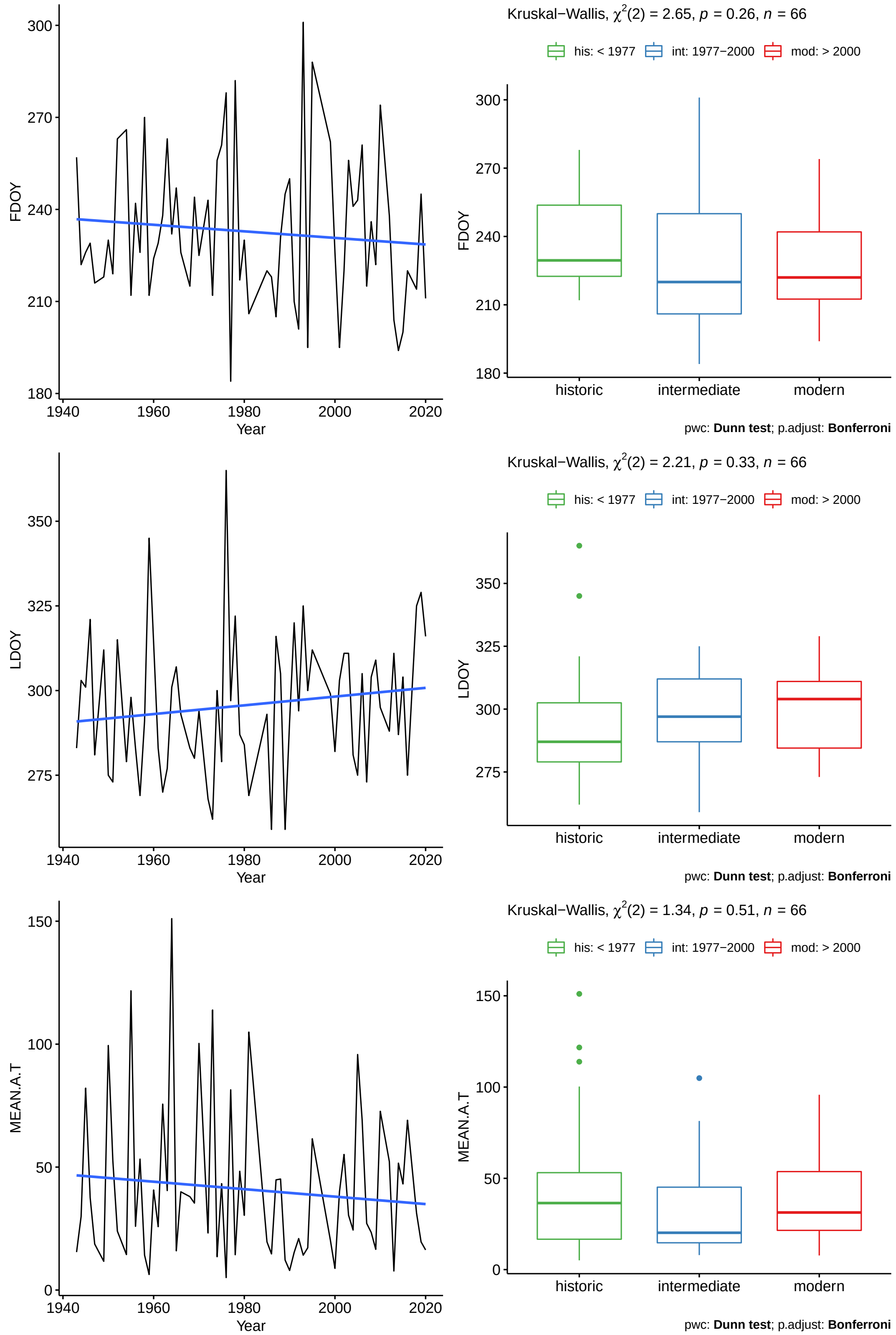


FIGURE A.8: Salmon (Somes Bar) Catchment (11522500) LDOY, FDOY, MEAN.A.T.

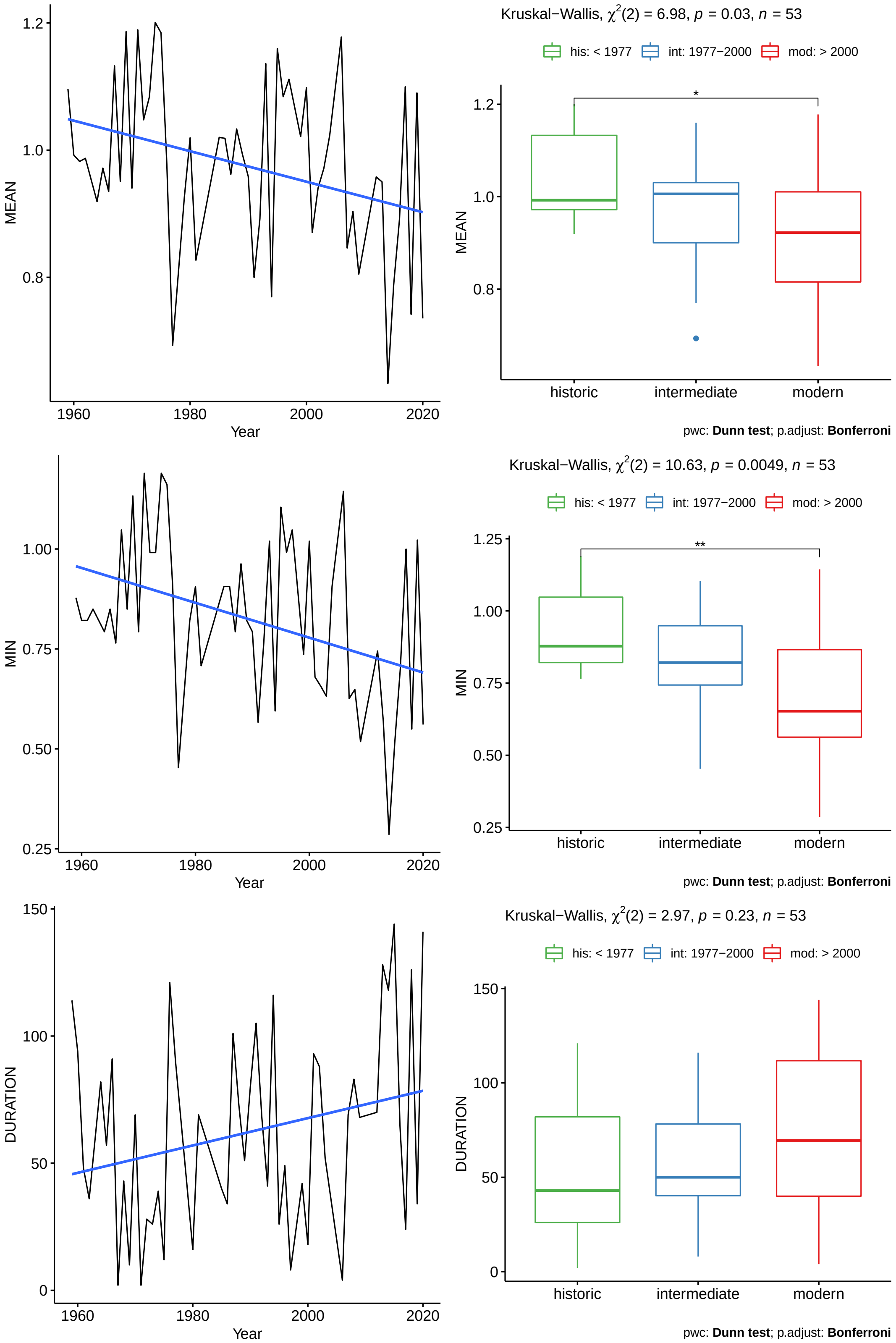


FIGURE A.9: Trinity (Trinity Center) Catchment (11523200) Mean, Min, Duration

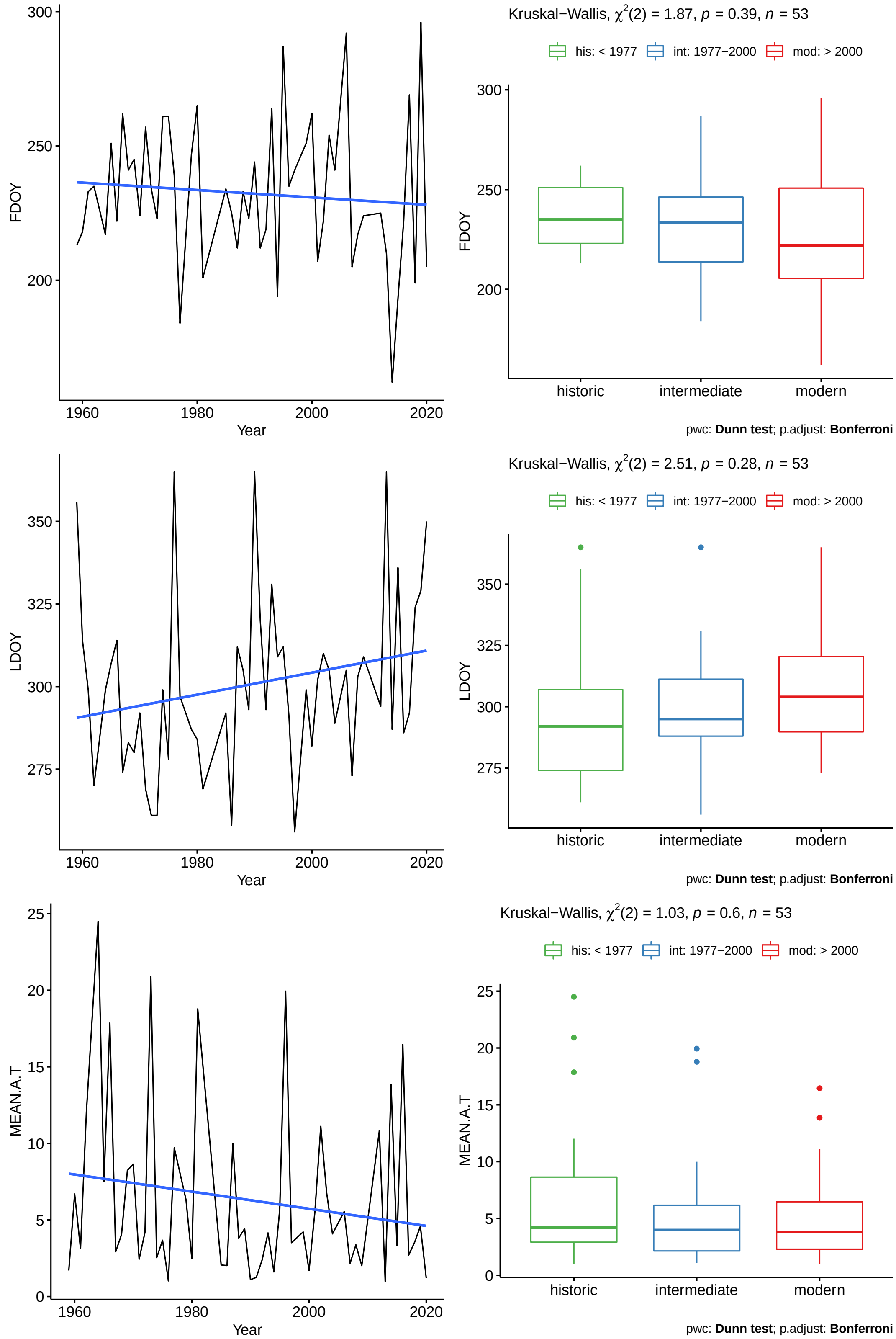


FIGURE A.10: Trinity (Trinity Center) Catchment (11523200) LDOY, FDOY, MEAN.A.T.

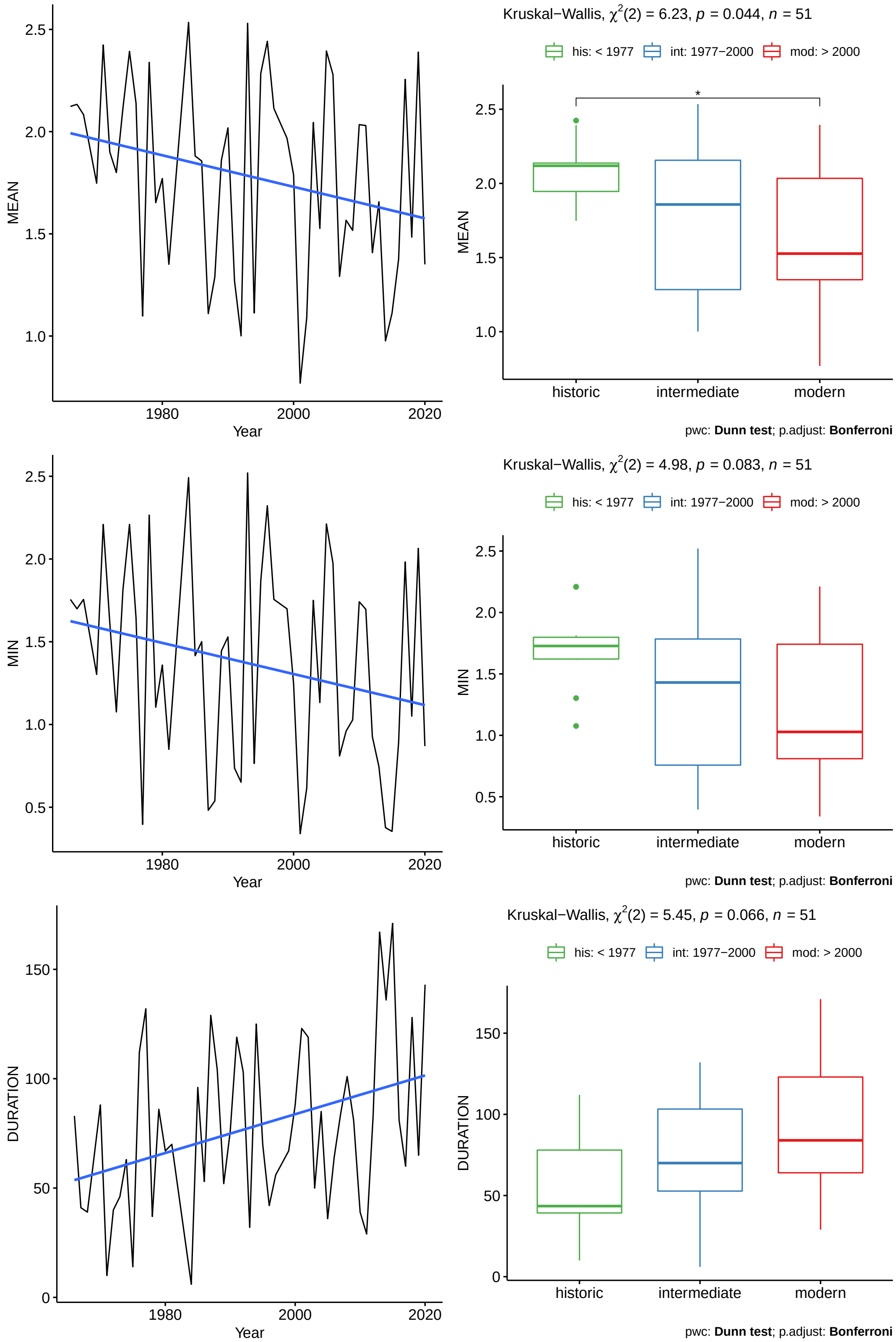


FIGURE A.11: Trinity (Hyampom) Catchment (11528700) Mean, Min, Duration

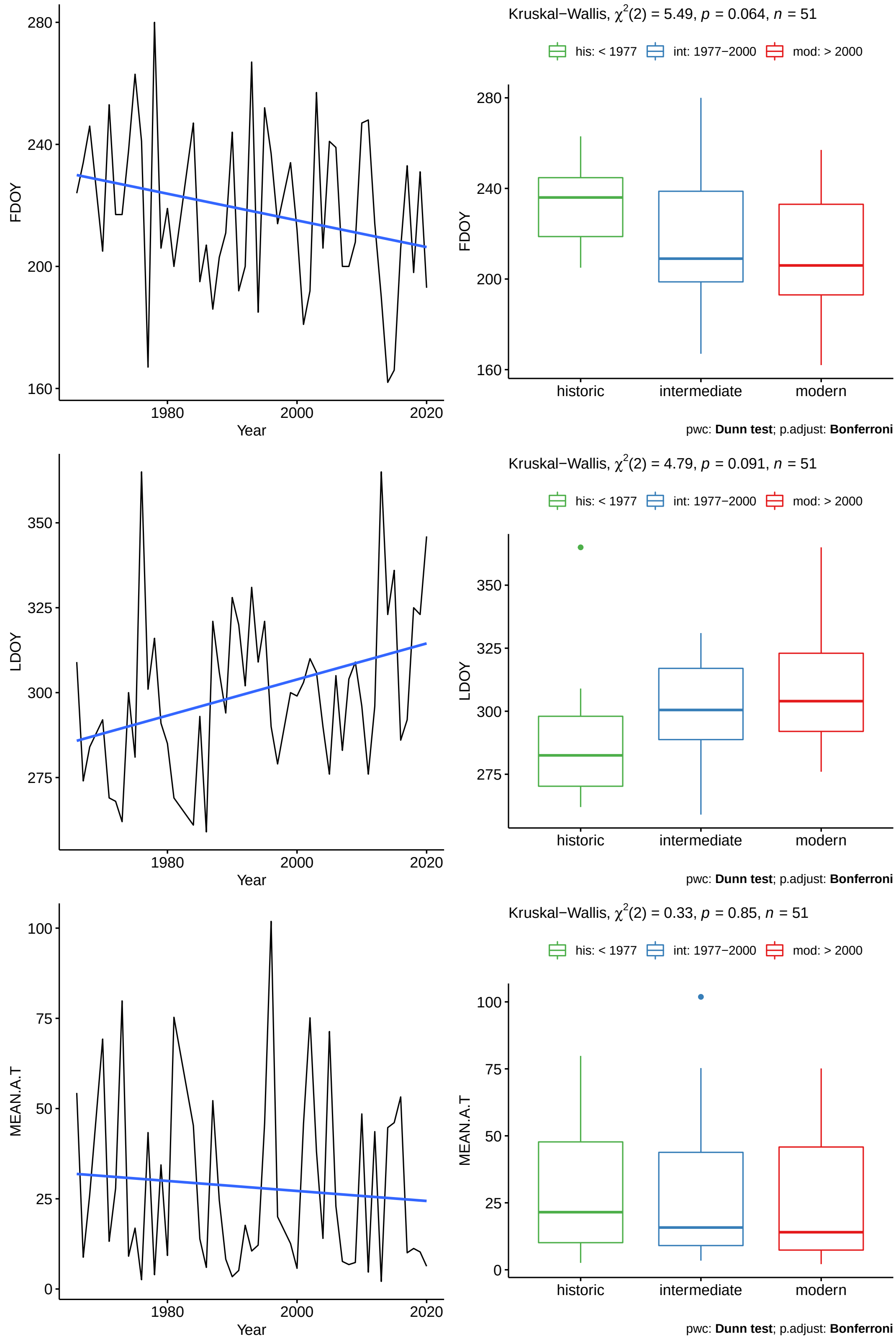


FIGURE A.12: Trinity (Hyampom) Catchment (11528700) LDOY, FDOY, MEAN.A.T.

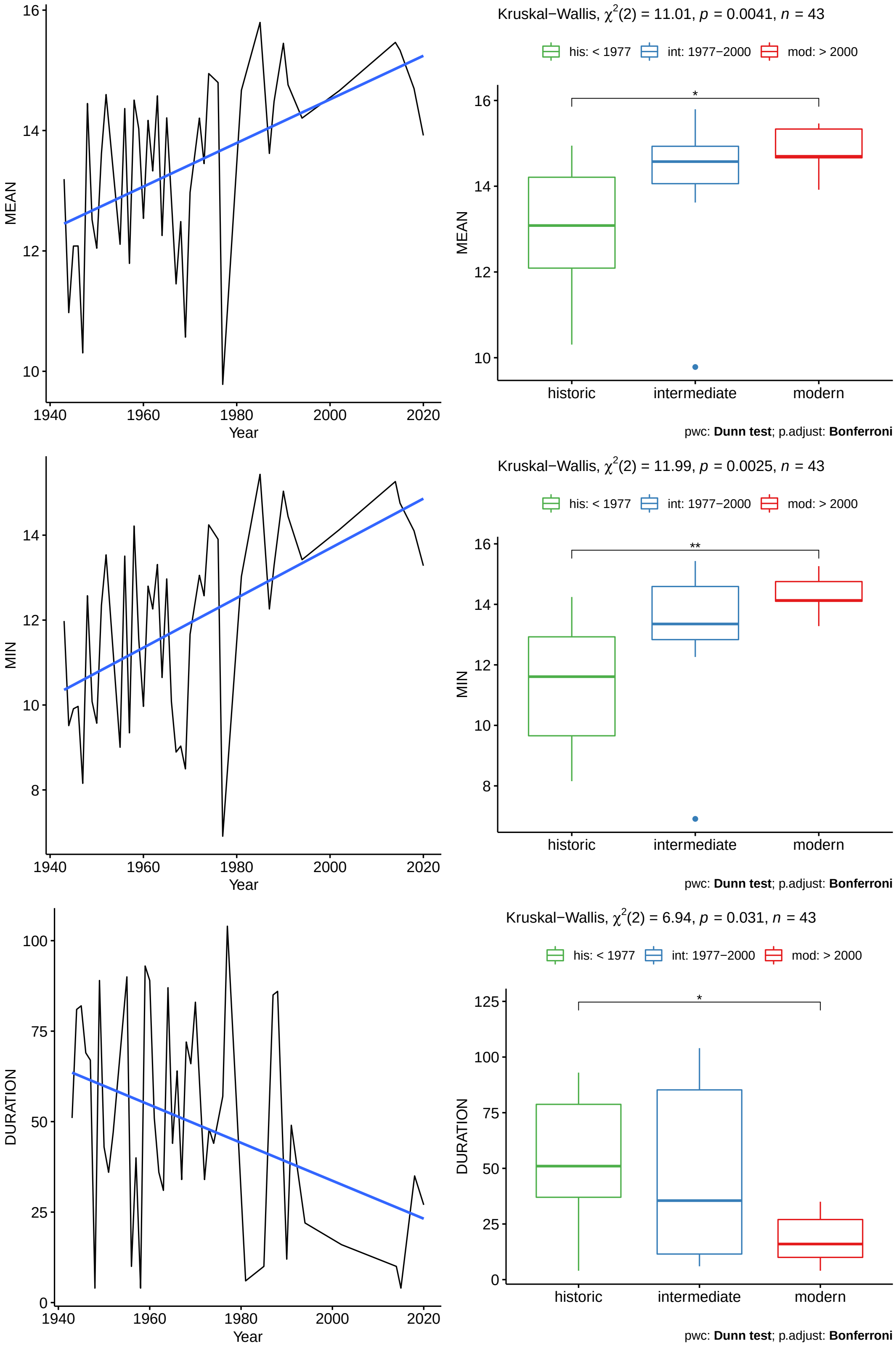


FIGURE A.13: Trinity (Hoopa) Catchment (11530000) Mean, Min, Duration

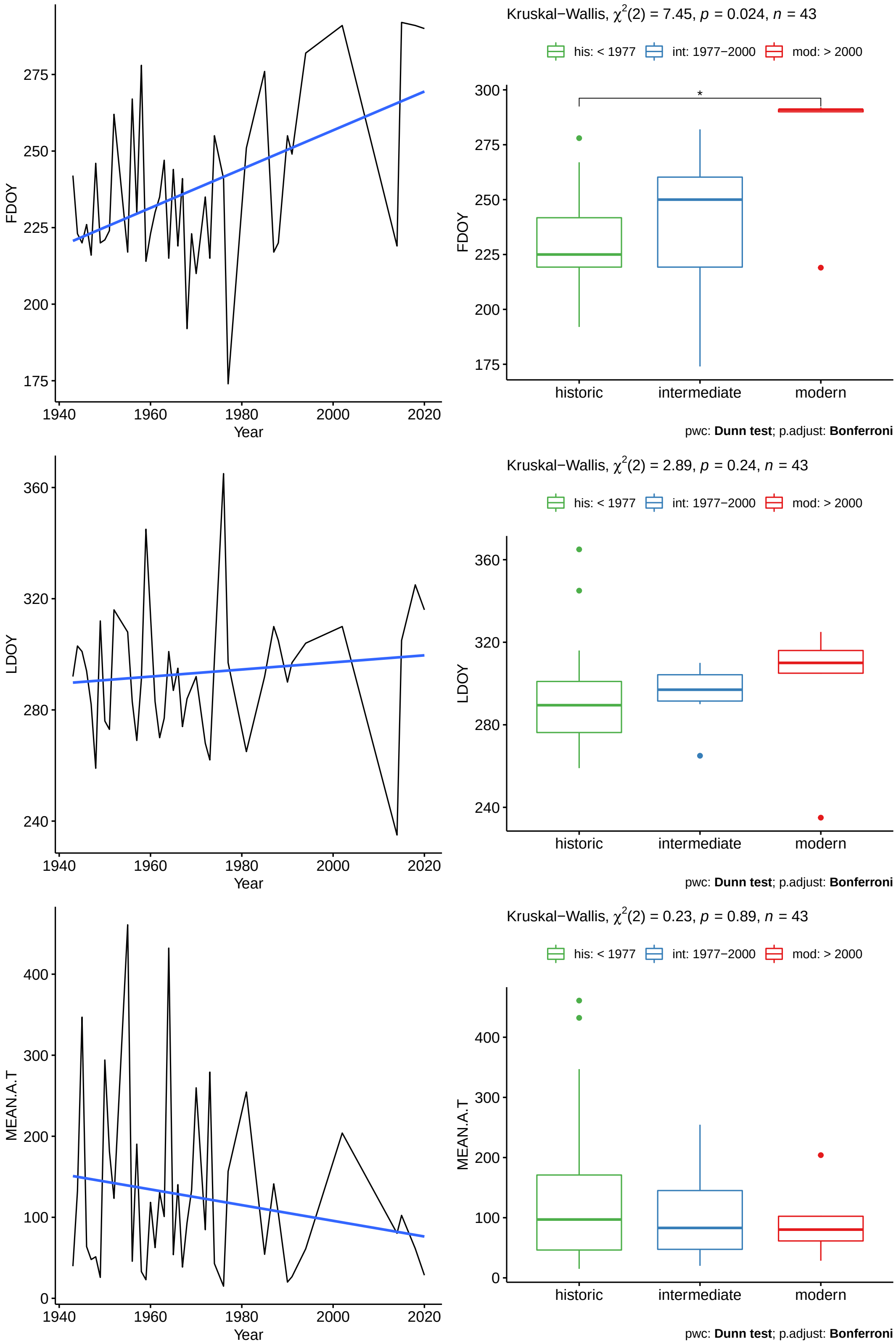


FIGURE A.14: Trinity (Hoopa) Catchment (11530000) LDOY, FDOY, MEAN.A.T.

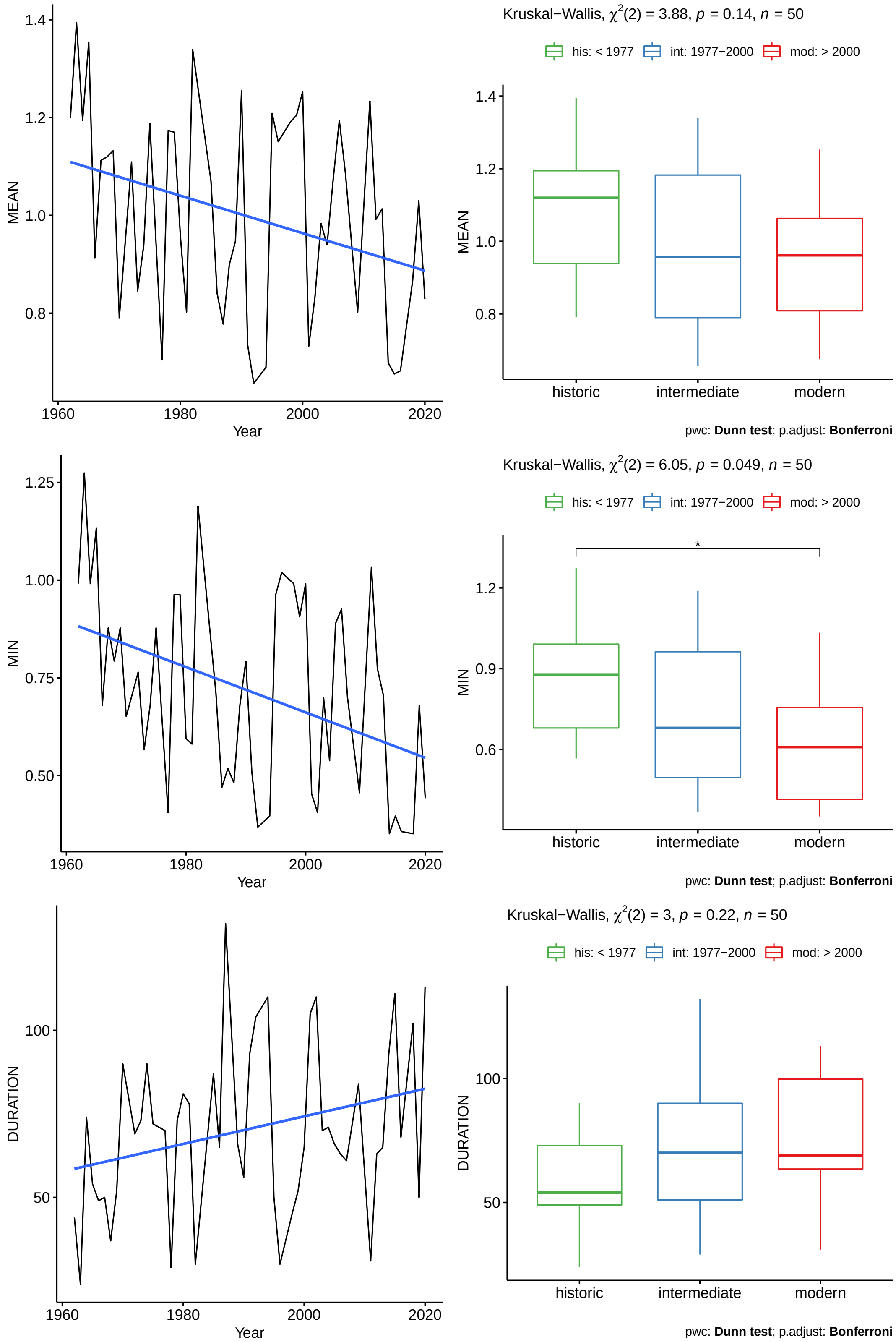


FIGURE A.15: Illinois (Kerby) Catchment (14377100) Mean, Min, Duration

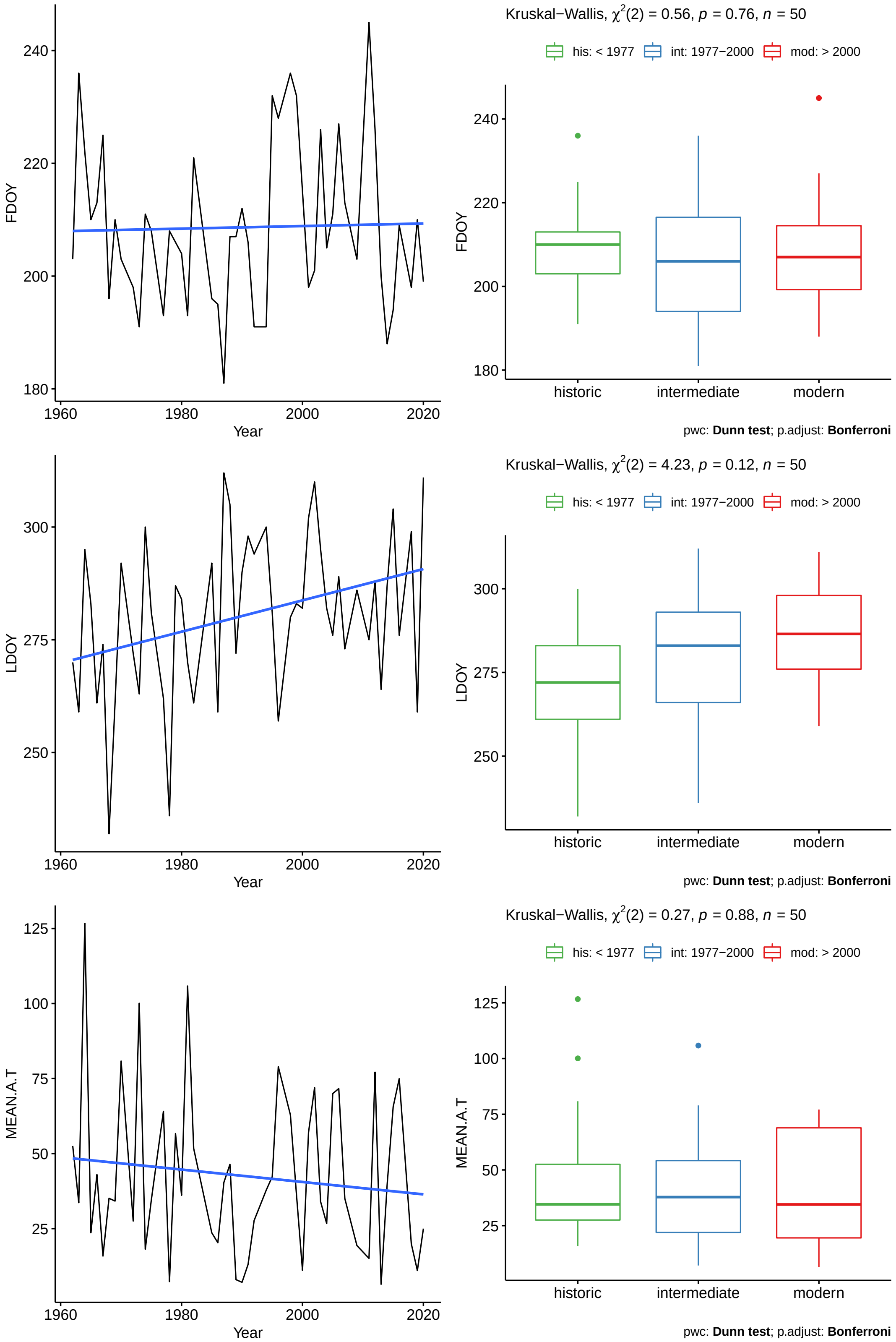


FIGURE A.16: Illinois (Kerby) Catchment (14377100) LDOY, FDOY, MEAN.A.T.

B Appendix SWE Trend Graphics

B.1 April 1 SWE snow courses

For information on how to read these figures see caption of Figure 4.3

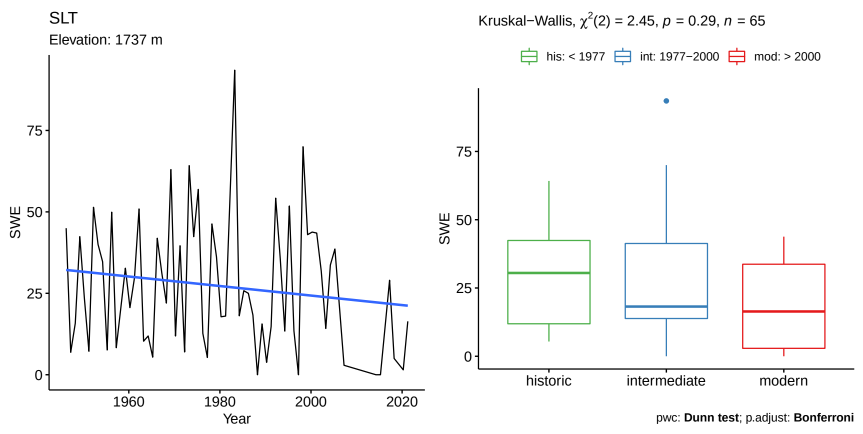


FIGURE B.1: SLT

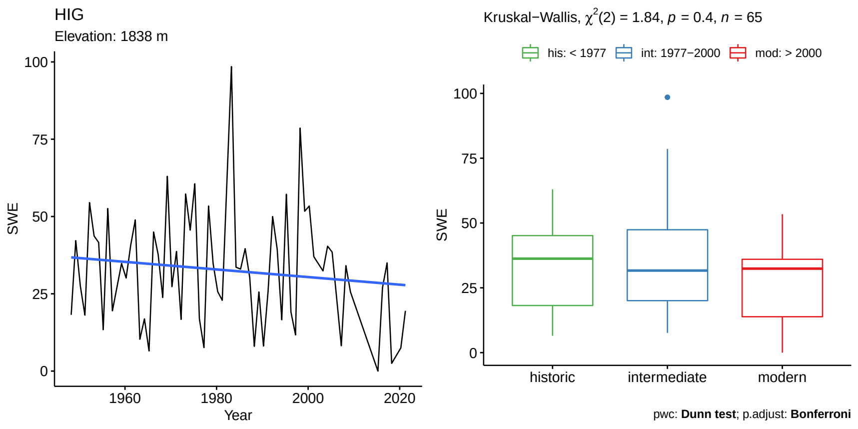


FIGURE B.2: HIG snow course

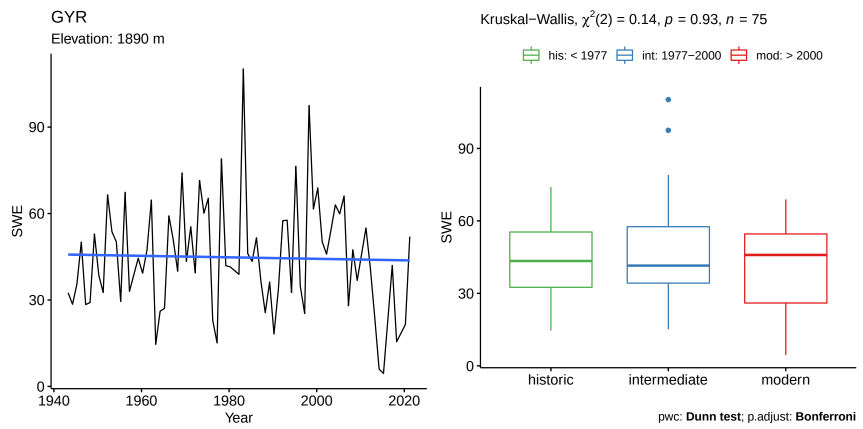


FIGURE B.3: GYR snow course

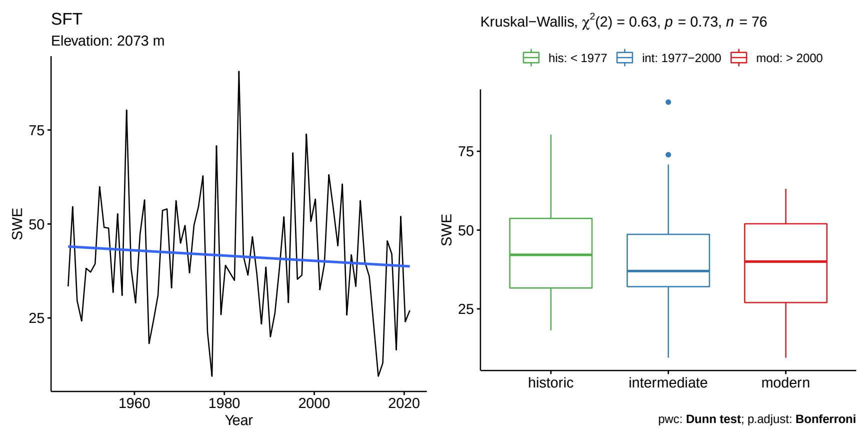


FIGURE B.4: SFT snow course

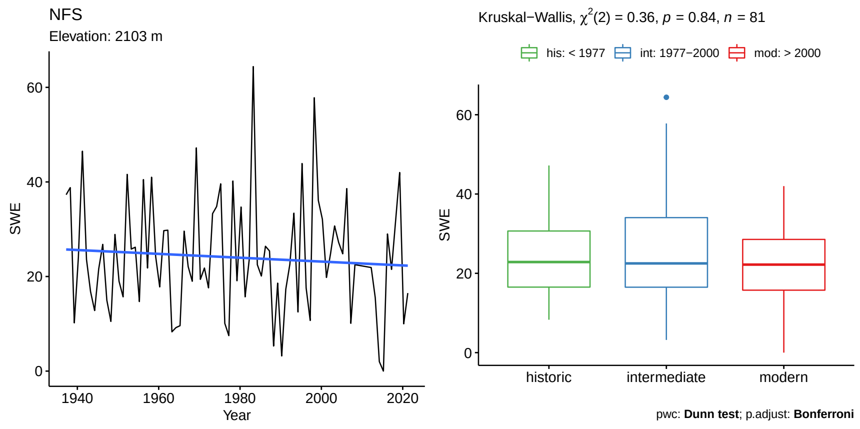


FIGURE B.5: NFS snow course

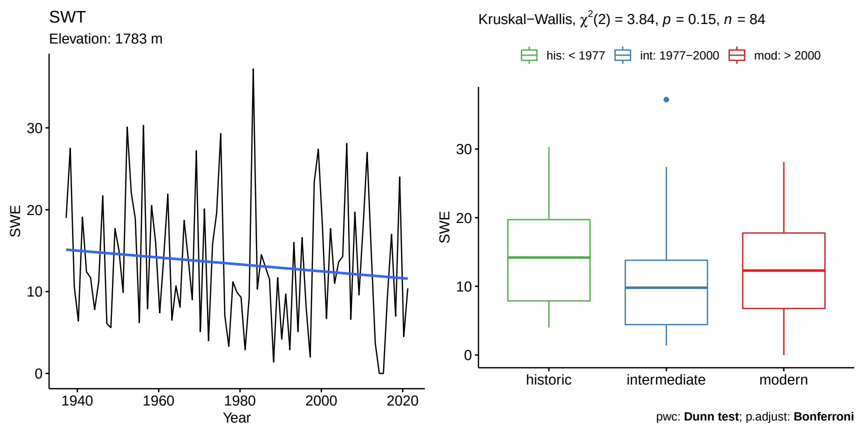


FIGURE B.6: SWT snow course

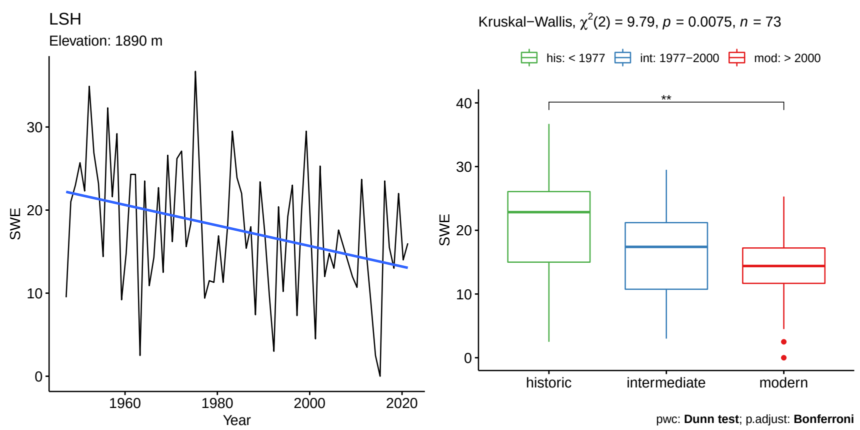


FIGURE B.7: LSH snow course

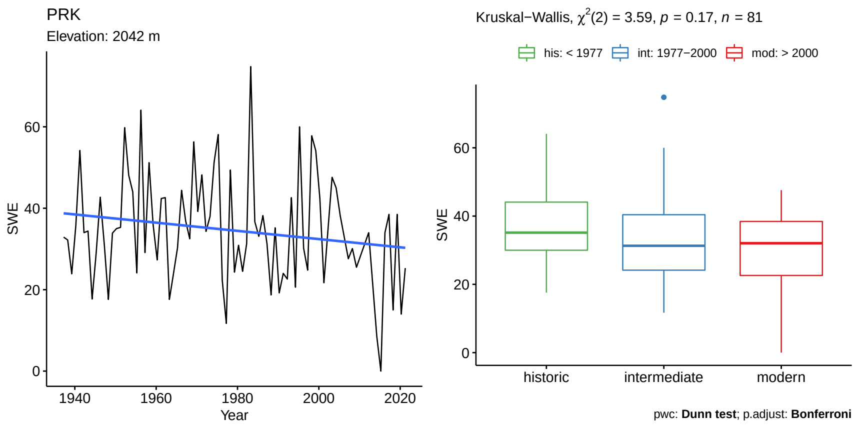


FIGURE B.8: PRK snow course

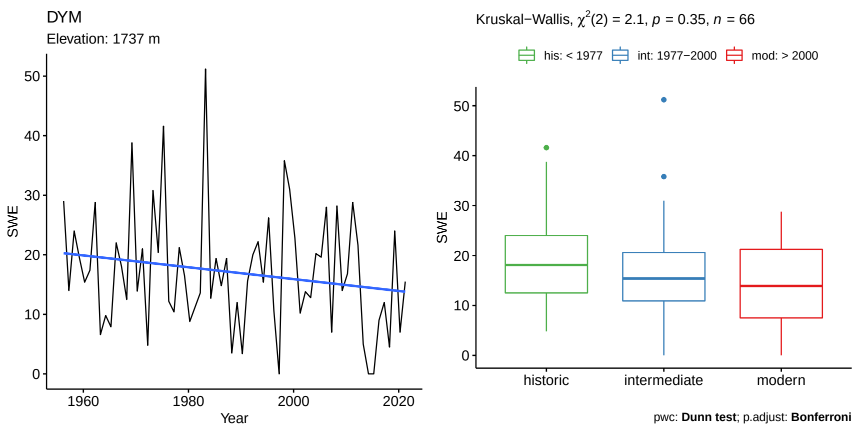


FIGURE B.9: DYM snow course

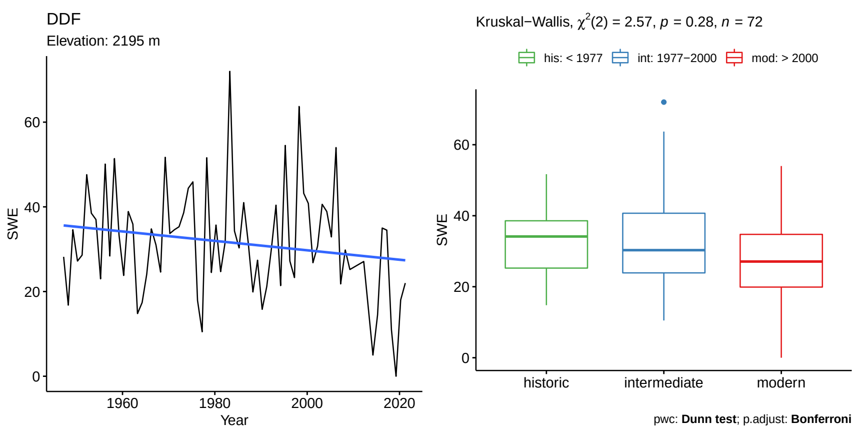


FIGURE B.10: DDF snow course

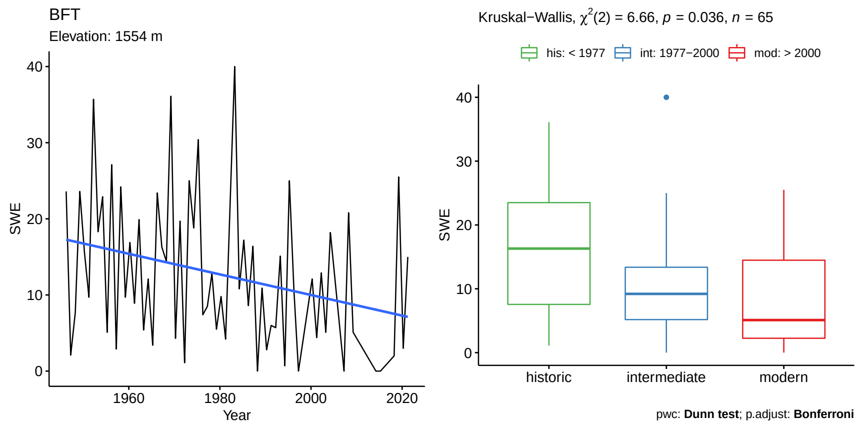


FIGURE B.11: BFT snow course

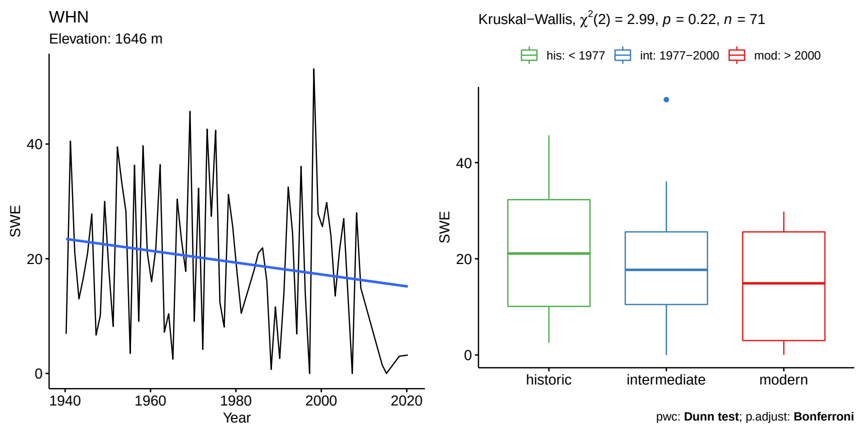


FIGURE B.12: WHN snow course

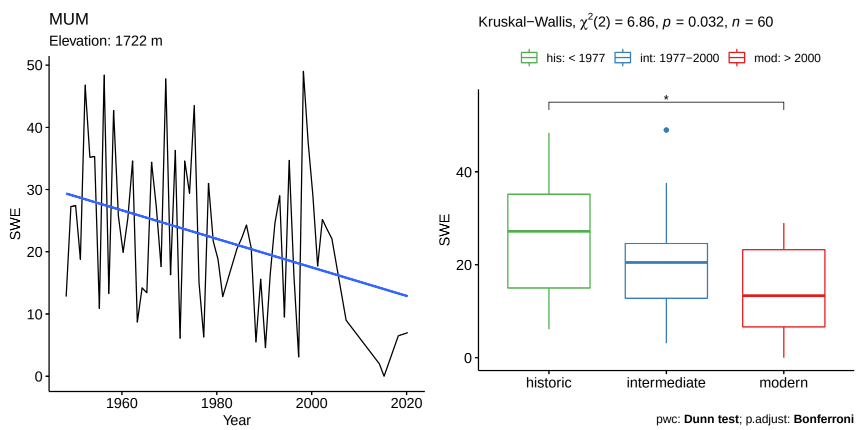


FIGURE B.13: MUM snow course

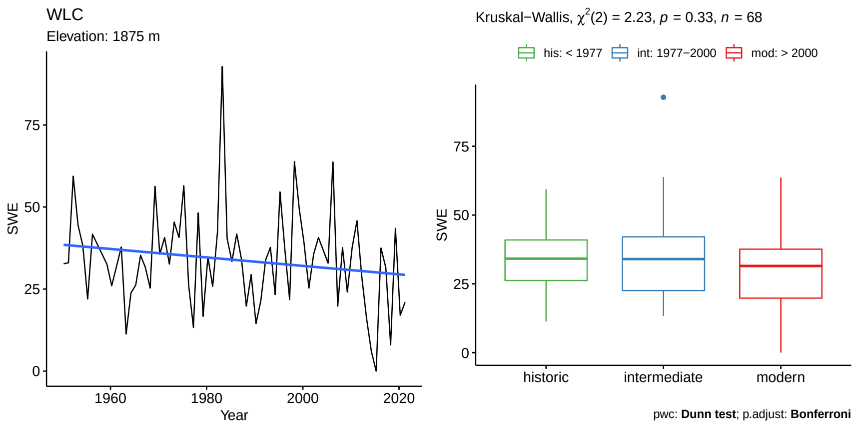


FIGURE B.14: WLC snow course

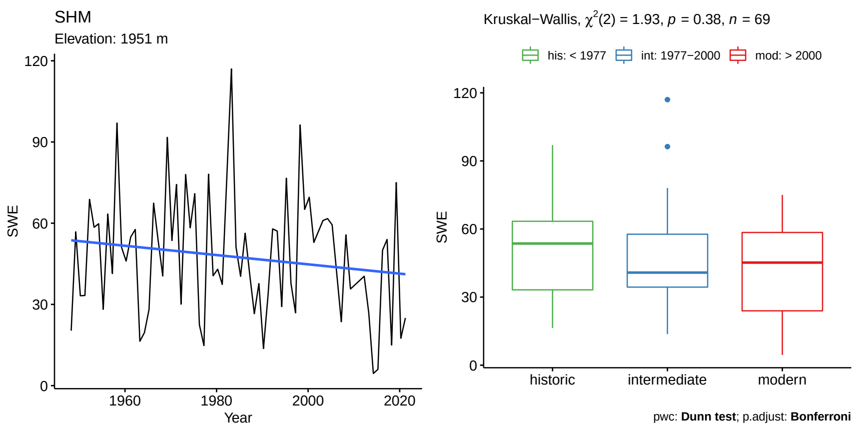


FIGURE B.15: SHM snow course

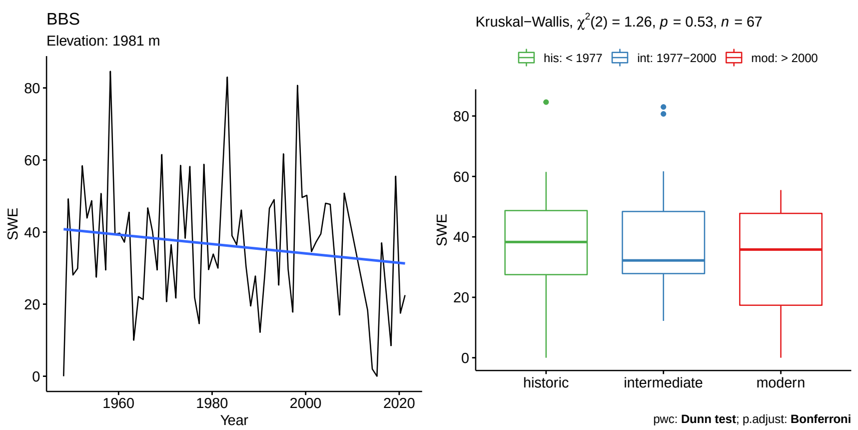


FIGURE B.16: BBS snow course

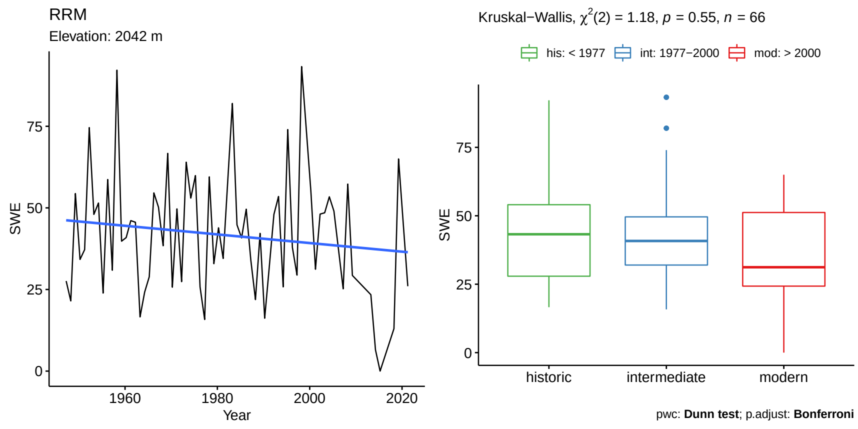


FIGURE B.17: RRM snow course

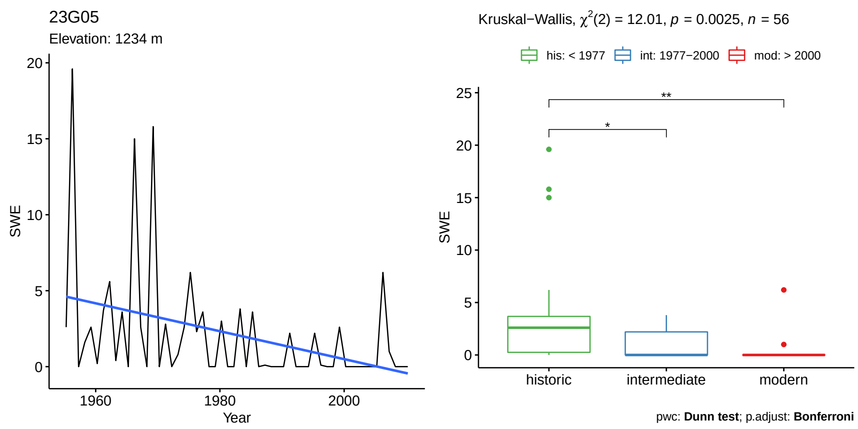


FIGURE B.18: 23G05 snow course

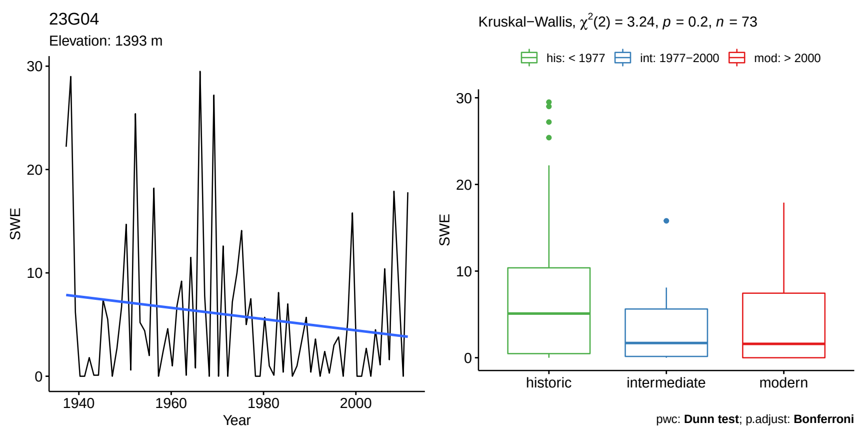


FIGURE B.19: 23G04 snow course

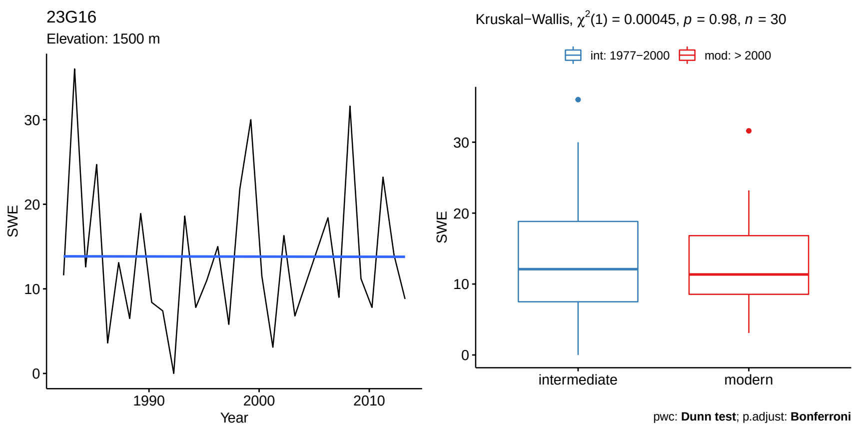


FIGURE B.20: 23G16 snow course

C Appendix Precipitation Trend Graphics

C.1 Precipitation

For information on how to read these figures see caption of Figure 4.1

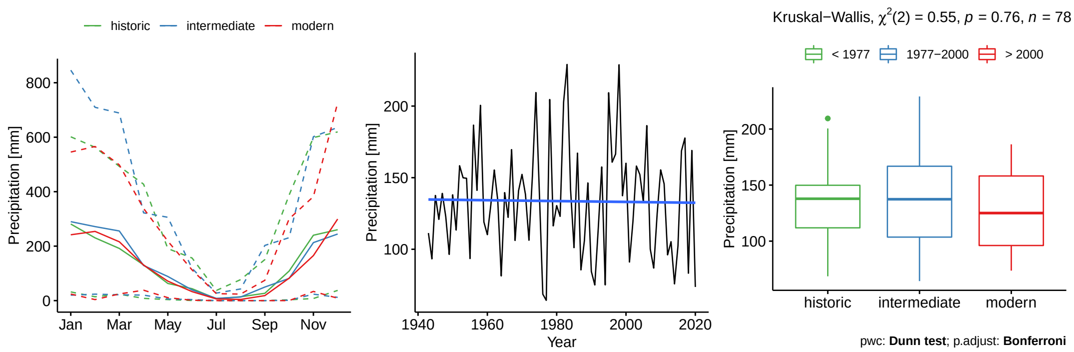


FIGURE C.1: Sacramento (Delta) Catchment (11342000) Precipitation

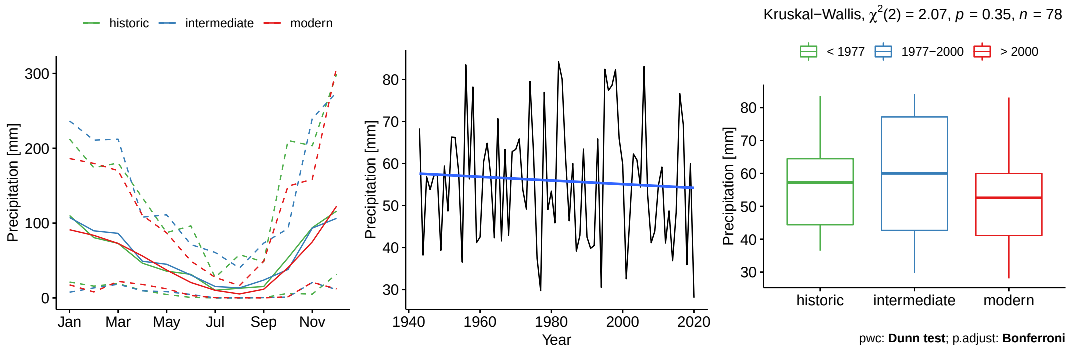


FIGURE C.2: Shasta (Yreka) Cacthment (11517500) Precipitation

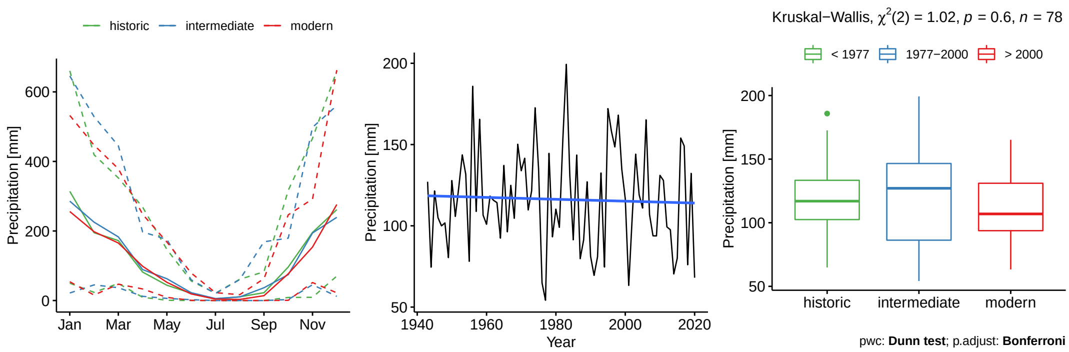


FIGURE C.3: Trinity (Hyampom) Catchment (11528700) Precipitation

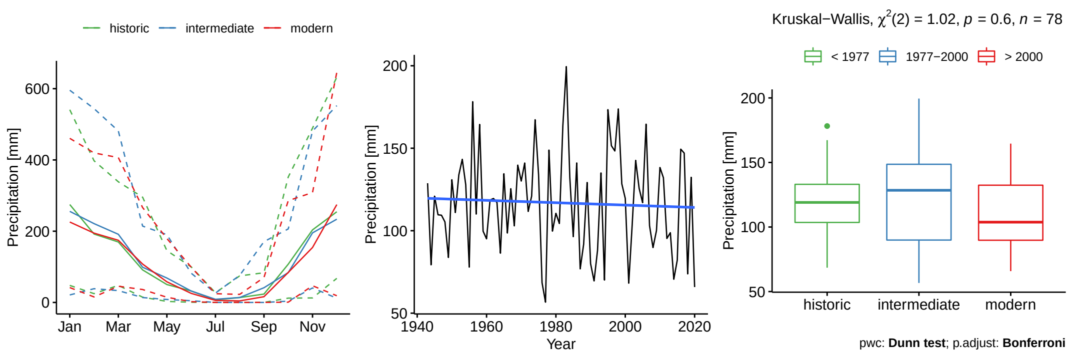


FIGURE C.4: Trinity (Hoopa) Catchment (11530000) Precipitation

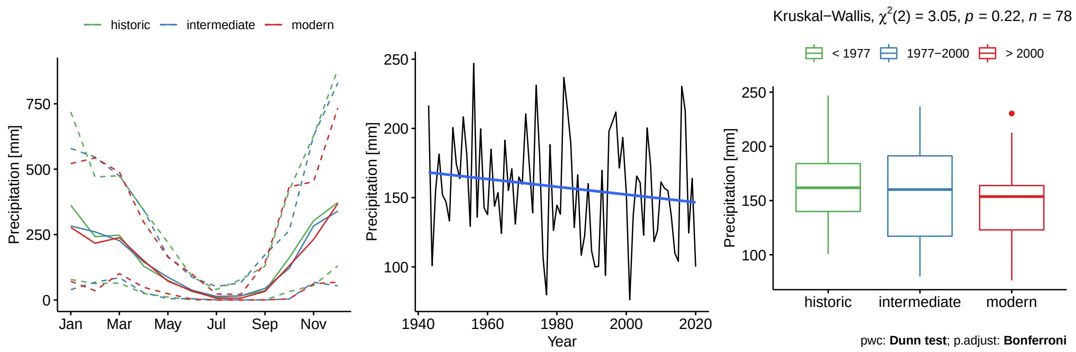


FIGURE C.5: Illinois (Kerby) Catchment (14377100) Precipitation

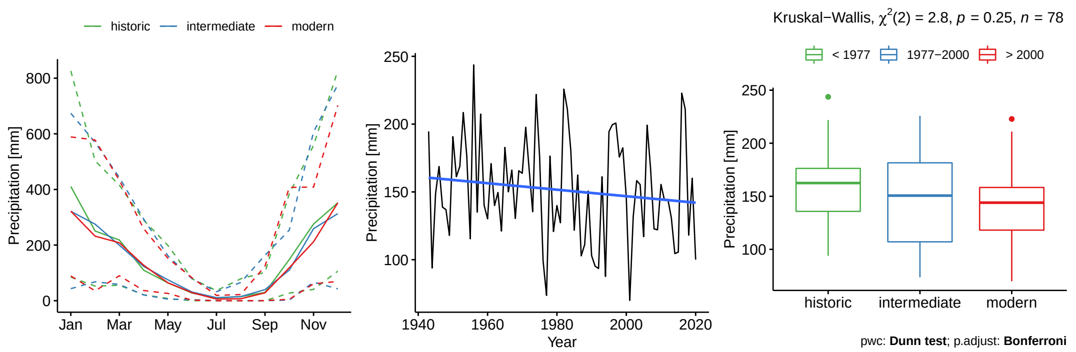


FIGURE C.6: Indian (Happy Camp) Catchment (11521500) Precipitation

D Appendix Maximum Vapor Pressure Deficit Trend Graphics

D.1 Maximum Vapor Pressure Deficit

For information on how to read these figures see caption of Figure 4.2

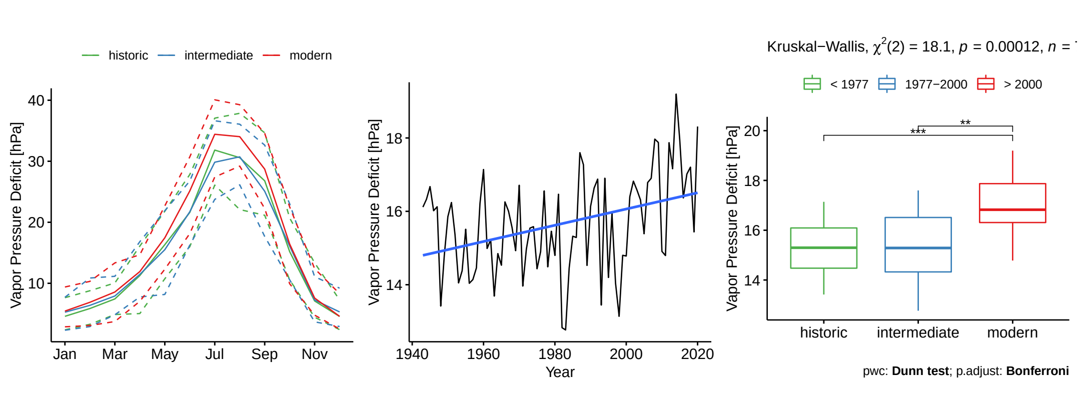


FIGURE D.1: Sacramento (Delta) Catchment (11342000) Maximum Vapor Pressure Deficit

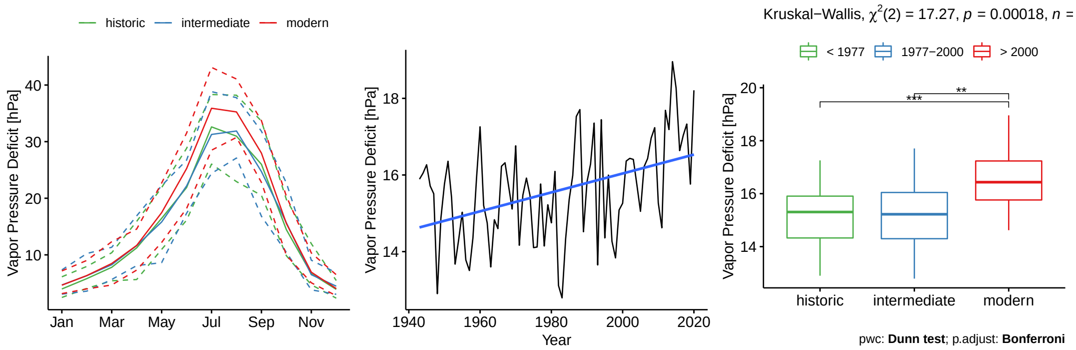


FIGURE D.2: Shasta (Yreka) Cacthment (11517500) Maximum Vapor Pressure Deficit

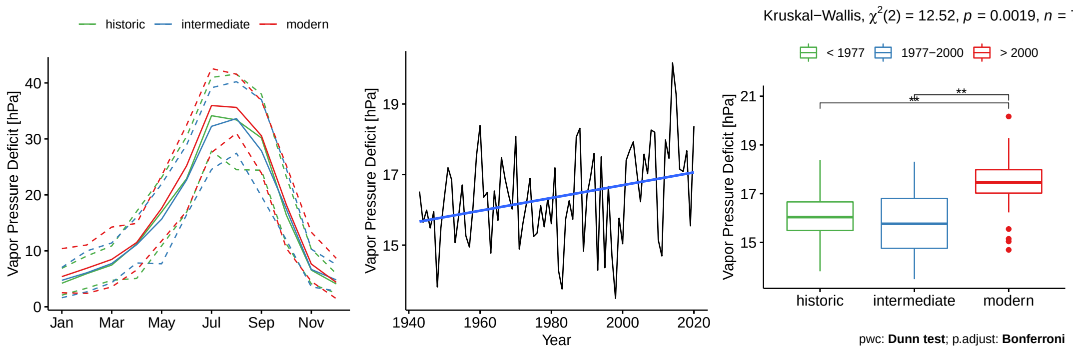


FIGURE D.3: Trinity (Hyampom) Catchment (11528700) Maximum Vapor Pressure Deficit

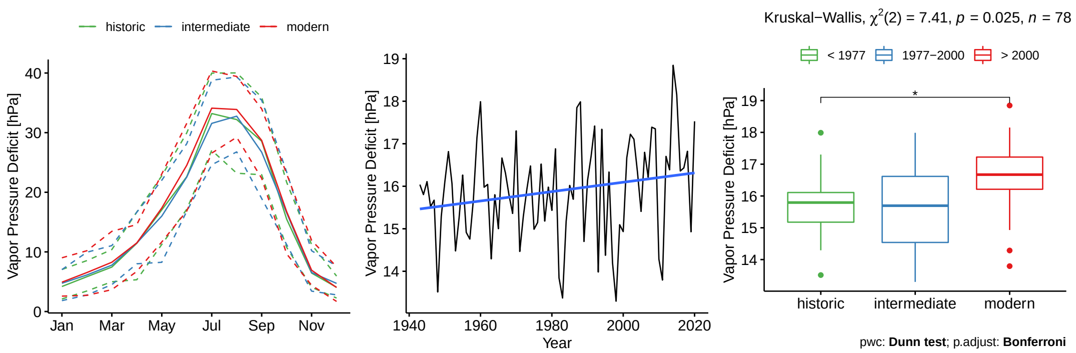


FIGURE D.4: Trinity (Hoopa) Catchment (11530000) Maximum Vapor Pressure Deficit

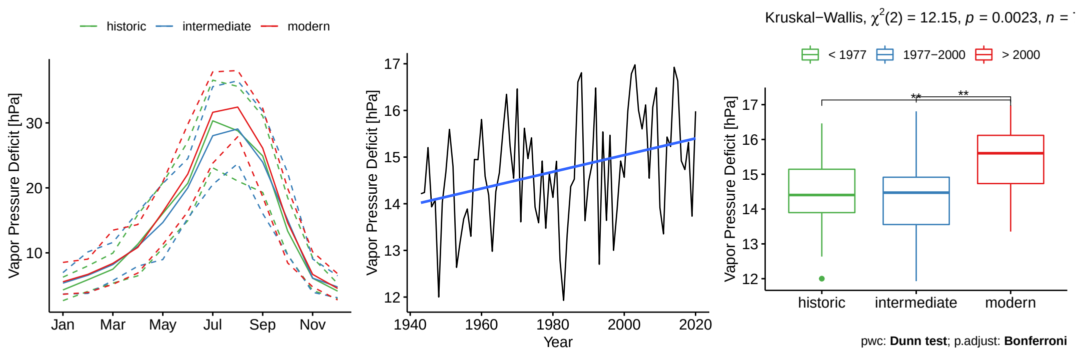


FIGURE D.5: Illinois (Kerby) Catchment (14377100) Maximum Vapor Pressure Deficit

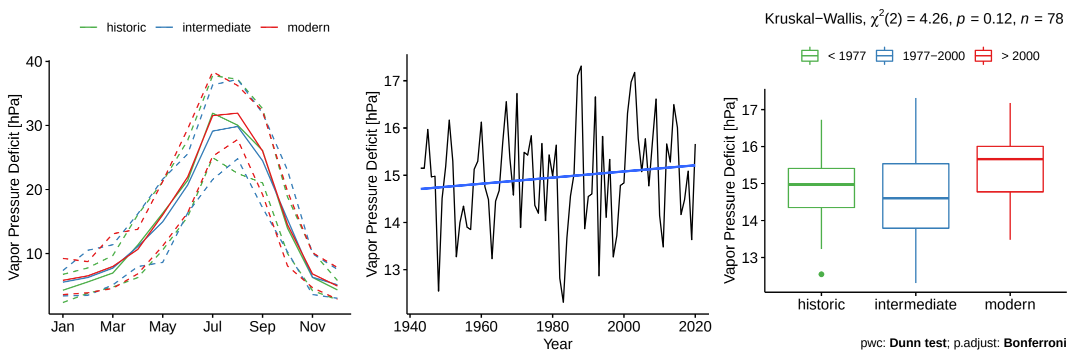


FIGURE D.6: Indian (Happy Camp) Catchment (11521500) Maximum Vapor Pressure Deficit

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